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MARINE SCIENCES INSTRUMENTATION

Volume 2

PROCEEDINGS
of the
SYMPOSIUM ON TRANSDUCERS FOR OCEANIC RESEARCH

Held November 8-9, 1962, at
San Diego, California

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PREFACE

The scope of the "Symposium on Transducers for Oceanic Research" was expressly limited to measurement devices because it seemed that transducers present the greatest technological obstacles to the advance of research in and over the ocean. It is appropriate that the second major meeting staged by the Marine Sciences Division of the Instrument Society of America should focus on the basic sensing devices in spite of the fact that national attention in oceanography, undersea warfare and marine engineering seems to be concerned with large systems and elaborate schemes. Ocean science and technology, under the pressure of practical demands for knowledge, is placing considerable stress on mental and physical resources at hand. In the final analysis scientific goals and operational concepts must recognize the limitations of tools and technology available for measurement if their planning is not to lead to frustration and failure.

Oceanography, like all other experimental sciences, requires the services of scientists and engineers from fields far removed from its basic areas of inquiry. Until fairly recently this requirement has been met by a small number of extremely versatile men who managed to design, and frequently hand-build, the apparatus they needed for their investigations. Most of the successful instruments in use today derive from this source. Present needs for instrumentation exceed the capacity of those rarely talented individuals who can bridge the gap between science and engineering with proficiency.

As the ocean research effort gains momentum organizations and professional people are moving with their talents and experience from related fields in an attempt to fill the stated needs. These same demands are pressing specialization and consequently widening the gap between people who design instruments and those who use them. Success must necessarily depend on the degree of mixing achieved. The science will not be served by conversations held exclusively among instrumentation engineers, nor are better instruments likely to appear unless scientists are continuously aware of advances in technology. Statements of needs and appreciation for the limits within which they may be satisfied are necessary before the applied scientist and engineer can offer the new measurement techniques that may make feasible previously impossible experiments. We believe that the collection of papers in this volume shows a high degree of mixing and offers a significant contribution to the fund of knowledge so essential to the advance of marine science.

During the course of the Symposium from which this volume has been drawn, one of the most successful practitioners of the art of oceanographic instrumentation remarked that he was disappointed in the number of papers describing instruments that had not yet emerged from the laboratory. His criterion for a successful paper required actual scientific data gathered with the instrument in question and a report based only on the results of prolonged field use. No one can argue the merit of a thorough testing in the environment as a means for evaluating an instrument; neither can an instrument be considered useful until it has contributed to a successful investigation. However, the rapid expansion of effort in the marine sciences demands an early transfer of information on research and development in progress if duplication and overextension are not to cause ineffectiveness through dilution of our resources.

A concerted attempt has been made in the editing of this proceedings volume to strike a compromise between publication lag time and maintenance of literary standards. Each of the associate editors served in the dual role of session chairman at the Symposium and technical reviewer of the papers presented in his session. The topical organization of the meeting has been preserved in the proceedings.

R. D. GAUL
College Station, Texas

D. D. KETCHUM
Vineyard Haven, Mass.

20 December 1962

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KEYNOTE ADDRESS

TRANSDUCERS FOR OCEANIC RESEARCH--A WIDE SCOPE

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From its title, this Symposium might appear to be just one more technical discussion of a highly specialized matter. However, this should not be inferred; it has been my observation that people who become involved with instruments, particularly those for oceanographic application, frequently are people having exceptionally wide interests and much curiosity about other things. I am deeply impressed with the very number of things that become involved in the development of new instruments, research instruments in general and especially those intended for the sea.

This breadth of scope seems to be borne out by history and is likely to remain true because of the nature of the ocean, instruments and man himself. I will try to make clear what I mean by tracing the evolution of one classical oceanographic transducer system. I should like to show how its development was coincident with and closely related to a burst of interest in oceanic exploration that rather abruptly influenced the thinking of a large number of people. I believe that somewhat similar circumstances and relationships still prevail.

It will be necessary, of course, to digress a bit from a mere description of this single transducer. Transducers are only part of the whole system; the rest must be taken into consideration somehow and I mean this quite broadly.

SETTING THE STAGE

Somewhat over a hundred years ago a philosophical curiosity of Professor Joseph Henry was converted into an extremely profitable invention by the persistence of an art teacher named Samuel Morse. This was the electromagnetic telegraph. It was useful to almost everyone--and it made money. Financing its spread was profitable though risky. Even the speculation presently associated with what is called "electronics" is tame compared with the wild promotion of the early telegraph systems.

Atlantic Cables

A web of wire soon spread over the continental surfaces. These soon would have been inter-continentially connected except for some

unpleasantness of the sort promoters and financiers are likely to pass off lightly as "technical difficulties." One was lack of thorough knowledge of the equipment, especially the cables; another was a vast ignorance of the oceanic areas that had to be crossed.

However, there is nothing more attractive than success and land telegraphy certainly was a success in a way easy to understand; consequently ample money was made available for plunging wires into the Atlantic whether or not wire or water was understood. Indeed, there were some heroic efforts thrown away at first, but before long the two land masses were joined.¹ Electrical signals, rather faster than packets, carried urgent information across the oceans.

Quite by accident, evidence concerning an entirely different branch of human interest was brought to light as a by-product of this engineering feat. Through the press, almost every intelligent person had become spectator to a controversy boiling up over the evolution of biological species and the cable grappling had brought up experimental evidence supporting Charles Darwin's views.² It was now apparent that the deep layers of the ocean should be a likely place to find answers to this question so greatly disturbing a large number of people.

THE CHALLENGER ADVENTURE

In 1872 H.M.S. CHALLENGER was sent round the world on what amounts to an official inquiry into the third dimension of the ocean, and in particular into the species that live there.³ This certainly was not the first oceanic survey but never before had there been such an undertaking so deliberate and systematic encompassing the whole oceanic domain within its objective.

The outcome was far reaching. It has been accepted by later oceanographers as the prototype oceanographic survey. Actually there was no popular hero this time corresponding to the cable-laying Cyrus Field. The CHALLENGER'S staff was altered several times during the cruise and it was because of this and the very mass of data collected that publication was delayed for many years. However, the scientific world for the

Superior numbers refer to similarly numbered references at the end of this paper.

first time was given a comprehensive picture of the sort it could understand. Dozens of people now could see what more had to be done and in this sense the CHALLENGER'S report became a text book. It is an interesting fact that one of the lessons taught (perhaps just a tiny bit too emphatically) was that patience and skill together with simple, conservative equipment will lead to satisfying success in deep sea measurements. The CHALLENGER spent three years at sea, went around the world, made many measurements and many collections, some to as deep as 3,000 fathoms. After the first year's shakedown she could proudly report having lost "not a fathom of cable or a single instrument."

This is a remarkable record--who has equalled it? No wonder a tradition grew out of these teachings and no wonder the image of the instruments she used became frozen in the minds of most later expedition planners. This image is not much blurred even now some 90 years later. Nansen bottles and reversing thermometers are today a prime consideration in the planning of any major expedition. It so happens that this is exactly the neat package that grew out of the success of this great survey.

CHALLENGER Equipment

It would be almost, but not quite, accurate to say that the familiar Nansen bottle assembly with its thermometric temperature and pressure registers were completely developed aboard the CHALLENGER. Actually, Nansen was only 11 years old at this time. However, the water bottle used on the CHALLENGER was very like the later Nansen modification with a major difference that the CHALLENGER most commonly used thermometers that registered without being upset. Therefore, they were not attached to water bottles; in fact, neither did the bottles themselves have to be upset. No messengers were used to actuate the valves and registering mechanisms; triggering was carried out by vanes or propellers that rotated only during haul-in. Nevertheless, as many as eight registering thermometers and water bottles were "bent" onto the sounding cable and the whole procedure at sea, as well as the general character of the results, was very close to that of a hydrographic cast on a present day vessel.

It is of no real significance, but of some curiosity to us now, that the preferred cable was made of 1-inch (circumference) Italian hemp,

carefully spliced, that was paid out and hauled in from a reel turned by two hand cranks. Both the messenger and steel cable had come into common practice before the "Narrative" was published in 1885, however. A bottom-coring tool, not unlike those used now, was attached at the bottom of the cast but the heavy iron weights were dropped automatically after a core was taken. Three thousand fathoms of cable required 2 1/2 hours to run out free.

Reversing Thermometer

The CHALLENGER went out with some thirty self-registering thermometers of the minimum-and-maximum reading type. This type had been used on land and on sea for more than two decades. During the cruise, the London instrument firm of Negretti and Zambra patented a workable form of their novel thermometer that was constructed so as to register when it was turned upside down.⁴ Several were sent out to the expedition for trial. The now-seasoned staff recognized the inherent merits of the new construction but, of course, readily recognized the failings of these prototypes in small but important detail and diligently reported them. Non-reproducibility in the breaking point of the mercury was even then the first complaint. Inadequacy of the scale construction was also noted. These complaints are still common--now directed toward features vastly improved.⁵

Although the CHALLENGER had to rely mostly upon other types of thermometers, the reversing type was being rapidly improved by Negretti and Zambra back in London. A protected* model having a cylindrical external shell quite like that of the modern instrument was available before the "Narrative" was published in 1885 but it had not yet acquired an auxiliary thermometer. This appeared some fifteen years later and was the last significant change in outward appearance of the classical oceanographic thermometer.

Piezometer

The CHALLENGER'S staff was well aware of the effect of the ocean's pressure squeeze on temperature reading; in fact, they overestimated it. Even earlier minimum registering thermometers designed for deep-sea work were shielded from hydrostatic effects by a glass envelope of some kind but this usually surrounded only the main bulb. Since the general effect of pressure was

*The earliest reference that I can find to the protected instrument is in a statement from the N & Z Company (page 6 of reference 4):

"In 1857, we specially devised and constructed for Admiral Fitzroy the double bulb Deep Sea Thermometer for taking sea temperatures at great depths. This is the only type employed at the present day for great depths. . ."

Fitzroy had just become Rear Admiral at this period and was ashore writing reviews of his long and broad experiences as geographer, meteorologist and hydrographer. His curiosity reached even to behavior patterns in primitive races.

well known, the earliest deep-sea reversing thermometer also had this same pressure protection. It is not so surprising, therefore, to discover that useful, and apparently original, piezometer was constructed during the cruise by removing the protective shell of one thermometer. The purpose obviously was to determine actual depth independent of length of cable paid out. This was especially important when a cable of hemp was used because of larger drag caused by water movement.

Unprotected Thermometer

The traditional depth gauge of oceanography, the unprotected reversing thermometer, grew out of these experiments at sea that were so well reported. Professor Tait of the University of Edinburgh made extensive investigations into the behavior of thermometers under pressure immediately following the cruise. As a matter of fact, there is a laboratory piezometer named after him that is essentially an unprotected thermometer.

Final Developments

The later models of reversing thermometers and Nansen's later modification of the stop-cock bottle, together with use of steel cable and sliding messengers, provided a compact and widely applicable measuring system. There never has been and never will be any such thing as a truly "universal" measuring instrument but this under-sea combination has come as close to "universal" application as can probably ever be hoped for. Work has been carried out with it over all the seas, from pole to pole, and from top to bottom. For roughly three-quarters of a century it has been seen on large ships and small as the backbone of the world's ocean measurement capability.

THE METEOR EXPEDITION

The high point of perfection of this system was realized during the METEOR expedition^o of 1925-27 when thermometer measurements, even at sea, were read out to 0.001°C (at least before sensible round-off). These were made by dedicated physical oceanographers, people so much interested in their work that they designed special thermometer scales, selected special instruments and then repeatedly made calibrations with great care whether ashore or at sea.

Still more significant, they became well acquainted with the manufacturers and shared their enthusiasm with them. This, together with training and discipline at sea, produced results perhaps never to be equalled. The Richter family of Berlin is now represented by the third generation associated with this specialized instrument. They cherish old letters indicating how often Nansen, Petersen and other oceanographers have visited their shop to bring the instrument into

a form more useful at sea. There have been times when hardly more than pride in this association kept this little firm going.

STATUS OF REVERSING THERMOMETER

The classical hydrographic bottle and its accessories are now taken for granted; to many they may constitute physical oceanography in its entirety. Truly, it is a perfect example of the very natural law that Darwin proposed, the one which sent the CHALLENGER out to sea. This mechanical transducer definitely has been a success and has survived in face of competition because it was at home in its environment and compatible with other measurement things. Few instruments have been so successful. Few have become so standardized for so long. The impression should not be left that the reversing thermometer persisted entirely because of good fortune. It is truly a remarkable instrument. It is hard to accept the historical evidence that most of this "selection" was carried out within a few years after the CHALLENGER returned and was likely due to her findings and definitive reporting thereon.

We all know the limitations of this classical thermometer. Many new ways for doing the same job better have been proposed. Significantly, one-third of the papers to be presented here in this Symposium concern long-needed systems and devices for measuring temperature, pressure, salinity and density; functions that the classical tool has so long performed.

Good Features

What other reasonably portable temperature recording instrument, old or new, can perform so reliably with so little attention? I know of few other transducers of any kind that can be calibrated (and I mean in an absolute sense) to $\pm 0.03\%$ and then continue to function with this precision over months and years. Yet, it is routine to calibrate to 1 part in 3,000; that is, to $\pm 0.01^\circ\text{C}$ over a 30°C range and to find satisfactory replication at a much later date. What other simple pressure transducer spans such a wide range and still can reproduce hydrostatic pressure measurements (also on an absolute basis) to the order of $\pm 0.1\%$. The reversing instruments in fact have carried out temperature and pressure measurements at sea with these precisions and absolute accuracies that are not too commonly seen with elaborate equipment in shore laboratories.

Most of the credit can be claimed by the basic mercury-in-glass structure. Some people have forgotten that this is a simple, relatively noise-free transducer, amplifier and "readout." Many years ago, at a time when it was of interest to standardize temperatures by means of liquid-in-glass thermometers, special glasses were developed to reduce hysteresis. All glass has

a memory of thermal history to some degree but these special thermometer glasses were chosen to reduce this to a minimum and provide reasonable stability even at high temperatures. It so happens that the range of temperature in the ocean is relatively short, a matter of only 35°C. In this short range thermal hysteresis is not appreciable; at least I was not able to detect any significant short term changes by repeatedly cycling a group of good instruments during one long expedition.

I point this out in passing because it appears to me that the primitive bulb-and-stem transducer still has certain unexploited merit for measuring relatively low temperatures as well as moderately high pressures. This structure appears to be one preferable to some that are employed in contemporary pressure transducers and it would appear to be no more difficult to link it with telemeters and recorders suitable for many types of work.

Limitations

Limitations to the reversing thermometers are well known. I will mention only a few.

The CHALLENGER report emphasized the value of making "serial" or multiple measurements on each sounding cast. This is still true but we now do not consider 8 or 10 transducers per cast sufficient coverage for all purposes.

Response is too slow for much of our present requirements. It can be shown⁷ that the protected instrument has a compound thermal lag described adequately by two lag constants; one of about 18 seconds and the other of about 120 seconds. This is a slow response even for mercurials. Speed has been compromised so as to provide pressure "protection."

The pressure effect on "protected" instruments has not been eliminated entirely. In some modern instruments the outer bulbs are overfilled with mercury and analyses of the mechanical structure⁸ seems to indicate that large enough pressure errors would enter to be significant in measuring deep water gradients. It would appear that these errors might approach 0.01°C per 1,000 meters change in depth. They are largest in deeper water which, unfortunately, is where small intervals of temperature are most likely to be of interest.

Adiabatic Errors

A most peculiar thermometric error comes to light upon inspection of the CHALLENGER'S reports, one that was not at all understood until much later when Professor Tait calibrated the thermometers under pressure in his laboratory. Many materials heat faster than water does when put under pressure adiabatically. Hard rubber that

was used for supporting the glassware in the CHALLENGER'S thermometers happens to be especially sensitive to pressure in this way. This led to real ambiguity in the CHALLENGER'S temperature readings. Reversing and minimum-registering instruments seldom agreed as would be expected from the considerations below.

The primitive reversing thermometers used on these first casts had to be "tripped" by hauling them up rapidly enough to make a propeller revolve. Because of this requirement, and because of adiabatic effects, these reversing instruments probably were slightly hotter than they should have been. The masses of hard rubber required some time to cool into equilibrium with the sea, but the CHALLENGER people were not aware of this and so probably hauled up too soon.

On the other hand, the minimum-registering thermometers always read the lowest temperature they encountered which, on a very deep cast, was not likely to be at the bottom. In fact, their readings would depend a great deal upon just how fast the cable was hauled in because the hard rubber parts continued to cool below ambient temperature as the pressure was relieved. Therefore, adiabatic errors in minimum-thermometers had opposite sign from those that pertained to the reversing thermometers thus adding to the discrepancy between instruments.

As a result of these inaccuracies the CHALLENGER was unable to report the important finding that there was a temperature minimum at about 400 fathoms over most of the world ocean based only upon the general trend of averages of a large number of deep readings.

Why Were Other Thermometric Instruments Not Perfected?

The question now can be raised as to why oceanographers have very nearly perfected this particular measuring system without devoting attention to other equally promising devices. This is especially interesting because there was placed aboard the CHALLENGER, as a gift of Sir William Siemens, the brother of the founder of the German Siemens-Haske firm, a complete electrical thermometric system which is recognizable as very suitable.

Only the briefest of tests of Sir Siemens' gift were carried out on the CHALLENGER even though it apparently was capable of very fine measurements. Its design was sensible and conservative. It employed a simple bridge circuit with null indicated by a marine galvanometer of the type invented for cable laying by Sir William Thompson some twenty years earlier. The measuring transducer, a coil of metal wire provided with three leads to compensate for cable resistance, seems to have been in every way as reliable (if not as convenient) as any we would choose today. Electrical balance was attained by a method truly

beautiful for its certainty and simplicity. The reference coil was merely put into a water bath along with hot and cold water in the proportions required to balance the galvanometer. A good mercury-in-glass thermometer then indicated the temperature. What an elegant experimental method limited hardly at all as to precision, certainly not by "contact resistance!"

Why did this prototype also not start a tradition long ago, one leading to routine electrical-wire hydrographic casting? This is a mystery to me. This system was not lacking a vigorous protagonist, Dr. Seimens, a scientist and engineer of great wealth and ingenuity. Moreover, he was a leader in meteorology and hydrography as was Admiral Fitzroy. Further, the "electricians" were at that time quite prominent in natural philosophy and were the ones who first floundered out to sea with machinery to lay cables. No doubt there was some missing ingredient. Perhaps something was found to be incompatible with some feature of the sea or maybe it was just poor cable insulation. It is hard to tell because the records of mild successes soon become dim.

WIDTH AND DEPTH OF INSTRUMENTATION OCEANOGRAPHY

Now I would like to go back to my original comments that inherently instrument-making has a very broad scope and that large forces frequently influence it. The origin of the reversing thermometer and its accessories has just been recited; this was to illustrate how many were the leading scientists of 100 years ago who entered into the evolution of just one single oceanographic instrument. It was pointed out also how many were the factors that entered during that period; commercial, philosophical, even emotional.

Now, perhaps more than in the past, large social forces are at work that are likely to exert their influence on the present day instrument man. Today many people are frantically "tying together" the continents in quite another sense. This time they are not content with sending back and forth mere telegraphic information. They appear to be preparing for the possible exchange of large and destructive packages while others are seeking ways of hiding from these. Except for a new element of fear the driving forces are not now too different from those that influenced the "electricians" on the GREAT EASTERN and the explorers (later to be called oceanographers) on the CHALLENGER.

Strangely, war thoughts are not much in evidence in the history of the CHALLENGER expedition though likely these too might have passed through official heads since H.M.S. CHALLENGER was a naval vessel; a three masted, screw driven, steam corvette of about 2,000 tons displacement and 400 horsepower. The most important similarity between then and now is the way in which great masses of people were excited by accomplishments depending upon technical skills and on new

instruments. As a result and because of this excitement financial sponsorship and promotion was easy, just as it is now.

The Present

I am not going to dwell long on the present day circumstances since this is the duty of the other speakers at this Symposium. Since 1872, however, much technical ground has been covered and we probably share in the awareness that not enough of this progress has been exploited at sea. That is why we are here today. We find that we must know a great deal more about the sea and again we are somewhat in a hurry with the realization that our sea-going tools have not been kept up-to-date. This group of professional people contains what are called "specialists" and it is true we have special interest in the problems that come up in the marine world.

The Reservoir

It appears to me that we are also characterized and identified by a common concern about ways of joining a very big supply with a very big need. I am tempted to say that I may be somewhat more impressed with the great size, the very formidable dimensions of the reservoir, than with the application of its contents to merely overcoming detail problems in the marine environment.

What I mean is that most of us are in this field because we like it and with relative ease and some little enjoyment we can put instruments together. However, our association with our sources of supply is one truly in the nature of a "discipline." It requires effort. It requires skill and patience. There are disappointing experiences and annoyances involved with bringing the products (and also the useful data) of other people into a position where an instrument, say oceanic transducer, can be made. If there is any outstanding difficulty in building research instruments it is in gaining thorough knowledge of what is available. I mean this very broadly. If there is such a thing as an "instrument man" (and this term is often heard now) he might best be recognized by his general skill in locating information widely scattered over the world and deeply buried in obscure records. I believe it is short-sighted to expect the instrument man to limit his attention merely to other instruments unless, of course, we carefully define these as "any tools man uses on earth, or ever has used."

Boundaries

Now this requires ranging over a large technical area. Boundaries will be encountered but I believe that crossing these boundaries is part of the professional skill required. Many things must flow across these boundaries--material, equipment, financial support and just plain data. None

of these flow freely except when a common enthusiasm has been generated on both sides. Perhaps this is the part that takes the greatest skill. Anyway, it is plainly evident in the history of any technical success that at least one person has inspired technical people on both sides of traditional barriers.

Examples are many of individuals who transcended the limits of specialization to accelerate the rate of progress.

1. Fridtjof Nansen first was a zoologist. He became a polar explorer and later a Professor of oceanography at Oslo. As I have already mentioned, Nansen's contact with the Richter family is probably what perpetuated their interest in ocean measurement.

2. Admiral Fitzroy was a skilled naval officer, meteorologist and expedition leader. He was master of the BEAGLE made famous by Darwin. He induced Negretti and Zambra to perfect the barometers and thermometers needed in oceanography. He too is the one who brought the primitive Terra del Fuegians to England to investigate experimentally the effect of sudden exposure to civilization.

3. William Thompson (Lord Kelvin) is known for his marine galvanometer and other "cable readout transducers" as we would call them today. Physicists remember him for his enunciation of the second law of thermodynamics but he also perfected the Kelvin oceanographic "sounding machine," long used.

4. Karl Siemens (later Sir William) was an industrialist; an electrical engineer who pioneered the "dynamo." He associated with the whole electrical world of his day. Nevertheless, he designed the cable ship, FARADAY, and assisted in outfitting the CHALLENGER. His brother, Walter, founded the famous Siemens-Haske firm.

5. Finally, we must mention that Samuel Morse, who certainly was concerned with electrical transducers, became so involved in pulling his invention together from all available sources that he was severely criticized.

CONCLUDING REMARKS

It is currently popular to drag instrument discussions deeply into philosophy. I will indulge a bit for my conclusion.

Dr. Norbert Weiner of M.I.T. very convincingly compares human reactions with servo responses and vice versa. He and others look into "feedbacks," memories and computer systems for keys to man's way of thinking.

Again, Professor P. W. Bridgman of Harvard is a physicist who is noted for great breadth of interest. He is particularly well remembered by all instrument men for his "unsupported area

principle" that first gave a rational direction to those who must work at the sealing and closing of pneumatic and hydraulic things. He too has just written a philosophical book.⁹ With great sincerity he searches his own vast research experience for connections between the reading of an instrument and an undefinable basic criterion of civilization that he calls "integrity," for want of a better word. He returns repeatedly in his arguments to the response of an instrument. And you must note that this is an "instrument man's instrument man." Among many other things Professor Bridgman has written the definitive, even classical, work on the physics of high pressures.¹⁰ His techniques have been translated to geological pressures and ultimately to ways for making artificial diamonds.

Finally, the radiocarbon people and archeologists several times have moved backward the birth date of man. A recent estimate¹¹ indicates man has been distinguishable for no less than 1.75×10^6 years. What is pertinent here is that it is by his tools that man is recognized from other animals. When we find a slender, glass arrow point penetrating a bison's skull, we just don't consider this the doings of a monkey.

Of course, you are quite aware by now that I get some personal enjoyment from hearing how our scientific heroes have responded to instrument building problems. This is true, and I perhaps generalize a little too much when dwelling on this pet subject. In conclusion I will try to be more specific but, unfortunately, I may not be any easier to follow. I will indicate by use of a hypothetical case just how ramified an instrument problem may become.

People study bats to learn about radar, an instrument. Similarly, some people who are interested in sonar (likewise an instrument system) study fish and porpoises.¹² Let us start by considering what chain of events (and thoughts) a study of porpoises might involve.

Let us first assume, for sake of a starting point, that the first attention came from an accidental eavesdropping on porpoises at sea. Immediately curiosity is raised as to what sort of sonic transducers might have produced these signals and what sort received them. These are considerations related to instrumentation.

Then, it may appear that this animal is not "transducer-restricted" but perhaps is limited by the reverberation that is so common in the sea. This decision also requires instrument experience, of course. It may follow that this animal's highly refined computer element is an exceptionally competent one, apparently capable of resolving and analyzing extremely complex signals. So perhaps he makes use of this reverberation by superb analysis and memory.

We flatter ourselves in recognizing in the porpoise traits that we believe are advanced, that is, "human-like." We note especially the

relatively large brain. It seems, with porpoises, that everyone sooner or later becomes interested in the intelligence of these likable little animals. This must surely lead to generalized thoughts on the meaning of intelligence itself.

Now, it so happens also that a great number of people are fascinated in what is called "outer space." It is highly probable that this also will influence our train of thoughts. I suggest, therefore, that someone is likely to propose next (if he has not already done so) a project for submitting to the judgment of porpoises samples of signals picked up from outer space (probably transmitted by other beings). Perhaps this clever animal will recognize "meanings" before we humans do. Why not? Why should other beings be more like humans than like porpoises? What happens next (if any action at all is taken) is a search for an instrument to communicate with porpoises and thus talk quite fluently in all the languages the porpoise understands.

We have now "come round full circle" because obviously the investigation depends for success upon new types of instrumentation; special transducers, linkages and analyzers. Just what is to be the nature of these new instruments? Who knows for sure that porpoises rely mostly on sound for their information? Perhaps they are still more perceptive through some other sense. Maybe they can better taste than hear certain details of important information, like the location of a distant school of fish, for example. Successful answer of this critical question hinges first of all on the interest of someone in understanding taste phenomena. It depends also upon someone who can somehow put together instrumental means for making the actual measurements that are required or, alternatively, someone who is capable of patiently finding out what things are available and how best they can be put together for this particular purpose.

This train of hypothetical events might be allowed to go "on and on" but I will stop it here to ask the grand final question. Where was the "instrument man" during this "trolley ride?" Did he get off at each place when a new type of transducer was required or did he ride along and learn as he went? Did he get to liking porpoises?

My personal feelings are, and history seems to confirm, that the instrument man indeed went along all the way. He was curious and interested from beginning to end--and he got to liking porpoises very much. I find myself somewhat impatient when I hear him spoken of as a "specialist." I don't yet know just how to define him, really, but certainly he isn't simply that!

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SESSION I

ELECTRICAL CONDUCTIVITY, SALINITY AND DENSITY

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INTRODUCTORY REMARKS
FOR
PAPERS ON ELECTRICAL CONDUCTIVITY, SALINITY AND DENSITY

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As an introduction to the papers presented on electrical conductivity, salinity and density, it seems appropriate to dwell briefly on accuracy required of transducers for measuring these parameters. The term "accuracy" is used in its scientifically accepted sense as associated with a 95% probability.

SALINITY

When asked about his requirements for accuracy in oceanic measurements of salinity, the oceanographer usually will give almost a stock answer of ± 0.01 parts per thousand. Since the salinity of the ocean is about 35 parts per thousand this represents an accuracy of about 1 part in 3,500. Actually, for many purposes, a lesser accuracy is permissible; in fact, until the advent of the salinity bridge in 1956 the accuracy was about 0.03 parts per thousand or less although few oceanographers clearly recognized that it was so poor. For other purposes, especially any studies in the deep ocean where gradients and temporal changes are extremely small, 0.01 parts per thousand accuracy may be marginal. In large deep estuaries accuracies of about ± 0.1 parts per thousand are desirable and in estuaries strongly influenced throughout most of their depths by fresh water, accuracies of ± 0.5 parts per thousand may be permissible.

DENSITY

It is sometimes implied that the oceanographer measures salinity only to obtain density. This is not true. If he could measure density to the required precision he could deduce circulation patterns by the geostrophic method, but there are other oceanic processes which would still require salinity measurement for their description. Consequently, there is not as much inducement to produce an in situ density probe as a salinity probe. If density is to be regarded as an indirect route to the measurement of salinity, note must be taken of the fact that an accuracy of 0.01 parts per thousand in salinity corresponds to an accuracy of 7×10^{-6} gm/cm³ in density. Such accuracies probably can only be obtained by differential measurements. Since the density dependence on

temperature is equivalent to salinity changes of about 0.4 parts per thousand salinity per degree C, precise control or measurement of temperature would be required.

ELECTRICAL CONDUCTIVITY

The electrical conductivity of sea water is of little interest in itself; it is normally used to determine the salinity. The electrical conductivity of sea water in millimhos is roughly the same as the salinity in parts per thousand, nominally 30 with a marked dependence on temperature. The conductivity increases with temperature by about 2% to 4% per degree C. To obtain an accuracy of ± 0.01 parts per thousand in salinity requires a temperature measurement accuracy, or at least a long term reproducibility, of about 0.01°C if all the error is due to temperature. The existence of other errors forces distinctly higher requirements on the temperature accuracy. Again, it should be evident that there is not much hope in making absolute measurements and that differential measurements referred to a stable temperature-compensating reference standard will be required. The electrical conductivity also has a pressure coefficient of the order of 0.0005% per psi so that at any great depth provision must be made for a pressure correction.

CONCLUSION

These are difficult requirements, all the more so because they must be met under rugged ship-board conditions and in the hands of technicians who are not experts in the art of measurement. I should like to remind you that in demonstrating the utility of a measuring instrument there is a great deal of difference between 20 measurements in a laboratory and a year of carefully documented testing at sea. There is also an important difference between the instability and inconvenience which will be tolerated by the enthusiastic inventor and that which will be accepted by the working scientist at sea. I hope we can begin to see more of thoroughly demonstrated instruments in distinction from those which are so inadequately tested that they are merely interesting.

A PROBE TYPE INDUCTION CONDUCTIVITY CELL

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ABSTRACT

The salinity of sea water may be calculated from measurements of water electrical conductivity and temperature *in situ*. A compact pressure-protected induction conductivity cell and a thermistor temperature sensor were mounted in a probe to form a salinity transducer. Constructed for installation in the nose of a deep-sea remote controlled underwater vehicle, the probe is readily adapted to other applications such as mounting on or towing behind a research ship. The conductivity cell is of the induction type, using two toroidal transformer cores to avoid the polarization and fouling problems of exposed electrodes. The toroidal cores are connected in a transformer bridge circuit which is adaptable either to direct or to servo actuated null balance readout. The probe has been proof-tested at pressures up to 3,000 psi.

INTRODUCTION

One measure of the salinity of sea water is its electrical conductivity. A conductivity cell for measurements of salinity may be calibrated in a sample of sea water of known salinity. The temperature of the sample must be carefully controlled since conductivity varies considerably with temperature. For *in situ* measurements of salinity the temperature of the water as well as the electrical conductivity must be accurately measured. The salinity transducer probe, as shown in Fig. 1, uses an induction conductivity cell and a thermistor temperature sensor. Constructed for use in the nose of a deep-sea remote controlled vehicle, the transducer posed a major design problem because of the crushing pressure at great depths.

In the past, accurate determination of conductivity has been a serious problem because fouling and polarization of exposed electrodes in a sea water environment can introduce serious errors in the results. To eliminate this inherent problem with exposed electrodes, the conductivity probe design was based on the induction technique described by Gupta and Hills.¹ The measure of conductivity is the coupling provided by a sea water path between two toroidal transformers.

OPERATING PRINCIPLE

The transformer cores are encapsulated on a common axis in a toroidal housing which allows the free flow of sea water through the common hole in the two cores. The arrangement is shown in Fig. 2. A primary winding on the exciting transformer core is connected to an alternating current power supply. A single turn secondary winding is formed by the conducting sea water threading through the hole in the toroidal housing. The return current path is the infinite liquid medium in which the unit is immersed. The current through the liquid path will be proportional to the electrical conductivity of the medium. The sea water current path is also the single turn primary winding for the pickup transformer core. The output signal is taken from a secondary winding on this core.

By placing on each core an additional winding connected in a series circuit with a variable resistance, the induction conductivity cell becomes a transformer bridge. The setting of the variable resistance required to give a null signal in the secondary winding of the pickup core is a measure of the electrical conductivity of the liquid path. An outstanding advantage of the transformer bridge circuit is that the null adjustment is essentially independent of variations in the transformer core losses due to temperature or pressure.

TRANSFORMER BRIDGE

Calvert *et al.*² have described the operation of the transformer bridge in some detail. Only a brief discussion of its application in the induction conductivity probe will be given here. Fig. 3 is a schematic diagram of the circuit. R_u represents the unknown conductivity of the sea water path. The circuit is adjusted to null by the variable resistance, R_s . The capacitor tunes the null signal to the power supply frequency. Tuning is desirable since it filters out noise above and below the power supply frequency and eliminates null signal phase shift with respect to the exciting voltage. Phase shift is undesirable where the null signal is compared with the exciting voltage as in applications using a phase sensitive detector or servo actuated null balancing system.

Superior numbers refer to similarly numbered references at the end of this paper.

Fig. 1. Salinity transducer probe.

It will be shown that for a discussion of the bridge null adjustment the transformers may be considered to be ideal. Core losses and magnetizing reactance in the exciting and pickup transformers shunt the power supply and the null signal, and as such tend to increase the required input power and reduce the circuit gain but do not change the null setting. In a like manner the copper losses (resistance) in the exciting and pickup windings, N_i and n_o may produce small

Fig. 2. Operating principle of induction conductivity cell.

changes in the required power and gain but not the null setting.

The important consideration for the accuracy of the transformer bridge is the stability of the voltage ratio, e_u/e_s , of the exciting transformer windings and the stability of the current ratio, i_u/i_s , at null (zero magnetic flux in the pickup transformer). The factors effecting these ratios are the turns ratios, N_u/N_s and n_u/n_s , and the leakage flux, i.e., magnetic flux not common to the pair of windings on each transformer. The turn ratios are determined by the physical construction of the induction conductivity cell and, therefore, are constant. By using high quality tape wound cores with high permeability, the leakage flux is reduced to an insignificant portion of the total flux. Copper losses are negligible in the present design since they each consist of only 18 turns of fairly large diameter wire.

The relationship between the resistance of the sea water path, R_u , and the known variable resistance is easily calculated. At null the magnetomotive force (ampere-turns) produced in the pickup transformer core by the sea water path must exactly balance the magnetomotive force produced by winding n_s :

$$i_u n_u = i_s n_s. \quad (1)$$

Using Ohm's Law:

$$\frac{e_u}{R_u} n_u = \frac{e_s}{R_s} n_s \quad (2)$$

or

$$R_u = \frac{e_u}{e_s} \frac{n_u}{n_s} R_s. \quad (3)$$

Fig. 3. Schematic diagram of transformer bridge.

Since the voltage ratio is equal to the turns ratio:

$$R_u = \frac{N_u}{N_s} \frac{n_u}{n_s} R_s. \quad (4)$$

Because the water path forms a single turn around each transformer this becomes:

$$R_u = \frac{R_s}{N_s n_s}. \quad (5)$$

It is seen that the sea water resistance is directly proportional to the known resistance.

For visualizing circuit parameters and for calculating bridge sensitivity the equivalent circuit shown in Fig. 4 is convenient. The fact that this is a bridge circuit is more readily apparent from the equivalent circuit than from the original circuit. All circuit values are reflected to the output or null circuit; that is, the values are the apparent ones seen from the output terminals of the pickup transformer. X_m and R_m represent the magnetizing reactance and the equivalent core loss resistance of the pickup transformer respectively. As explained previously the magnetizing reactance and core losses do not affect the null balance but do reduce the gain or sensitivity and therefore must be considered in the circuit analysis. The magnetizing reactance and equivalent resistance of the exciting transformer are not shown in the equivalent circuit as it is assumed that the power supply source impedance is sufficiently low that these parameters do not affect the null signal.

Fig. 4. Equivalent circuit for transformer bridge.

In the transformer bridge circuit discussed, the variable resistance, R_s , is proportional to the water resistance, R_u . In many applications it is more desirable to have the variable resistance proportional to water conductivity rather than resistance. In low salinity low conductivity water, the resistance, R_s , would be extremely large. To obtain a variable null setting

Fig. 5. Schematic diagram for null setting proportional to conductivity.

It has been found that a small quadrature (reactive) component may be present in the bridge circuit that interferes with obtaining a sharp null. Compensation for this component may be made with a small variable capacitor connected across R_s .

PHYSICAL DESCRIPTION

The tape wound cores used in the transformers are each encased in a rigid housing to give protection from external stresses. The exciting transformer core is wound with tape of approximately 50% nickel and 50% iron composition for high saturation flux density and good permeability. The pickup core is wound with Supermalloy which has the highest initial permeability and lowest core loss of any commonly available magnetic material.

Fig. 7 shows the physical layout of the probe. The toroidal head of the probe is 2 1/2 inches in diameter and 2 3/8 inches long. The cores are of the tape wound variety each enclosed in a rigid case. A high strength outer housing constructed of stainless steel tubing and Nylatron GS encloses both transformers. All voids in the conductivity head are filled with a high strength epoxy resin. To eliminate the possibility of crushing pressure being transmitted to the transformer cores, a cushion of foam silicone rubber is placed between the epoxy resin and the wound cores. Magnetic shielding materials are incorporated in the conductivity head to eliminate direct magnetic coupling of the transformer cores.

The temperature sensor is a glass enclosed thermistor probe located in one of the four stain-

Fig. 6. Equivalent circuit for null setting proportional to conductivity.

directly proportional to conductivity, the circuit of Fig. 3 may be modified to the arrangement of Fig. 5. The setting of the potentiometer, R_p , in Fig. 5 is directly proportional to the water conductivity providing the impedance of R_p is considerably less than that of R_s to minimize potentiometer loading. An equivalent circuit is shown in Fig. 6.

Fig. 7. Probe construction details.

less steel legs of the instrument. Holes drilled through the leg allow free circulation of water past the thermistor. The legs were designed to crush or shear upon severe impact without destroying the watertight integrity of the free-swimming vehicle.

The instrument was proof pressure tested at 3,000 psi which corresponds to a depth of approximately 6,800 feet. The instrument was also cycled repeatedly between normal atmospheric pressure and 2,000 psi without ill effect.

POWER SUPPLY

In the original application the conductivity cell was excited by a 320 cps power supply. This power supply could be constructed to operate the conductivity cell at 400 cps to power standard servo components for automatic null balancing. Fig. 8 shows the power supply with the outer housing removed. This rugged compact unit consists of a transistorized audio amplifier driven by an enclosed tuning fork oscillator.

Fig. 8. Power supply.

CONDUCTIVITY MEASURING SYSTEM

The conductivity measuring system with which the probe was originally used is shown in Fig. 9. This is essentially a conductivity deviation circuit, i.e., the variable resistor in

Fig. 9. Conductivity deviation measuring system.

the bridge circuit was set for a null at a particular value of water conductivity and the output signal was a measure of deviation from this particular value. A more sophisticated system is diagrammed in Fig. 10. Here, a two-phase servo motor drives the bridge circuit to a null setting. Since the circuit is always driven to null, errors due to variations in transformer magnetizing reactance and core loss and in power supply frequency and voltage are largely avoided.

Fig. 10. Servo null balance conductivity measuring system.

Trial runs of the induction conductivity probe mounted in the nose of the underwater vehicle have been made at moderate depths. Additional laboratory and field tests will be made to more completely evaluate this technique for salinity measurements.

ACCURACY

It is difficult to establish a definite accuracy figure for the instrument since this will depend on the type of measuring system and data recording systems used and on the environmental conditions encountered. The effects of the temperature and hydrostatic pressure on cell stability have not been fully evaluated but investigations made to date show these effects to be small, particularly where the servo null balance system is used. Since the output of the induction conductivity cell is a low level signal, careful

consideration must be given to elimination of noise and channel cross-talk pickup. With reasonable care in its installation, the accuracy and reliability of the induction conductivity cell is expected to exceed that of conventional cells.

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A PROPOSED IN SITU SALINITY SENSING SYSTEM

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ABSTRACT

This paper describes a system for the in situ measurement of salinity. The basic components are (1) a salinity bridge composed of an inductively-coupled conductivity sensor and a network of temperature and pressure sensors for accurately compensating for the effects of temperature and pressure on the conductivity of sea water and (2) an oscillator whose frequency is accurately and directly controlled by the salinity bridge output voltage to input voltage relationship.

INTRODUCTION

Before the design of a salinity system can be considered, it is mandatory to study such parameters as the temperature and pressure effects upon the conductivity of sea water and upon the conductivity sensor, the optimum method of sensing the conductivity, methods of compensating for the effect of temperature and pressure on the conductivity of sea water, the effects of marine fouling organisms on the sensors, telemetry methods and, of course, the desired performance with respect to accuracy and other factors. Before selecting the method of sensing the conductivity of sea water from an in situ instrument, the immediate factors to be considered are the electrical, mechanical and chemical effects on the sensor of: (1) pressure, (2) temperature, (3) fouling and (4) corrosion.

PLATINUM ELECTRODE CONDUCTIVITY SENSORS

Glass conductivity cells with platinum electrodes have been used with considerable success by a number of workers^{1,2,3,4,5} in laboratory type salinometers and conductivity measuring devices where they have not been subjected to organic and inorganic fouling and extreme environmental conditions. In some cases they have been used successfully at sea^{6,7} but only on instruments that are lowered from ships for relatively short periods.

In all these instruments an accurate check on cell drift is made by the use of standard sea water. However, the problems of electrode fouling and the impracticability of filling an

electrode type cell mounted on an in situ instrument with standard sea water make them unsuitable for long term use in in situ devices.

CAPACITIVELY-COUPLED CONDUCTIVITY SENSORS

Capacitively-coupled electrodes have been demonstrated experimentally^{8,9} but have not been used in a workable field instrument. This type of electrode does offer freedom from the degrading effects of surface films but requires the use of very high frequencies (typically 10 Mcps) which create severe problems when accurate measurements are to be performed in an in situ instrument.

INDUCTIVELY-COUPLED CONDUCTIVITY SENSOR

Consideration of the inductively-coupled sensor^{10,11,12,13,14} indicates that the effects of pressure on the "cell constant" can be made small and highly predictable. Fig. 1 shows a typical sensor using the inductively-coupled principle. Sensors similar to this have been used successfully by the author and others at Woods Hole Oceanographic Institution¹⁴ to depths of 18,000 feet.

It can be shown that if the center hole of the sensor is fitted with a Pyrex glass tube arranged to have the same pressure on the outside diameter as on the inside diameter, the change in dimensions of this tube due to the bulk modulus, i.e., compressibility, of the glass would be negligible. Taking a value of 3×10^6 psi as a minimum for the bulk modulus, K, of glass, the total volume change, dV , of a tube would be given by:

$$\frac{dV}{V} = \frac{P}{K} \quad (1)$$

where P is the ambient pressure. For a depth of 1,000 feet, $P = 440$ psi and

$$\frac{dV}{V} = \frac{440}{3 \times 10^6} = \frac{1}{6,800} \quad (2)$$

Superior numbers refer to similarly numbered references at the end of this paper.

Fig. 1. Conductivity sensor for in situ salinity system.

Since the dimensional changes are equal in all directions, the change in length and circumference will each be one-third the proportional change in volume. Since the "cell constant" is proportional to area/length, the change in "cell constant" will be one-third the proportional change in volume, i.e., 1 part in 20,000 at a depth of 1,000 feet. Obviously the use of a glass tube in this manner would mean that a direct electrical path between the outside of the glass tube and the inside of the insulated steel liners (Fig. 1) would have to be prevented. This technique is the one used successfully at the Woods Hole Oceanographic Institution to depths of 18,000 feet.

If the glass tube is made from Pyrex, the effect on the "cell constant" due to changes in dimension caused by changes of temperature would also be directly related to the linear changes. Taking a value of $3.2 \times 10^{-6}/^{\circ}\text{C}$ as the temperature coefficient of Pyrex, the linear changes, and consequently the "cell constant," over a temperature range of $\pm 15^{\circ}\text{C}$ will be ± 48 parts per million, i.e., approximately ± 1 part in 20,000.

Fouling due to the deposition of thin films on the surfaces of the sensor have no significant effects. Fouling due to the growth of marine organisms in the center hole of the sensor would be a problem if it became so gross as to change significantly the effective dimensions of the center hole. It should be noted that any system yet devised senses the conductance of a particular geometrical configuration of the conducting medium and not its specific conductivity. This means that any type of sensor will suffer from the effects of gross fouling. However, electrode type sensors are affected by minute surface films on the metal electrodes whereas the capacitively and inductively-coupled sensors do not have this problem. Also, the inductively-coupled types have better electrical

characteristics if the center hole is large, whereas the electrode cells suffer from an unfavorable ratio of "polarization" resistance to overall resistance if the inside diameter of the cell is made very large. The use of larger diameter center holes in inductively-coupled sensors make them less affected by fouling organisms and easier to maintain in a clean condition than would be the case if a small hole were used.

EFFECT OF TEMPERATURE ON THE CONDUCTIVITY OF SEA WATER

The effect of temperature on the conductivity of sea water is very large. For a temperature change from 0 to 30°C the conductivity of sea water approximately doubles. This means that the temperature effect must be accounted for very accurately if precise salinity information is to be obtained. The following are some of the temperature compensation techniques that are to be considered.

Computation of Salinity

The first method used to measure salinity in situ involved computation of salinity from measured values of conductivity and temperature. However, the accurate determination of salinity requires a very accurate measurement of temperature as well as conductivity. Since the computation is rather complex, a digital computer would be necessary to handle even small amounts of data.

Thermistor Compensation

The earliest methods of automatic temperature compensation used a thermistor-resistor network

Fig. 2. Thermistor compensation network and graph of salinity correction as a function of temperature for water of salinity of 35.3 parts per thousand.

which was designed to have a resistance temperature relationship similar to sea water.^{2,7,13} In Fig. 2 a typical circuit and its compensation curve are shown. The errors between 5°C and 20°C are usually quite small but outside these limits increase quite rapidly as shown. In some cases, depending on the characteristics of individual thermistors, errors can be as low as ± 0.05 parts per thousand in salinity from 0°C to 25°C. However, thermistors have a number of serious disadvantages. They are non-uniform in characteristics and are sometimes unstable. The compensation accuracy is generally inadequate as shown in Fig. 2.

Compensating Cell

A theoretically ideal method of temperature compensation using sea water itself as the compensating element was experimented with by the author and others at the Woods Hole Oceanographic Institution. This technique utilized Copenhagen standard sea water in a small sealed platinum-electrode glass conductivity cell. The cell was fitted with a flexible membrane so that the sealed sample of standard sea water in the cell was at the same pressure as well as temperature as measured sea water sample. The earlier experimental units had a thermal response time of 0.8 seconds. However, their long term stability is poor, at least in the cells made to this date. They are also fragile and difficult to fabricate.

Platinum Resistance Thermometer Bridge Circuit

A compensation circuit consisting of a double bridge circuit incorporating two precision platinum resistance thermometers has been studied. Two variations of this scheme are shown in Fig. 3. Even though the temperature coefficient of a platinum resistance thermometer is only about

Fig. 3. Double Wheatstone bridge compensation circuit (above) and double transformer compensation circuit (below).

one-sixth that of sea water at 15°C and of opposite sign, it can be shown that the circuits shown in Fig. 3 can be made to have a temperature coefficient closely matching that of sea water from 0 to 25°C.

An examination of a simple Wheatstone bridge with a resistance thermometer in one arm will show that the relative temperature coefficient of the ratio of the output short circuit current to input voltage, $(I/I_o)(dI_o/dT)$, becomes progressively larger as the bridge approaches balance and reverses sign on the other side of the balance point. However, an analysis of the simple bridge shows that if the bridge is adjusted to give accurate compensation at 15°C, the temperature coefficient of the bridge rapidly deviates from that of sea water at higher and lower temperatures. However, a detailed analysis of the double transformer bridge circuits shown in Fig. 3 leads to the results shown in Table I. For the various values of R_s the bridge resistors, R_{F1} and R_{F2} , were adjusted so that the temperature coefficient of the bridge exactly equalled that of sea water at 15°C. Where R_s is large the temperature coefficient of the bridge circuit closely matches that of sea water over a wide range. In Fig. 4 a plot is shown of the salinity errors (for $S = 35$ parts per thousand) with R_s at a very large value. The salinity errors are quite small for temperatures below 22.5°C and due to the stable characteristics of well designed platinum resistance thermometers these errors are quite stable and can be allowed for in the final analysis.

PRESSURE COMPENSATION

The effect of hydrostatic pressure on the conductivity of sea water¹⁵ is very considerable as shown in Fig. 5. The figure also shows that the relationship between pressure and conductivity is not linear and that at pressures as

Table I.

Temperature (°C)	Double Bridge Temperature Coefficient (%/°C)			Sea Water Temperature Coefficient (%/°C)
	$R_s=0$	$R_s=120$	$R_s=2000$	
0	3.069	3.020	2.986	2.999
5	2.763	2.734	2.714	2.708
10	2.505	2.492	2.484	2.481
15	2.286	2.286	2.286	2.286
200	2.099	2.108	2.114	2.118
25	1.935	1.952	1.963	1.976

Fig. 4. Compensation errors for circuit shown in Fig. 3 and difference in temperature coefficient between circuit in Fig. 3 and sea water.

small as 50 psi an error equivalent to 0.01 parts per thousand in salinity results. Also, the pressure effect is quite dependent on temperatures¹⁶ as shown in Fig. 6. The effect of pressure at 0°C is twice as great as at 30°C. Consequently, any pressure compensating device must take into account the temperature. Fig. 7 shows a circuit that has been designed to provide an input-output relationship that closely simulates the changes in conductivity due to changes in pressure.

The loading effect of R_3 on the pressure potentiometer is adjusted so that the relationship between E_0 and the pressure applied to the pressure potentiometer closely simulates the conductivity pressure relationship of sea water. The reduction in the pressure coefficient with increasing temperature is closely simulated by

Fig. 5. Change of conductivity of sea water.

Fig. 6. Effect of temperature on pressure coefficient at 1,500 psig.

the change in resistance of a thermistor resistor combination, R_{TH} and R_1 . By adjusting R_1 , R_2 and R_3 , the effect of pressure on the conductivity of sea water can be simulated with an overall accuracy of 1% at temperatures below 10°C. At

Fig. 7. Pressure compensating circuit.

Fig. 8. Complete salinity bridge.

20,000-foot depth, i.e., 8,800 psi and 0°C , the increase in conductivity due to pressure is approximately 5.5%. Therefore, at this depth and pressure, the uncertainty due to pressure compensation errors is ± 0.02 parts per thousand. At shallower depths the uncertainty is reduced in proportion.

COMPLETE SALINITY SENSING BRIDGE

The salinity bridge circuit complete with temperature and pressure compensation circuits is shown in Fig. 8. A current, I_w , is induced to flow in the sea water loop by the application of E_i to the toroidal transformer, T_1 . I_w , which is proportional to the conductivity of the sea water loop, sets up a magneto-motive force on the magnetic circuit of T_2 . A counter mmf proportional to the difference between $I_1 N_1$ and $I_2 N_2$ is set up by the combined outputs of the pressure and temperature compensating circuits.

At one particular value of salinity (depending on R_S) these mmf's will be in balance and E_o will be zero. Any change in I_w at constant salinity due to temperature or pressure changes is balanced by a similar change in the output of the temperature or pressure compensating circuits, thus maintaining a balance dependent only on salinity.

Fig. 9. Block diagram of salinity oscillator.

SALINITY OSCILLATOR

In a simple system the salinity bridge shown in Fig. 8 could be balanced by a servo system acting on R_S . R_S could be a precision potentiometer coupled to a shaft encoder for digital readout. However, this system would require considerable amounts of power in an underwater package and would have the disadvantage of larger size and lower reliability due to the number of moving parts. An improved system might utilize the output voltage to input voltage relationship of the salinity bridge to control the frequency of a special phase shift oscillator. A block diagram is shown in Fig. 9.

It can be shown that with suitable design the error voltage, E_o , from the salinity bridge is either in phase or 180° out of phase with the bridge input voltage, E_i . If the error voltage, E_o , is added to a voltage, E_q , which is 90° out of phase with E_i , then the phase of the resultant $E_o + E_q = E_r$, will shift as the bridge balance changes with changes in salinity. The resultant, E_r , is amplified and then applied to a phase shifting network consisting of R_A , R_B , C_A and C_B . The output of the phase shifting network is amplified in A_2 and applied to the input of the bridge, thus closing a complete loop. The loop will oscillate at a frequency at which the sum of the phase shift between E_r and E_i plus the phase shift in the phase shifting network amounts to 180° . Experimental oscillators of this type have shown that the salinity uncertainty due to supply voltage and temperature variations on the electronics is not worse than ± 0.003 parts per thousand in salinity for an oscillator covering a range of 5 parts per thousand.

The quadrature voltage circuit shown in Fig. 9 has to be temperature compensated because when the bridge is off balance, E_o will not be zero and will vary with temperature at a given salinity. This means that E_q should vary with temperature by the same proportional amount as E_o . However, the accuracy with which E_q is compensated becomes less critical as the bridge approaches balance and is completely unimportant at the balance point. Consequently, the accuracy with which E_q is

compensated is only important when the salinity value is a long way from the value at which the bridge is balanced. To insure good stability in the basic oscillator, the amplifiers A_1 and A_2 have very good phase shift stability and the level of oscillation is controlled by the automatic gain control circuit to a level well below overload.

CONCLUSIONS

It is estimated that the combined stability of the conductivity sensor, the temperature and pressure compensating circuits and the electronics will yield a repeatability of ± 0.005 parts per thousand and an accuracy of ± 0.05 parts per thousand in salinity including both temperature and pressure compensation errors from 0 to 25°C and 0 to 20,000-foot depth. However, the compensation errors can be accurately determined and allowed for in the final analysis with a resulting accuracy approaching ± 0.01 parts per thousand salinity.

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AN IN SITU CONDUCTIVITY METER

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INTRODUCTION

An indirect technique commonly used for salinity determination is the measurement of the electrical conductivity of the water. Conductivity cells using platinum or similar metallic electrodes have been used for conductivity measurements. However, electrode polarization and contamination has limited the long term accuracy of calibration of such devices.

Some of the more recently developed conductivity meters have used induced currents in the water to measure the conductivity. This technique eliminates the problems of electrode polarization and contamination and appears to lend itself to use as an in situ instrument.

THE WESTINGHOUSE CONDUCTIVITY METER

An induction conductivity meter suitable for use as an in situ instrument is being developed by the Westinghouse Electric Corporation. This meter utilizes two toroidal inductors in a balanced bridge circuit. A simplified circuit diagram is shown in Fig. 1.

The inductors, L_1 and L_2 , are wound on magnetic toroids made of a ferrite material and are constructed as nearly identical as possible. The resistors, R_1 and R_2 , are identical and their resistance is approximately equal to the inductive reactance of L_1 and L_2 at the frequency used. As a result the bridge circuit should be balanced there being no signal output to the null detector.

To make measurements of conductivity, the inductor, L_1 , is submerged in the fluid whose conductivity is to be measured. The fluid around and through toroidal inductor L_1 comprises a one turn secondary winding on L_1 with a resistive load inversely proportional to the fluid conductivity. When placed in a fluid, the fluid induces a resistive component into L_1 , unbalancing the bridge circuit. A secondary winding is placed on L_2 and is loaded with a variable resistor. This resistor and secondary winding induce a resistive component into L_2 and the variable resistance can be adjusted until the bridge is again balanced. The value of this resistance is thus a measure of the conductivity of the fluid surrounding L_1 .

Fig. 1. A simplified circuit diagram of the Westinghouse induction conductivity meter.

The inductor L_2 is exposed to the surrounding fluid in a manner similar to L_1 and in close proximity to L_1 , but the medium is prevented from loading L_2 by the presence of a thin, compliant, electrically insulating membrane closing the hole through the center of the toroid. Thus inductor L_2 is exposed to the same thermal and pressure environment as L_1 . Inductors L_1 and L_2 are physically made as identical as possible. Thus the thermal and pressure effects on the two inductors should be the same and as a result the bridge balance should be inherently independent of pressure and temperature effects.

Because L_1 and L_2 are identical as are R_1 and R_2 , the bridge balance is also inherently independent of the frequency, amplitude and waveform of the signal source. This is of considerable value when the meter is used as an in situ instrument where it might be difficult to maintain accurate frequency and amplitude control on the signal source.

ACCURACY CONSIDERATIONS

The accuracy of this circuit is fundamentally limited to measurement of the smallest change in conductivity that will produce a bridge unbalance signal larger than the input noise of the null detector. Therefore, electrical and physical

circuit conditions, which will produce the greatest percentage change in the impedance of L_1 for a given change in fluid conductivity, are the conditions for greatest accuracy.

The impedance of L_1 is essentially equal to the reactance of the inductor paralleled by the induced loss resistance due to the conductive medium. The circuit conditions which will make the value of this parallel resistance smallest and the value of the parallel inductance relatively greatest will produce the greatest accuracy until the resistance is small compared to the inductive reactance. When this condition is reached the effect of the parallel inductance will be small and the bridge will essentially consist of 4 resistive elements. Under these conditions the percentage change in the impedance of the L_1 arm of the bridge will be determined directly by the percentage change in the conductivity of the surrounding medium. Until this condition is reached, the accuracy of the meter is determined by the following considerations.

The value of the induced loss resistance considered in parallel with the inductive reactance of L_1 is numerically equal to the resistance of the fluid path through and around the toroidal inductor multiplied by the square of the number of turns on the inductance. The value of the induced resistance can then be decreased by decreasing the resistance of the fluid path and by decreasing the number of turns on the inductor. Decreasing the number of turns of the inductor decreases the parallel inductance by the same ratio that the induced resistance is decreased so that the sensitivity is independent of the number of turns comprising the inductor. The resistance of the fluid path is determined by the physical geometry of the inductance. Increasing the area of the hole through the toroid and decreasing the length of the hole as well as decreasing the cross-section of the core, windings and covering material will decrease the resistance of the fluid path and hence increase the sensitivity of the device.

The sensitivity of the device can likewise be increased by increasing the relative value of the parallel inductive reactance of L_1 and L_2 . The inductance of L_1 and L_2 can be increased without increasing the value of the induced resistance by increasing the permeability of the magnetic core material used. The inductance can also be increased by increasing the frequency of operation. Thus it is seen that the accuracy of the device is proportional to the permeability of the core material and the frequency of operation and is dependent on the physical geometry of the cores.

PRACTICAL CIRCUIT CONSIDERATIONS

In practice the two inductors, L_1 and L_2 , cannot be made exactly identical. They will be found to differ both in inductance and loss. As a result, some means must be provided to

compensate for differences of inductance and loss so that an initial balance of the bridge can be obtained. Assuming that the loss component of the impedance of the inductors is small compared to the reactive component, the effect of an inductance unbalance can be compensated by changing the values of R_1 and R_2 . The effect of a loss component unbalance can be compensated by shunt resistors across the appropriate inductor or across both inductors. In practice R_1 and R_2 have been made variable in different degrees to provide coarse and fine inductance balance controls. Likewise, variable resistors shunted across L_1 and L_2 have been provided to obtain coarse and fine loss balance controls.

As was mentioned earlier it is desirable to wind the inductors on toroidal cores having as high a magnetic permeability as is possible. As it is also desirable to operate at as high a frequency as is practical, many high permeability core materials cannot be used because of the great amount of loss at high frequency. As a result a compromise must be reached between these conflicting factors. At present, toroidal cores made of a ferrite material having a permeability in the region of 800 to 1,000 are used at a frequency of approximately 500 Kcps.

The impedance of the elements of the bridge circuit is determined by the inductive reactance of L_1 and L_2 . If the impedance is made too high, stray capacity will alter the desired circuit conditions and will make the circuit balance frequency sensitive. If this impedance is made too low, stray lead inductance will have the same effect. This latter consideration has been a problem particularly in designing the balance resistance connected to the secondary winding on L_2 . If stray inductance is present here, it introduces a reactive component into the null voltage, thereby reducing the accuracy with which the null can be detected. In general the impedance level of bridge components has been kept in the region of 100 to 1,000 ohms.

As it has been found possible to balance the bridge circuit so that the amplitude of the output to the null detector is of the order of 120 db less than the input signal level, it is necessary to design the apparatus physically so as to prevent disturbances from outside influences. The electrical circuitry is all enclosed in shielded containers and the toroidal windings isolated with Faraday shields. The mechanical supports for the inductors are made quite rigid so as to isolate the toroidal cores from mechanical stress. This is necessary since the permeability of the ferrite core is a function of the mechanical stresses in the material. Care must be taken to prevent variation of the circuit characteristics by the use of good quality components and rugged physical construction.

An alternate method of balancing the loss component induced in L_1 by the conducting medium is by the use of a variable shunt capacitor across R_1 . In this case, the secondary winding and

balance resistance connected with L_2 are eliminated. It can be shown in this case that the circuit is balanced when the balance capacity is equal to the inductance of L_1 divided by the product of the resistance R_1 and the induced loss resistance. Again the balance is found to be independent of frequency. As in the other balance system, L_1 is assumed equal to L_2 , and R_1 is assumed equal to R_2 . No loss is assumed for L_1 and L_2 and, as this is not the case in actual practice, the circuit balance is slightly frequency dependent. An advantage of this circuit is that it eliminates the problem of a sliding contact in the balance resistance which had been found to introduce an uncertainty into the value of the balance resistor.

THE IN SITU INSTRUMENT

For convenient use as an *in situ* instrument, the bridge circuit is supplied with a self-balancing system to reduce or eliminate the interconnecting cable requirements between the instrument and the survey ship. The balance system used with this bridge utilizes the fact that the signal out of the bridge to the null detector reverses phase as the bridge is adjusted through the null point. Therefore, the null point is characterized by both an amplitude minimum and a phase reversal. A block diagram of the balance system used is shown in Fig. 2.

The bridge output is amplified and fed to a phase sensitive detector. A reference signal for the phase sensitive detector is obtained from the oscillator which is used to drive the bridge. The output of the detector is a DC voltage whose amplitude is proportional to the amplitude of the input signal and whose polarity is a function of the relative phases of the input and reference signals. The phase of the reference signal is adjusted so that the output of the detector is positive on one side of the null and negative on the other side. This signal is amplified and used to drive a reversible DC motor which in turn adjusts the balance resistance in the bridge in such a direction as to effect a null. A data telemetering system transmits the shaft

position, which is now a function of conductivity, to the survey ship.

As was mentioned previously, stray reactances in components of the bridge circuit introduce a reactive component into the null voltage which reduces the accuracy with which the null can be determined. The phase sensitive detector however responds only to signals which are in phase or 180° out of phase with the reference signal. Since the reactive voltage component mentioned above is made to be in quadrature with the reference signal it does not affect the output of the detector. In the case of a laboratory or manually balanced instrument, this type of null detector has been found to give considerably more accurate results than a simple amplitude null detector.

SYSTEM ACCURACY

Calibration of a conductivity meter in absolute values is a difficult process when a high degree of accuracy is desired or required. Solutions of known salinity must be used and the temperature must be known to a degree of accuracy similar to the required conductivity accuracy. It is considerably easier to make an estimate of the expected accuracy by measuring the repeatability of the device. To measure the repeatability, it is only necessary to know the absolute salinity and temperature roughly and to be able to measure relative temperature to a high degree of accuracy.

A sample of artificial sea water was made up with an estimated salinity of 35 parts per thousand. As a considerable period of time is involved in making repeatability measurements, evaporation from the sample was inhibited by floating a film of oil on the surface of the sample. The absolute temperature of the sample was measured with a mercury thermometer and a thermistor thermometer was used to measure relative temperature to a repeatability of 0.01°C . The sample was stirred continuously to maintain a uniform temperature.

One preliminary laboratory model of the conductivity meter has been tested for repeatability under these conditions over a test period of several days. The repeatability was found to be ± 0.1 millimhos for a solution whose conductivity was approximately 55 millimhos. A large part of this error could be attributed to contact noise in the adjustable balance resistor as was mentioned earlier. It is estimated that elimination of the contact noise problem would improve the repeatability of this particular device to ± 0.05 millimhos. As this device did not use the best known physical configuration, it is estimated that an improved model now under construction can improve this repeatability figure by a factor of 10.

Fig. 2. A block diagram of the self-balancing scheme for the *in situ* instrument.

CONCLUSIONS

It is believed that the circuit described will give an estimated accuracy and repeatability of ± 0.005 millimhos or better in its final form. Furthermore, the circuit is inherently insensitive to external influences, thereby enabling it to be adopted to use as an in situ instrument.

ULTRASONICALLY CLEANED ELECTRODE

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ABSTRACT

Electrodes, such as used in pH, Redox dissolved oxygen and electrical conductivity measurements of solutions are frequently subject to fouling when used in biological laboratories or marine environments. A probe electrode has been devised which can be subjected to high intensity ultrasonic vibrations to eliminate the accumulation of fouling materials on the electrode surface. The electrode is driven by a tube of a magnetostrictive material rigidly attached to the electrode. An alternating magnetic field is supplied by a solenoid wound around the probe. A compact transistorized power supply has been constructed to energize the solenoid. The ultrasonic electrode was originally developed for Redox measurements. Cells for electrical conductivity measurements in two and three electrode configurations are currently under test and results will be described.

INTRODUCTION AND BACKGROUND

All electrode reactions are either oxidation reactions or reduction reactions and these are responsible for typical marine pitting and galvanic corrosion which are so costly to the industrialized parts of the world. Oxidation is de-electronation and reduction is electronation, to use the terminology of Professor E. C. Franklin of Stanford University.¹ Corrosion protection is therefore obtained by cancelling these effects against each other with sacrificial materials or by supplying a counter electron current. These reactions are further useful since titration end-points may be obtained for certain reactions by measurement of the oxidation-reduction potential.² Servo-electric control of a reaction can also be affected by this measurement but the metallic electrode must be in electrical contact with the solution in which the reaction is taking place.

The susceptibility to biological fouling of electrodes in aqueous solutions is well known and several recent ISA papers describe efforts directed toward relieving this difficulty in measurement of electrical conductivity of solutions.^{3,4,5,6}

A single metal electrode was recently required to be used for control feedback measurement in a

solution of human body wastes in which photosynthesizing algae would flourish to provide oxygen and protein food for mock space flight. The prototype system (Fig. 1) involved a large resin kettle with the electrode inserted through one cork hole.

Fig. 1. Prototype scrubbed electrode system.

Superior numbers refer to similarly numbered references at the end of this paper.

THEORY OF OPERATION

Analysis indicated that comparatively low level excursions of a disk electrode at a high rate should provide sufficient flow, due to non-linearity of the hydraulic coupling, that a strong scrubbing action would occur, even in the absence of cavitation, and that this scrubbing might prevent or remove the normal biological fouling.

DESIGN

A half-wavelength magnetostrictive tube was rolled of sheet nickel and supported at the nodal midpoint by three setscrews (Fig. 2). It was excited at its resonant frequency of 32 Kcps by an efficient solid-state driver of simple design.

electrical noise pickup in the cable or electrode. This precaution proved unnecessary, apparently due to shielding precautions and effects of symmetry.

POTENTIAL FUTURE APPLICATIONS

Success of this design has lead to several programs for further development. Design of a similarly rugged pH cell using the antimony, antimonytrioxide electrode is being evaluated. This cell is typically erratic in its behavior, but a surface contamination may be the reason. The application of the self-scrubbing principle for improving the thermal contact of thermistors, platinum resistance thermometers and thermocouples in solutions and powders is underway. Evidence shows that a considerable fraction of

Fig. 2. Half-wavelength magnetostrictive tube.

A 0.5-inch diameter brass endplate was rigidly fastened to the tube and the exposed surface heavily gold plated. The assembly was seated with silicone rubber in a tube of Nylatron GS, a molybdenum disulphide-filled nylon, which also formed the bobbin for the exciting winding. The winding was potted with an epoxy resin that bonded the conductors mechanically and simultaneously offered chemical protection. Electrical connection was made directly to the brass plate by soft-soldering the copper center-conductor of an unterminated miniature low-noise coaxial cable (Microdot). The complete unit is shown in Fig. 3.

Power connections were to ordinary 115 volt 60 cps AC although any source could be utilized by the semiconductor driver which requires a total of 15 watts. The electronic design is perhaps most notable because of the fact that only twenty components are required, of which twelve are in the power supply circuits. This has allowed six months operation without a component failure and should meet all requirements of both inner and outer space.

A pi-section rejection filter was designed and included to reduce anticipated ultrasonic

the boundary layer insulation effect can be eliminated by sufficiently strong circulation.

Heat flow from the magnetostrictive driver losses, as well as from the energetics of fluid reaction, must be considered in the design, although the acoustic power is in the milliwatt region and is of lesser importance.

Electrode measurement of conductivity in natural environments, as opposed to the electrodeless transformer methods discussed earlier^{3,4,5,6} has the advantage of utilizing basic measures of length and current with greatly reduced complexity and with higher accuracy than is possible with electrodeless methods.

Fig. 3. Self-scrubbing electrode assembly.

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SESSION II

TEMPERATURE

Chairman: M. P. WENNEKENS
Naval Ordnance Test Station
China Lake, California

AN IN SITU TEMPERATURE SENSOR

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ABSTRACT

Discussed is a unit for temperature measurement at a remote point (accurate to $\pm 0.02^{\circ}\text{C}$) with a high Q mechanical resonator whose frequency is temperature dependent. The resonator is novel in that a mechanical Q near 80,000 is attainable at 30 Kcps with an aluminum resonator whose support posts may be one-third the size of the resonator itself. The posts allow for rapid thermal stabilization.

INTRODUCTION

An *in situ* temperature sensor has been developed for use in oceanographic measurements and is capable of measuring the temperature of the ocean accurately to $\pm 0.02^{\circ}\text{C}$. This instrument would also be used in conjunction with an induction conductivity meter which, it is hoped, will determine salinity to an accuracy of 0.02 parts per thousand. The temperature sensor-conductivity meter package will ultimately be capable of operation to depths of 4,000 fathoms.

PRESENT METHODS

At present the most popular method for measuring temperatures to this accuracy employs a thermistor in a Wheatstone bridge circuit, the thermistor being connected to the bridge by long wires. While the thermistor is capable of this accuracy, there are some shortcomings to its convenient use, the most significant being the heating of the thermistor due to the current in the bridge circuit. A newer method is to use a thermistor in an RC network in a phase shift oscillator, but this requires an extremely stable circuit or one that is calibrated often.

DESCRIPTION OF DEVICE

A more satisfactory way to measure temperature employs the device shown in Fig. 1. Inside the brass housing is an aluminum resonator which acts as a high-Q resonant filter whose frequency is temperature dependent. The resonator and amplifier shown comprise an oscillator circuit, and the temperature is converted to a frequency which is transmitted through a pair of conductors and registered on a counter. A two wire cable

of any length connects the sensor to the counter, the DC power and temperature signal being superimposed on the same line. This sensor is especially suited to unattended operation for long periods of time without losing calibration and the frequency can be easily used to modulate a transmitter if needed. The frequency for 25°C is about 36 Kcps for the resonator shown, and the frequency change is approximately 10 cps for each degree Centigrade. The resonator housing is evacuated to eliminate any mechanical loading on the resonator because the accuracy of temperature measurement is related to the mechanical Q of the resonator.

A more detailed view of the temperature sensitive resonator is shown in Fig. 2. The disc between the two posts vibrates in a flexural mode with two nodal diameters, two piezoceramic elements being fastened at the pickup and drive points. The motion is best depicted in the lower left view; in the top view it may be imagined as occurring in and out of the paper, the top and bottom quadrants moving opposite to the left and right. The nodal diameters are stationary.

The two piezoceramic elements are bonded to the disc with conducting epoxy. The elements are made of a lead zirconate titanate and the disc's resonant frequency is far below their natural resonance. Wires are attached to the elements with conducting epoxy using small phosphor bronze springs for compliance as shown in Fig. 2. It is important to recognize that the disc responds to the longitudinal or left-right motion of the element and not to the thickness motion. The aluminum is connected to the ground potential of the oscillator and the circuit is thus completed to the bottom plates of the elements.

Heat is conducted to or from the disc by way of one of the two posts in the resonator of Fig. 1. Ultimately, both posts will be exposed in order to reduce the temperature time constant. Large posts may be used without affecting the Q because the load presented to the disc by the post is reactive. The equal and opposite forces on the post cancel, leaving the post out of the resonant system. The response of this disc to a temperature step function results in a time constant of about one minute, or one minute to complete 63% of the frequency change. This time constant can be reduced by decreasing the ratio

Fig. 1. Photo of temperature sensor prototype.

of the mass of the disc to the area of the post. The practical minimum time constant is not determined by the resonator, however, but by the frequency counter. A counter requires a minimum of 10 seconds to count a 36 Kcps frequency to the required 6 places; it is probable that the temperature time constant of the resonator can be reduced to match this.

MATHEMATICAL EXPRESSION

The expression for a thin disc with no post and vibrating flexurally with two nodal diameters is

$$f = \frac{0.238}{R^2} t \sqrt{\frac{Y}{e(1-\sigma^2)}} \quad (1)$$

where f is resonator frequency in cps, R the radius of the disc in cm, t the thickness in cm, Y is Young's modulus in dynes/cm², σ is Poisson's ratio and e the mass density in gm/cm³. The change in Young's modulus with temperature accounts for most of the frequency changes, Y changes about 0.04% for each degree Centigrade change. The frequency changes due to expansion alone are of an order of magnitude less. Varying the thickness to diameter ratio changes the disc frequency, as the expression indicates, but the mode of operation is lost as the thickness-diameter ratio approaches one. The expression becomes inaccurate as the disc becomes thicker and with the addition of posts.

Fig. 2. Detailed schematic of mechanical resonator.

ACCURACY CONSIDERATIONS

The accuracy with which the frequency of this type of resonator follows temperature changes depends upon the Q of the resonator, for the frequency must remain constant and be repeatable for any one temperature. The higher the Q , the less the frequency will be permitted to wander. An approximate calculation (Fig. 3) shows that if a maximum random phase variation of 45 degrees is assumed in the amplifier circuit, an accuracy of $\pm 0.02^\circ\text{C}$ requires a resonator Q of 45,000. Most experimental resonators have had Q 's of 45,000 and above when operating in a vacuum; in fact, one was as high as 80,000.

A wide band amplifier in the oscillator circuit with a resulting random phase shift much less than 45 degrees would permit a lower Q resonator to be used. However, this is not feasible due to the presence of harmonics of the described fundamental and many other modes that can be excited and hence must be suppressed, either by tuning the amplifier or filtering. Either method will introduce some phase instability. A typical spectrum is shown in Fig. 4. This spectrum is shown from a slightly different type of disc, having only one smaller post, but the spectrum is typical. Most of these frequencies belong to other modes of vibration.

Only the second line at about 60 Kcps can be considered a legitimate overtone to the first line with the characteristically high mechanical Q . The fundamental frequency is used in the oscillator circuit. The small circuit of Fig. 1 contains two tuned circuits--a tank circuit tuned to the fundamental frequency and a trap at the first overtone. For laboratory measurements, however, a low pass, sharp cut-off filter is used, following an untuned amplifier (see Fig. 5). This method results in less change of phase with different oscillation frequencies and greater stability of phase at a given frequency. This is shown by the fact that if all the inductors in the filter circuit decrease their inductance by 20%, the resulting phase shift through the filter at a given frequency is only about 20 degrees. Not shown in Fig. 5 is a phase shift circuit following the filter which is necessary to obtain oscillations and will also be used in the final unit to check periodically the resonator Q . This will be done by introducing a known phase shift and noting the resulting frequency change.

LABORATORY TESTS

Laboratory tests have been conducted to check the repeatability of the temperature sensor

CALCULATION OF NECESSARY RESONATOR Q

UNIVERSAL RESONANCE CURVE

PERMISSIBLE TEMP. READING ERROR
RANGE ——.04°C

FREQUENCY-TEMPERATURE
COEFFICIENT ——.10 CYCLES/°C

∴ ALLOWABLE FREQUENCY
DEVIATION ——.04 × 10 = .4 CYCLES

ASSUME AMPLIFIER PHASE VARIATION
OF 45°:

THEN .4 CYCLES $\approx \frac{\Delta f}{2}$

WHERE Δf = FREQ. RANGE
BETWEEN 90° PHASE ANGLE CHANGE

Δf = .8 CYCLES

$$Q = \frac{f}{\Delta f}$$

$$Q = \frac{36000}{.8}$$

$$\underline{Q = 45000}$$

Fig. 3. Calculation relating error, amplifier characteristics and resonator Q.

measurements because this repeatability or frequency-temperature stability determines directly the accuracy. To test this repeatability a special double resonator, shown in Fig. 6, has been fabricated with two built-in Veco 51A1 thermistors. It is housed in a brass container and evacuated. This arrangement permits the greatest flexibility for measurements and comparisons between the four temperature measuring devices.

The double resonator was checked for repeatability by submerging the entire housing in a water bath. The bath was alternately heated and cooled over a one degree temperature range near 25°C. The resonators were incorporated one at a time in an oscillator circuit consisting of a 60 db amplifier with automatic gain control and the previously mentioned sharp cut-off, low pass filter. The frequencies were monitored by a counter which read to 6 places.

The best indication of repeatability is the plot of Fig. 7 which is one resonator's frequency against the other. Ideally the points should lie in a single straight 45° line. Actually, the points lie close to a line and the width of the cluster determines the repeatability. The points on this plot are numbered in the order of their

being taken and they show a repeatability, and therefore a potential accuracy, of about 0.01°C. This indication of repeatability must be verified by a plot of one of the sensors against a thermistor (Fig. 8) to indicate any frequency-temperature hysteresis in the aluminum or temperature gradients due to insufficient time for temperature equalization. Either effect would show as increasing temperature points lying consistently to one side of the line and decreasing points to the other. This plot shows no such error. The final plot (Fig. 9) is of one thermistor against the other to show the thermistor repeatability.

Of course, these tests fail to indicate the long term repeatability that might be expected of the temperature sensor. Barring any loss of vacuum, the only change in calibration that can occur is perhaps through some aging of the aluminum; the resonator's frequency is otherwise independent of the external circuit, changes in the ceramic elements or any environmental factor except temperature.

Fig. 4. Spectrum of similar resonator.

MATERIAL CONSIDERATIONS

Some factors that are important in order to produce a good resonator should be discussed. The material must have high heat conductivity. Aluminum has more than twice the conductivity of brass and four times that of steel. Copper and silver have about twice the conductivity of aluminum but are not hard enough to permit a high Q. Aluminum has another advantage in that its heat capacity is low due to its low density. Two aluminum alloys have been used, designated 6061-T6 and 7075-T6. The latter is the harder and results in a higher mechanical Q. Also, two other materials have been used, Invar and Ni Span C. Invar does not expand with temperature changes; its applications make use of this fact. An Invar resonator has a positive temperature coefficient of 200 ppm instead of the usual negative one. Ni Span C is used in resonant magnetostrictive applications and its frequency is relatively stable with change in temperature. A high Q resonator can be made with this material for temperature independent applications.

OSCILLATOR CIRCUIT

RESPONSE OF FILTER

Fig. 5. Basic oscillator system.

Fig. 6. Experimental double resonator.

Fig. 7. Short term repeatability of sensors.

Fig. 9. Short term repeatability of thermistors.

Fig. 8. Frequency-temperature hysteresis and thermal gradient test.

A RAPID RESPONSE HIGH ACCURACY THERMAL PROBE

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INTRODUCTION

The temperature measuring system described here was evolved in an effort to furnish the oceanographer with an accurate, rapid response measuring system, approaching the precision of the reversing thermometer but being a continuous reading device and one not requiring manipulation by highly skilled personnel. Realized is an arrangement (Fig. 1) with a raw accuracy of $\pm 0.05^{\circ}\text{C}$ over a 25°C span which may be corrected to $\pm 0.02^{\circ}\text{C}$. The system will maintain this accuracy, when properly used, for periods of months and it is not affected by normal handling. The time constant is better than one second in flowing water.

PROBE SELECTION

In approaching such a device, the basic sensor choice was almost immediately limited to resistance type elements by considerations of accuracy. Thermocouples and filled system thermometers are not sufficiently precise. The same is now true of relatively novel methods such as paramagnetic susceptibility or capacitance change. In the area of resistance thermometers, the thermistor is outstanding for its high output and rapid response. However, our concern over long term thermistor stability, even after aging, made us abandon the device and employ metallic sensors for the very high accuracies required. Here the stability and ease of reproduction, inherent in platinum, dictated its choice in spite of its low output. Fortunately the linearity of platinum is quite good. Using platinum, stability and reproducibility of resistance change is several orders better than the accuracy required, and in fact, a thermometer not dissimilar in construction defines temperature between -182°C and $+603^{\circ}\text{C}$.^{1,2}

The probe output follows the Callendar relation of temperature to resistance

$$T = \frac{1}{\alpha} \left(\frac{R_T}{R_0} - 1 \right) - \delta \left(\frac{T}{100} - 1 \right) \left(\frac{T}{100} \right) \quad (1)$$

Fig. 1. Probe assembly.

¹Superior numbers refer to similarly numbered references at the end of this paper.

$$\alpha = \frac{1}{100} \left(\frac{R_{100}}{R_0} - 1 \right) \quad (2)$$

$$\delta = \frac{T_s - \frac{1}{\alpha} \left(\frac{R_s}{R_0} - 1 \right)}{\left(\frac{T_s}{100} - 1 \right) \left(\frac{T_s}{100} \right)} \quad (3)$$

where T is temperature in °C, R_T and R_0 are resistances at T°C and 0°C respectively, R_{100} and R_s are resistances at 100° and melting point of sulfur respectively and T_s is temperature of melting point of sulfur. Representative values for α and δ are 0.00392 and 1.49, respectively, giving a nonlinearity over a 25° span of approximately 0.1%.

In order to obtain a reasonably dimensioned package, together with rapid thermal response, a small diameter tube was utilized for the element housing. This combines a relatively low mass with a short thermal path and high structural strength. In practice, a flexible mandrel is wound spirally with reference grade platinum resistance wire. Over this spiral, aluminum oxide or beryllium oxide beads are threaded, leads affixed, the whole slipped into a tube and the assembly then swaged down to final form. Total tube diameter approximates 0.060 inch and in one configuration the outer tube wall is 0.006 inch thick.

TIME CONSTANT

The thermal response of a probe can be calculated as the algebraic sum of the separate time constants. The thermal situation is analogous to an electrical network of resistance and capacitance where the time constant, T, is equal to RC (Fig. 2). For a cylinder of unit length,

$$R = \frac{\ln \frac{r_2}{r_1}}{2 \pi K} \quad (4)$$

$$C = \pi \rho C_p \left(r_2^2 - r_1^2 \right) \quad (5)$$

$$RC = \frac{\rho C_p}{2K} \left(\ln \frac{r_2}{r_1} \right) \left(r_2^2 - r_1^2 \right). \quad (6)$$

The values of constants in the above equations for the particular probe under consideration are given in Table I.

Fig. 2. Schematic diagram of (a) thermal configuration and (b) electrical equivalent for calculation of thermal response.

Table I. Thermal probe constants.

Parameter	Stainless Steel	Aluminum Oxide
r_2 is outside radius of cylinder in feet	0.00233	0.00175
r_1 is inside radius of cylinder in feet	0.00175	0.00092
ρ is density #/ft ³	498.	230.
C_p is specific heat Btu/#/°F	0.175	0.125
K is conductivity Btu/hr/ft/°F	9.5	1.0

In the probe, which consists essentially of a metal cylinder surrounding a ceramic cylinder with the element beneath, the time constant of the sheath equals

$$R_1 C_1 = \left(\frac{(498)(0.125)}{(9.5)(2)} \right) \left(\frac{\ln 0.00233}{0.00175} \right) \left(0.00233^2 - 0.00175^2 \right)$$

$$= 0.322 \times 10^{-5} \text{ hrs}$$

$$= 0.0166 \text{ sec}$$

Fig. 3. Complete probe equivalent circuit.

and the time constant of the insulation equals

$$R_2 C_2 = \left(\frac{(230)(0.175)}{(1)(2)} \right) \left(\frac{\ln 0.00175}{0.00092} \right) \left(0.00175^2 - 0.00092^2 \right)$$

$$= 2.87 \times 10^{-5} \text{ hrs}$$

$$= 0.104 \text{ sec.}$$

The volume of the 0.0017-inch diameter platinum wire is small and is neglected.

Solving for the series circuit shown in Fig. 3 yields

$$\frac{T_o}{T_i} = \frac{1}{1 + S(C_1 R_1 + C_2 R_2 + C_2 R_1) + S^2(C_2 R_2 C_1 R_1)} \quad (7)$$

Letting $T_o = 1$, as a convention, and S as the transfer function equal to the negative reciprocal of RC or the reciprocal of the time constant, T , gives

$$T^2 + (C_1 R_1 + C_2 R_2 + C_2 R_1)T + (C_1 R_1)(C_2 R_2) = 0. \quad (8)$$

Substituting $C_1 R_1 = 0.012$, $C_2 R_2 = 0.104$ and $C_2 R_1 = 0.005$ gives a characteristic time constant polynomial

$$T^2 + 0.121T + 0.001248 = 0$$

which yields $T = 0.1118$ second. This varies from the experimentally determined value by a factor of 3 which is presumably due to boundary layer effects. No effort has been made to solve with the complex physical shapes involved.

PRESSURE EFFECT

The pressure resistance of the probe may be calculated using Lane's empirical approximation for the crushing strength of long tubes³

Fig. 4. Bridge circuit.

$$P = 80,000 \times \left[\frac{t}{D} - \left(\frac{t}{D} \right)^2 \right] \quad (9)$$

where t is tube wall thickness in inches, D is tube diameter in inches and P is crushing pressure in psi. The constant in the foregoing gives a result reasonably valid for material with a yield strength of approximately 40,000 psi. The configuration described withstands about 8,000 psi. It should be noted that some care is necessary in manufacture to avoid making the element susceptible to changing pressure as in a strain gauge. In units tested, strain effect was not measurable (less than 0.001 C) at an external pressure of 1,000 psi.

THE BRIDGE

To avoid unpredictable sources of error due to resistance in conductors and from resistance changes in similar but not entirely equal lead conductors, the measuring bridge (Fig. 4) is installed in the bulb head where it is protected by the relatively uniform water environment from the effect of gross thermal change. Since the bridge is unbalanced a zener voltage regulator is also mounted at the probe. The unbalanced bridge has an output computed as follows from Thevenin's principle:

$$E_o = \frac{E(AS - BX)}{R_E(A + B + S + X) + (A + B)(X + S)} \quad (10)$$

where E_o is open circuit voltage across detector, E is source voltage, A , B and S are fixed bridge resistors, X is the platinum resistor and R_E is the source impedance. The current, I_d , passing

through is

$$I_d = \frac{E_o}{R_d + R_B} \quad (11)$$

where R_B is the bridge resistance seen by the detector and R_d the detector impedance. An additional nonlinearity accrues from the unbalanced bridge which is minimized by keeping the percentage of resistance change in the bridge relatively low and the amplifier impedance high.

Bridge output changes proportionally in the unbalanced bridge with bridge voltage supply. However, the load is relatively fixed and temperature changes are small so there is little difficulty in zener regulating the bridge supply to 0.015%. Manganin bridge resistors are used, suitably aged. Care must be exercised in avoiding thermocouples at junctions. (Manganin has an output of 3 microvolts/°C with respect to copper.)

The bridge is mounted in a cylindrical pressure housing approximately 1.75 inches in diameter by 3 inches long, made of steel or high strength bronze. One end houses a conventional 4-conductor underwater electrical connector. Various mounting arrangements are furnished for attaching the probes to cables or structures. Sealing is accomplished with "O" rings. A mechanical shield for the sensitive element is insulated from the housing.

FOULING

Where thermal probes are to be immersed for long periods in relatively shallow water, marine fouling of the element will increase the time response sharply. As an example, a coat of paint on an element of the type described delays response time about 25%. We have noted weed formations several inches long and barnacles 3/8 inch in diameter after 3 weeks of unprotected immersion in tropical waters. The element shield therefore is made of nonfouling sintered material impregnated with anti-fouling agents. We find that this arrangement, with the relatively high and constant toxic dispersion mechanism, holds an area several inches adjacent to it clear of marine life except for some of the bacterial slimes. These vary in thickness and tenacity and the anti-fouling agents have some effect on them but at this time we have no definitive information as to their thermal conductivity. It is believed that slime acts as an additional boundary layer.

SIGNAL CONDITIONING

To convert the relatively low output of the probe to a signal suitable for feeding a data system a multiple stage second harmonic magnetic amplifier (Fig. 5) has been designed. This has the advantage of being hermetically sealed and not subject to maintenance so that its precision

Fig. 5. Amplifier - power supply assemblies.

is not a matter of careful adjustment. These second harmonic amplifiers have a null shift into the bridge impedance of the order of 10 microvolts referred to the input over a 40° to 140°F temperature span and a ±10% supply voltage variation. A feedback factor of several hundred stabilizes the gain and linearizes the output, usually 0 to 5 volts DC.⁴ The same amplifier housing furnishes an individual DC bridge supply, an on-off switch and circuit protection.

A SPECIAL APPLICATION

An interesting application of the probe suggests itself for dynamic height measurements. If one probe uses the pressure protective sheath and another a compliant sheath, we have the equivalent of protected and unprotected reversing thermometers of the same or perhaps improved accuracy. It is practical, in this instance, to use a 2-conductor cable carrying DC power to the assembly and 2 frequencies proportional to temperature to the surface. All of the hardware is available and could be packaged in a cavity about 2 inches in diameter and 4 inches long. The addition of an *in situ* salinometer to this package would take over some Nansen bottle functions and the combination could make rather rapid deep stations possible.

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A MOBILE INSTRUMENT FOR STUDY OF OCEAN TEMPERATURE IN THE THERMOCLINE REGION

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INTRODUCTION

A heavy fluid with a free surface, having a density variation only in the vertical direction (for the undisturbed medium), is subject to two basically different types of gravity wave excitation: (1) surface waves and (2) internal waves. Internal waves are characterized by having, for every mode, the maximum vertical particle displacement below the free surface.

For many analytical purposes most of the ocean for most of the year can be taken to consist of three strata. The first stratum is the surface layer consisting of well mixed, nearly isothermal water. The second part is the lower, more dense water in which the temperature and density vary slowly. Separating these two parts of the ocean is the (seasonal) thermocline region in which the vertical temperature gradient is relatively large. Since the horizontal salinity gradient is very slight in this region, isothermal surfaces nearly coincide with isopycnal surfaces. Thus, an obvious way to observe internal waves is to measure the vertical temperature structure in the vicinity of the thermocline.

A vertical string of thermistor temperature sensors for detection of the passage of internal waves was first used by Ufford;^{1,2} such arrays are commonly used today. This technique is widely applicable in shallow water and can even be used in deep water when attached to deep-sea mooring devices. When it is necessary to survey an area, an instrument on a moving platform is desirable. One such scheme is a towed chain designed for measurement of thermal microstructure in the upper 500 to 1,000 feet.³ To measure the vertical displacement of isotherms in the thermocline where steep temperature gradients are encountered, fairly close spacing of sensor elements, precisely located, is required. Close, precise spacing can be achieved with the moving strut internal wave recorder described herein.

APPARATUS

The vertical sensing array consisted of normalized thermistors spaced equally in the leading edge of a vertical strut mounted on the bow of a submarine. The first strut (Fig. 1)

Fig. 1. Low drag strut array mounted on USS BAYA.

was 18 feet long and made of wood with a streamlined cross-section. Its base was mounted in a steel boot and the main member was held in place by a number of smaller struts. The temperature sensors were placed 2.5 feet apart. The shoulder of the sleeve of the sensor element was flush with the leading edge and the thermistor bead extended about $1/8$ inch into the fluid stream.

The strut current in use (Fig. 2) is made of three 10-foot sections of a commercial antenna tower. Each section is triangular in cross-section. The tower is guyed laterally as well as fore and aft. Operation is satisfactory up to

Superior numbers refer to similarly numbered references at the end of this paper.

Fig. 2. Tower array mounted on USS SEA DEVIL.

5 knots and guy wire vibration is excessive at 6 knots. There are 34 thermistor beads in the vertical array. Of these, 26 are spaced at 1-foot intervals and used with a digital data system. Five are used as in the original array except that they are spaced at 6-foot intervals. The remaining 3 beads all have fast thermal response and are used for continuous temperature measurements. Two of these beads are located near the middle of the tower while the third is located at the top. In addition there is a fixed resistor which is mounted at the foot of the tower.

It is clear that the motion of the platform through the water causes an essentially time-independent distortion of the streamlines about the bow. This leads to a distortion of the time-dependent vertical temperature structure and the shape of the internal wave is modified. Since the distortion is most severe near the hull, the lowest beads are mounted some distance above it

and data from the upper part of the strut are preferred.

TEMPERATURE INDICATING SYSTEM

Thermistors were chosen as temperature sensor elements because of their high sensitivity and simplicity. Thermistors have a large negative temperature coefficient of resistance and the resistance is an exponential function of temperature. Commercially available thermistors do not have the same resistance vs. temperature characteristics (typical variations are $\pm 20\%$ in nominal resistance at 25°C) and hence are not directly interchangeable. Since the feature of interchangeability in sensor units is very desirable, a method was worked out for determining the optimum values of 2 resistors, one in series and one in parallel with the thermistor, that would successfully match the sensor outputs. The thermistors used were Veco 32A1 (Victory Engineering

Fig. 3. Thermistor assembly.

Corporation) which is the bead type with a glass probe covering. They are 2 inches in length, have adjacent leads and have a nominal resistance of 2,000 ohms at 25°C.

The construction of the thermistor assembly is shown in Fig. 3. The thermal time constant of the thermistor thus encapsulated was approximately 0.5 second. Since the temperature readings were to be taken at intervals of from 10 seconds to 1 minute, "aliasing" of the temperature signal could occur unless a thermal lag was introduced. For this reason, the thermal time constant was increased to about 16 seconds by applying several coats of an epoxy resin.

PRESSURE INDICATING SYSTEM

It was necessary to record depth variations concurrently with the temperature records for subsequent compensation during analysis. Since the depth desired was that of the temperature sensors, the ideal location of the pressure transducer inside the hull would be directly under the strut or tower containing the temperature sensors. The transducer was simply connected to the nearest sea chest by means of a high pressure line within the hull. The pressure at the sea chest has a quasi-static component and a fluctuating component due to the surface wave action. The latter pressure drops off exponentially with distance from the free

surface and in usual operation is attenuated below the system detection level. Near the surface these fluctuating components would have to be filtered out to prevent aliasing when the pressure reading is sampled at intervals equal to or longer than one-half the period of surface waves present.

A Statham Laboratories, Inc. Model PA208TC unbonded strain gage pressure transducer was used. This was an absolute gage with a range of 0-500 psia and a combined nonlinearity and hysteresis of less than $\pm 0.75\%$ of full scale.

MONITOR AND RECORDING SYSTEMS

The main purpose of this paper is to describe the transducers so the following discussion of recording techniques is limited to features that are pertinent to transducer design or operation. An independent and relatively simple visual monitor and data recording system (Fig. 4) employs strip chart recorders to handle temperatures from 5 thermally lagged thermistors, a single pressure transducer and the relatively fast temperature fluctuations of one uncoated thermistor. All data analysis is done on a CDC 1604 (Control Data Corporation) digital computer. A block diagram of the digital data recording system designed to match the CDC 1604 is shown in Fig. 5. The bridges were built at USNEL; the associated digital system was built according to our specifications

by Electro-Instruments, Inc. An input scanner, with a maximum switching speed of 50 channels per second, selects sequentially 26 temperature outputs, one pressure output, 3 calibration outputs and 2 time signals. The signals are amplified in a DC amplifier of adequate bandwidth. The analog to digital conversion is accomplished by means of a digital voltmeter with a maximum conversion rate of 1,000 readings per second. The time base for logging is a digital clock. The logging control allows for selection of scan cycles with intervals of from one second to 30 minutes (also continuous). Recording is by means of a printed tape recorder and/or a tape punch.

With the current set of thermistors, the logging rate is normally set at 10 seconds. In this mode both the tape punch and the printed tape recorder are used at all times in recording data.

Fig. 4. Visual monitor and recording system.

By cutting the printed recorder out of the system and using only the tape punch, the sampling rate may be increased from 3 to 4 channels per second to 9 to 10 channels per second. With a faster tape punch the sampling rate may be increased to approximately 17 channels per second and additional changes can be made for further increases.

OVERALL ACCURACY AND PRECISION

The accuracy of the temperature measurement depends on the accuracy of the calibration, linearity of the bridges and the accuracy of the digital system. The maximum error is $\pm 0.005^{\circ}\text{C}$. The overall precision of the temperature measurements, using probable error as the criterion, is the square root of the sum of the squares of the precision of the calibration and of the precision of recording which has been evaluated at $\pm 0.0032^{\circ}\text{C}$. The accuracy and precision of the depth indicating system are not well known but are probably a small fraction of a foot.

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Fig. 5. Digital data recording system.

TOWED SEA TEMPERATURE STRUCTURE PROFILER

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ABSTRACT

Vertical strings of temperature transducers have been deployed by the U. S. Navy Electronics Laboratory from fixed platforms buoyed from floats or the sea floor and towed horizontally. The technique of towing from surface ships has proved most valuable in the study of internal waves, fronts and other thermal structures in the program to achieve vertical profiles of the sea.

The USNEL thermistor chain is a string of 34 temperature sensors that operates in essentially a subsurface vertical line as the ship moves on the surface. The signals from the sensors are scanned electronically and interpolated for all whole degree Centigrade isotherms, which are printed on a continuous chart. In addition to the analog presentation of 2 dimensional temperature structure (depth and distance) the water temperatures at the 34 levels are planned to be punched on computer tape for later machine analysis. The depth of the array is monitored by means of a pressure transducer at its submerged end. The thermistor chain has been used for a year and a half in the Pacific Ocean from Canada to Central Mexico and as far afield as Honolulu. The main difficulty experienced, now eliminated, was lack of watertight integrity in the underwater temperature sensors, electrical harness and cable connectors.

The advantages and disadvantages of the equipment for oceanographic research as well as some of the results are discussed.

INTRODUCTION

The USNEL towed sea temperature structure profiler is essentially a string of thermal sensors held suspended in a near vertical attitude in the sea while the ship is moving forward. The sensing elements are located at selected intervals along the faired link chain from the surface to a depth of 800 feet and cause associated electronic recording equipment to provide isotherm profiles that are recorded with reference to depth and distance while the ship cruises ahead.¹

The USNEL thermistor chain thus makes feasible a worldwide acquisition of data on the vertical temperature structure of sea water since the oceanographic research vessel USS MARYSVILLE (Fig. 1), which deploys the chain, is capable of sailing anywhere in the oceans.

The hardware, consisting of hoist and chain, was designed and manufactured by the Commercial Engineering Corporation of Houston, Texas. The contouring temperature recorder was manufactured by the Scientific Services Laboratory, Inc. of Dallas, Texas, and is based on a design by Dr. W. S. Richardson of the Woods Hole Oceanographic Institution.² Three previous units have been constructed. The thermistor beads were produced by S. P. Fenwal Electronics, Inc. of Framingham, Massachusetts, from specifications by the Scientific Services Laboratory, who encapsulated the beads. The harness (underwater electrical leads) were manufactured by Spectra Strip Wire and Cable Corporation of Garden Grove, California.

DECK AND SEA UNITS

Oceanographic Chain Hoist

The oceanographic chain hoist³ is a self-powered winch designed for oceanographic work requiring measurements to depths as great as 840 feet when the ship is underway at very slow speed and to depths of approximately 540 feet at a speed of 13 knots. The hoist that raises and lowers the chain is powered by a diesel motor and controlled by a hydraulic drive, all on a single foundation measuring 11.5 by 18 feet. The drum is 7 feet in diameter and its total height with chain is 9.5 feet from the deck. The drum stores 900 feet of articulated chain. The 900-foot chain, the drum on which it is wound and the hoist weighs a total of 37,500 pounds.

The towing device connecting the surface vessel to the weight, or "fish," is a special articulated tow chain (Fig. 2) which is composed of fairly flat streamlined links about a foot long, 9 inches wide and 1 inch thick.

Between the two steel fairing cheeks on each link is a channel to house the electric cable

¹Superior numbers refer to similarly numbered references at the end of this paper.

Fig. 1. USNEL sea temperature profiler (thermistor chain) hoist on USS MARYSVILLE.

Fig. 2. Chain links, harness and fairings.

Fig. 3. Encapsulated thermistor bead:
(a) thermistor bead, (b) phenolic resin, (c) silicone rubber, (d) "O" ring seal, (e) silicone rubber cap and (f) leads.

harness. The plastic fairings that form the trailing edge of each link serve to reduce drag and hold the electrical conductors in position. When the harness is inserted in the channel, the plastic fairings are pushed into place between the cheek plates and are held in position by springs which snap into holes in the cheek plates. To prevent tension in the harness when the chain is bending sharply over the towing sheave, the harness is looped into two rounded depressions in the fairings. The 34 fairings that hold temperature sensors have a drilled hole for insertion of the thermistor bead and a drilled diagonal channel that permits water to flow over the bead as the chain is towed through the water. At the lower end of the chain a streamlined, 2,300 pound weight holds the chain in a nearly vertical position while it is being towed.

Beads and Connectors

The thermal sensing beads used are type GB 32 P168 thermistors whose resistance varies as a function of temperature, yielding ambient temperature measurements in the form of electrical current amplitude. The beads are carefully matched at a fixed temperature to an accuracy of 1 part in 2,000, equivalent to 0.02°C , at the matching temperature. Each bead and its two connecting leads are encased in silicone rubber (Fig. 3).

Fig. 4. Detachable connector from bead to harness: (a) leads, (b) neoprene cap, (c) neoprene body, (d) gold-plate brass male connector, (e) gold-plate brass female connector, (f) neoprene body, (g) neoprene cap and (h) lead to harness.

A watertight connection between the leads and the harness is important because this is the most probable location of water leakage. The connectors, consisting of brass plugs crimped on the end of each lead and then soldered, are inserted in special neoprene connecting plugs that fit together without air space as the brass connections are made. A watertight neoprene sleeve slides over the wire leads and the connected plug. Any defective thermistor can easily be replaced by unplugging the unit and inserting a new one.

The leads extending from the encapsulated beads (F, Fig. 3) developed leaks after prolonged use. The addition of a silicone rubber cap (E, Fig. 3) provided a satisfactory seal.

Another important improvement was made in the connectors which now consist of tightfitting neoprene sleeves so constructed that there is no air space to permit leakage (Fig. 4). These connectors, manufactured by Electro-Oceanics, have proved watertight through long immersion.

Harness

The present harness, manufactured by the Spectra Strip Wire and Cable Corporation is made of No. 22 19-strand copper wire. It is first covered with a 0.008-inch layer of polyethylene to prevent water from getting between copper and insulation. Then a 0.008-inch layer of polyvinyl chloride is applied to reduce abrasion in the links. Nine color-coded wires are cemented together with polyvinyl to form a ribbon. Thirteen of these ribbons make up the harness, a total of 117 leads, which is preformed in a zig-zag fashion, taped at intervals and laid in the channel of the chain (Fig. 5). All 117 leads do not go the full length of the chain but are sealed off at different distances along the harness so that only 27 leads reach the chain end.

The 34 thermistor beads use 2 leads each and 3 leads service the pressure element. The thermistor chain thus requires a total of 71 leads, leaving a number of spares. The inner leads of the harness are normally used as conductors since they are less susceptible to chafing and leaks.

An initial difficulty was the lack of watertight integrity in the electrical harness. Points of vibration and friction in the bundle of wires, connections of the thermistors to leads, connection of leads to the detachable plugs and the plugs themselves all proved susceptible to leakage. Connections at the greatest depth were the most prone to leak.

The first attempt to prevent leakage utilized a heavy rubber jacket over leads and vulcanized connectors. This proved too stiff to spread properly as the chain passed over the sheave on the fantail and to loop back into the channels in the links when the chain hung vertically.

ELECTRONIC COMPONENTS

Contouring Temperature Recorder

The contouring temperature recorder, built by the Scientific Services Laboratories,⁴ is the heart of the unit, taking information from the thermistors in the chain towed behind the ship and plotting the vertical distribution of temperature as a continuous record (Fig. 6). Each isotherm (line of constant temperature) is displayed as a depth profile similar to that made by a depth recorder and the complete record gives a 2 dimensional representation of the thermal structure of the sea. Since the thermistors are scanned from top to bottom the vertical scale of the record represents the length of the chain in the water.

The thermistors are placed at even intervals on the chain. Usually 34 measuring thermistors, spaced at 27-foot intervals, are programmed. As these are towed through the water the recorder interpolates and prints on the paper roll the contours of the various isothermal surfaces where the horizontal scale represents either time or distance and the vertical scale depth. Since the ship speed at 6 knots is believed to be several times faster than internal waves, the effects depicted are primarily spatial. Normally temperature increases toward the surface. However, in case of temperature inversions, where warm water underlies cold, the positive temperature gradient area may be shaded on the record for identification.

Fig. 5. Preformed harness: (a) preformed bead and (b) lead for bead.

The lower quarter of the chart (Fig. 6) is marked every 6 minutes with a vertical row of 16 dots by means of timing pips. For temperature readings the dots represent temperatures at 2-degree intervals from 0° to 30°C . A continuous line marks the temperature of the selected sensor. When the temperature of the bead is known the upper isotherm on the record and all other isotherms are easily identified.

The depth of the pressure transducer near the end of the thermistor chain varies with ship speed and with subsurface currents. For recording this depth on the lower part of the chart the 16 vertical dots represent depth at 60-foot intervals from the surface. There is no possibility of confusing the depth record with the temperature record for the values are simultaneously shown on 2 of the dial indicators at the base of the instrument (Fig. 6). Moreover, the depth reading is likely to decrease as the speed of the ship increases. A third dial indicator at the base of the instrument is connected with the scanning mechanism which prints temperature contours on the upper part of the chart and shows the temperature currently being plotted.

The recorder uses the helical-drum-and-blade principle and writes on electrosensitive paper such as Westrex Timemark No. 118 or Westrex No. 44. It can accommodate rolls of paper 19 inches wide and 400 feet long. The paper speed may be varied from 2 to 12 inches per hour but

the most satisfactory speed for presenting internal waves is approximately 6 inches per hour. At this speed a 400-foot roll should last approximately 33 days.

Several difficulties were experienced with the temperature contours due to shorts or open circuits in the harness and connecting leads. Other troubles in the recorder were caused by skewed paper feed, burning of paper, shorts in the circuit, smudging of records and improper scanning of the input resulting in flat isotherms.

Most of the difficulties were eliminated by proper tuning, adjustments and replacement of parts. One improvement was in the change from Westrex No. 44 paper to Westrex Timemark No. 118 paper which gave a better quality of trace and reduced handling and recording smudges. Malfunctions still occur but sufficient spare parts now insure a successful cruise.

Recorder Schematics

The thermistors are arranged in an array. Each thermistor forms one arm of a voltage divider similar to those used at USNEL on other temperature measuring devices.⁵ The voltage at the junction of any thermistor with its load resistor is the analog function of the temperature of that thermistor. Several such thermistors equally spaced on the chain produce analogs of temperature

Fig. 6. Contouring temperature recorder: (a) isotherms, (b) surface temperature plots, (c) depth of end of chain plot, (d) patch panel for incoming leads, (e) recorder paper case, (f) scan temperature dial, (g) station temperature dial and (h) transducer depth dial.

at those stations. A block diagram of the profiler system is shown in Fig. 7.

A commutating switch connects these stations sequentially to the interpolating potentiometer which assumes a linear temperature gradient between any two successive stations. As the wiper of this interpolating potentiometer travels along its resistance path the wiper picks off a uniformly graduated voltage between successive thermistors. Since the water temperature at the thermistors will not fall at whole degrees Centigrade (nor even at whole tenths of degrees), it is necessary for the potentiometer to interpolate

between degrees and fractions of degrees to obtain whole degrees Centigrade or tenths of degrees. The interpolated voltage produces a continuous gradient that can be followed by an amplifier and servo-mechanical components. This scan voltage is fed into a scan servo-amplifier.

The servo-amplifier and its associated follow-up mechanism comprises a DC amplifier loop. The feedback from the potentiometer on the servo-mechanism is a nonlinear function adjustable to the nonlinearity in the thermistor output voltage. The nonlinearities cancel, producing an output shaft rotation that is linear with reference to temperature variations.

Since the output of this servo-mechanism is linear with temperature, it is only necessary to provide a pick-off suitable for printing on a record, such as slotted or digitizing drum driven by a scan servomotor through gearing so arranged that one turn of the motor equals 1°C . The drum is slotted for $1/10^{\circ}$ and $1/20^{\circ}\text{C}$ marks. These slots allow light to actuate photoelectric cell pick-offs whose outputs operate the print coder, print amplifier and recorder at the moment of passing through a given temperature. As the linear interpolation progresses down the record temperature marks appear at the same depth as long as the temperature at the thermistor beads remains constant.

The measuring circuits cover a range from -20°C to 32°C and 1° isotherms can be plotted for this entire range. When gradients allow finer plotting, 0.1° and 0.05° isotherms can also be recorded. While the rate of scan can be varied, 12 seconds is the optimum setting for the overall cyclic process of taking temperature information from the nearly vertical column of water, the surface bead and the pressure sensor. At this setting the isotherms are contoured in 8 seconds, the remaining 4 seconds being used for plotting depth and surface.

Depth Sensing Element

The depth sensing element is a Bourdon tube driving a potentiometer. The DC output signal from this potentiometer is balanced against the DC feedback from the feedback potentiometer in the depth servo-mechanism. The balanced signal is then amplified by a conventional 400-cycle servo-amplifier.

The depth of the pressure transducer is recorded on the lower portion of the paper record which is interrupted every 6 minutes while the scale marks are printed. This interruption distinguishes the depth record from the temperature line. The vertical scale marks represent depth at 60-foot intervals from the surface and they are 6 minutes apart horizontally.

Fig. 7. Schematic diagram of profiler.

Fig. 8. Profile of temperature structure.

TYPICAL TEMPERATURE STRUCTURE PROFILE

An example of vertical temperature structure of sea water recorded with a thermistor chain off the coast of Mexico is shown in Fig. 8. Here

each printed line represents whole degree isotherms. The vertical scale represents depth and descends from the surface to 800 feet. The horizontal scale represents both time and distance; in this example either 24 miles or 4 hours. Normally this is taken as a distance plot.

The example indicates the nature of vertical oscillations in the thermal structure which are commonly called internal waves. It is apparent that the cycles in the vertical displacement of the isotherms contain a wide spectrum of wavelengths. The longer and higher waves are found where the vertical gradients are weaker, in this case near the surface and at the greater depths of 600 to 800 feet. In the main thermocline where the isotherms are more compact, around 200 to 300 feet, wavelengths of 0.2 to 0.5 mile are common but not uniform. The heights of the larger waves are about 20 feet in the thermocline, whereas at the other depths they may be several hundred feet.

Most of these small waves on different isotherms in the thermocline are in phase with each other; however, this is not necessarily true of the larger waves above and below the thermocline. In fact, around the 6 mile range the 14 degree and 18 degree isotherms are almost out of phase. Another feature is the temperature inversions that occur below the main thermocline in the 11 and 12 degree isotherms. This example clearly shows the nature of sea water temperature structure recordings that can be obtained with the thermistor chain system.

CONCLUSIONS

The USNEL towed sea temperature structure profiler is a satisfactory device for measuring and recording the thermal structure of the ocean. This profiler has been very successful in recording, for the first time, the details of the thermal structure of the Pacific Ocean and the nature of fronts and internal waves which cannot be obtained by any other means at the present time.

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AIRBORNE INSTRUMENT FOR PRECISION MEASUREMENT OF SEA SURFACE TEMPERATURE USING INFRARED RADIATION EMITTED BY THE SEA

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INTRODUCTION

The combination of a precision radiation collecting and detecting system with highly stable electronics has resulted in an infrared radio-meter capable of measuring absolutely the temperature of the sea surface to an accuracy of $\pm 0.2^{\circ}\text{C}$. The instrument uses an in-line black body reference radiation cavity temperature controlled to better than $\pm 0.05^{\circ}\text{C}$. Integral with the cavity are the detector, germanium optics and chopper system, comprising a highly stable optical unit independent of temperature. The electronics system is largely transistorized and uses precision components to provide the overall stability to maintain the 0.2°C performance.

Operation of the instrument has been reduced to the essential steps, requiring only selection of temperature range and selection of the mode of operation. No other operating adjustments are required. The output is a direct indication of sea surface temperature and it is presented in degrees Centigrade on a meter and on a strip chart recorder.

A second highly compact instrument, known as the infrared thermometer, of a less complex design has also been developed. It is capable of a measuring accuracy of 0.5 to 1.0°C . Its output is displayed directly in degrees C on a panel meter.

THEORY OF OPERATION

Radiation Characteristics of the Ocean Surface

Over different parts of the earth the temperature of the ocean surface ranges from a minimum of -2°C (271°K) to a maximum of $+35^{\circ}\text{C}$ (308°K). Only a thin layer of water is required to absorb infrared radiation completely. In the infrared region of from 4 to 12.5 microns the emissivity of the ocean surface is 0.98 for radiation normal to the surface. The reflection for normal radiation is 2% and increases to 4% for radiation incident at 60° from the normal.

The ocean surface has essentially the radiation characteristics of a black body at 300°K .

Such a surface emits maximum radiation at a wavelength of 9.6 microns. The radiation emitted for the extremes of ocean surface temperature are shown in Fig. 1 as radiation emission curves for black bodies at $+35^{\circ}\text{C}$ and -2°C . Examination of these curves shows that the major portions of both peaks are included in the region between 6 and 20 microns.

Atmospheric Attenuation

Since the instrument is to be used aboard aircraft it is important that atmospheric attenuation effects be considered. Fig. 1 also shows a curve of the spectral attenuation through $1,000$ feet of atmosphere in the 6 to 20 micron region. The curve shows that there is a good transmission window between 7.5 and 12.5 microns and that the infrared radiation outside of this window will be highly attenuated by the atmosphere. The effects of atmospheric attenuation, therefore, can be largely eliminated by use of a 7.5 to 12.5 micron band-pass optical filter. Approximately 29% of the radiation emitted by the surface of the ocean falls within this band-pass and would be available for detection.

In this application an optical filter consisting of arsenic trisulfide glass and a thin coated slab of indium antimonide was used. The transmission characteristic is shown in Fig. 2.

There is still some attenuation present within the pass band. It is possible to account for this effect and correct the temperature measurement by introducing a quantity known as "optical thickness" which is dependent on specific humidity, pressure and layer structure of the atmosphere.

Another approach to eliminating atmospheric effects is to use a narrower window, 9.2 to 10.9 microns. Fig. 1 shows the relatively complete transparency of the atmosphere in this region.

Fig. 1. Blackbody distribution (Planck Law) for -2°C and $+35^{\circ}\text{C}$ and atmospheric attenuation of 1,000 feet of air path at sea level.

Fig. 2. Filter percent transmission (upper trace shows 100% transmission).

Energy Considerations

The least amount of radiation available for detection is from the ocean at a water temperature of -2°C (271°K). It is further required to detect a 0.2°C change at this temperature. The change in radiation emission for a small change in temperature can be found from the differentiated form of Stefan-Boltzmann Law

$$\Delta W = 4\sigma\epsilon T^3 \Delta T. \quad (1)$$

Thus at $T = 271^{\circ}\text{K}$, $\Delta T = 0.2^{\circ}\text{C}$ or 0.2°K ,
 $\Delta W = 8.5 \times 10^{-5} \text{ w/cm}^2$ (total into a hemisphere).

Experience with detectors in previous applications indicates that it is quite practical to detect radiation differentials of this order. In fact, in the spectral region of interest (7.5 to 12.5 microns) a thermistor bolometer has been found to be quite capable of detecting considerably smaller radiation differentials than that calculated.

DESCRIPTION OF AIRBORNE RADIATION THERMOMETER

General

The airborne radiation thermometer equipment consists of 3 basic parts: a radiometer optical head, an electronic processing system and an indicating-recording system. The radiometer optical head collects radiation from the sea surface and generates an electrical signal proportional to the difference between this radiation and the radiation from a precisely controlled internal black body reference source. This signal is processed by the electronic circuits to produce a precise DC signal. This output is linearized and broken up into 4 overlapping temperature ranges, each spanning a 10°C interval with 1°C overlap. Finally the measured signal output is monitored on a panel meter while a continuously operating strip chart recorder simultaneously produces an accurate and permanent record of the sea surface temperature data.

As shown in Fig. 3 the airborne radiation thermometer is integrated into a single cabinet. Controls, panel meters and the recorder are arranged on the sloping control panel of the cabinet for maximum operating convenience. The radiation collecting and detecting unit is located at the base of the cabinet behind the forward-bottom access plate and faces out through an opening in the bottom of the cabinet. Its line of sight is directed vertically downward and a shutter mechanism in the base of the cabinet covers the entrance aperture when the radiometer is not in use.

Printed circuit and component boards, mounted primarily at the rear of the cabinet, contain the electronic circuitry. Access plates are provided and some panels are hinged so they

Fig. 3. Model 14-320 airborne radiation thermometer.

may be serviced on either side without removing them from the cabinet. When the unit is in operation these panels are secured into position by spring lock fasteners.

Special provisions have been made to keep a record of the selected temperature range while the instrument is in use and a marking system is incorporated into the recorder to mark the range setting of the instrument in code along the edge of the strip chart.

Radiometer Optical Head

A layout of the optical system is shown in Fig. 4. Radiation enters the system through a germanium doublet which focuses the energy onto a thermistor detector. The detector is mounted at the apex of a temperature controlled black body cavity operating at 50°C and assumes the temperature of the black body. A chopper blade and mask, each consisting of two opposed 90° sectors, are placed at the front end of the cavity. The chopper blade rotates, and as it rotates it either completely blocks the incoming radiation by closing the 90° sector openings in the mask or allows entering radiation to fall on the detector when the chopper blade sectors are aligned with the mask sectors. The inner surface of the chopper blade is gold plated and highly

Fig. 4. Optical system layout.

reflecting in the infrared. When the cavity is closed to incoming radiation the detector receives the cavity black body radiation as reflected by the gold plated surfaces. Thus, as the blade rotates, the detector alternately receives the target and the black body radiation.

The detector consists of a thermistor bridge network which produces an output signal proportional to the difference between the incoming radiation and reference black body radiation. The radiation is chopped at a rate producing a 20 cps signal which enters a high gain, highly stable hybrid preamplifier which amplifies the signal approximately 2,000 times.

A second chopper blade, external to the optical system, is driven by the chopper blade motor through a timing belt to provide a square wave signal in phase with the detector signal. The signal is generated as the second chopper blade interrupts a light beam directed on a phototransistor. The reference generator is called a "phototransistor reference pickup" (PRP). The PRP signal is used later on in the electronic circuits for synchronous rectification of the signal generated by the thermistor detector. An electronic temperature offsetting signal (E.T.O.) for zero suppression in range selection is also derived from the reference signal.

The black body reference cavity is of the conical type and its temperature is precisely controlled and monitored with thermistor beads embedded in the cavity and used as resistance

thermometers. The control circuit for the cavity is designed to maintain its temperature at 50°C to 0.02°C .

Considerable care has been taken with radiometer design to provide a thermally-stabilized optical structure. This has been accomplished by placing the detector and signal chopping elements within an enclosure consisting of the cavity and germanium lenses in a compact in-line thermal structure, thereby achieving, as far as possible, an isothermal entity. This is done to minimize the effects on the system of thermal variations due to changes in lens emission and chopper mask emission as well as changing lens transparency. Changes in detector responsivity also occur with varying detector temperature.

A point of particular interest is that in order to achieve the in-line structure the chopper blade drive shaft actually passes through the germanium lenses through an on-axis hole ground in each lens.

Electronic Processing System

Details of the electronic processing system are shown on the right hand half of Fig. 5. The output of the preamplifier is a 20 cps signal composed of the thermistor generated signal and an out-of-phase offsetting signal. This composite signal is fed to a synchronous rectifier where it is converted to a DC signal. Synchronous rectification, as used here, provides the equivalent of a very narrow band-pass circuit; hence, it affords a great reduction in noise signal while operating at low signal levels.

As mentioned earlier, the signal used for both offsetting and as a reference for the synchronous rectifier is obtained from a second chopper in the radiometer structure. Linearizing and range determination occur automatically during range selection by simultaneously switching in the proper amount of E.T.O. and appropriately changing the system gain. The resultant output signal is fed to the panel meter through a meter amplifier and to the strip chart recorder.

Since black body radiation normally varies as the fourth power of its temperature, linearizing is necessary if the total temperature range is to be presented on a linear scale. The linearizing, and range determination and selection, are accomplished in the following way. Referring to Fig. 6 the output of the synchronous rectifier is fed to an adjustable attenuator controlled by the range selector switch. A second deck on the range switch receives the E.T.O. signal and feeds a selected portion of it to the preamplifier. The E.T.O. signal reduces the output signal to zero at the beginning of each range (-2, +7, +16, +25) and each section of the gain attenuator reduces the slope of the output function from that of the fourth power curve to that of the linearized curve, providing a signal to the

Fig. 5. System block diagram.

Fig. 6. Linearizing and range changing block diagram.

recorder such that a 10°C change in sea surface temperature produces a full span deflection of the recorder.

As indicated in Fig. 5, the temperature controller precisely maintains the reference cavity at $50^{\circ}\text{C} \pm 0.02^{\circ}\text{C}$. The cavity temperature is sensed by a thermistor bead embedded in the cavity and used as one arm of a Wheatstone bridge. The error signal from the bridge controls a thyatron which proportions the current through the heating element of the cavity. A second thermistor bead, located within the cavity, is used to monitor the cavity temperature. Changes in resistance of this bead are monitored by the reference bridge circuit. The bridge output is displayed on the reference temperature

meter which is calibrated to read cavity temperature directly in degrees Centigrade.

Thermistor operation requires a DC bias which is developed by the electronic bias supply. It originates in a 5 Kcps transistorized oscillator. The output voltage is stepped up and then rectified to produce an output of ± 300 volts. The DC output voltage is additionally filtered and highly stabilized using RC networks and zener diodes.

The DC power required for operating the various circuits is obtained from a transistorized regulated power supply operating from the 117 volt 60 cps line. The supply also provides a highly regulated output at 26.5 volts.

In an effort to produce a precision instrument of high reliability, considerable attention has been given to design fundamentals. These include temperature stabilization of the detector, the cavity and optical elements, compensation of the preamplifier and detector at 20 cps to provide a nearly perfect flat response to eliminate the effects of chopper speed variation and reduction of the dynamic range over which circuits are required to operate to insure a high degree of linearity. In addition, extreme care has been taken in the choice of circuits, selection of components and method of fabrication to achieve a highly stable electronic system, e.g., large amounts of feedback are used in the preamplifier; silicon transistors are employed to avoid

temperature dependency; wire wound resistors are selected wherever dividers or calibration adjustments and networks are used; very highly regulated power supplies are employed using either closed loop regulation or precise zener diode regulation; highest quality components are utilized and all leads that might be a source of extraneous or varying pickup are shielded.

Presentation

Data output is provided in two forms. An approximate value of the sea surface temperature is indicated continuously on the sea surface temperature panel meter. Temperature precise to $\pm 0.2^{\circ}\text{C}$ is presented as an instantaneous indication in the form of a continuously printed recorder output on the strip chart.

Both the panel meter and strip chart recorder present the data in four 10°C ranges; -2°C to $+8^{\circ}\text{C}$, $+7^{\circ}\text{C}$ to $+17^{\circ}\text{C}$, $+16^{\circ}\text{C}$ to $+26^{\circ}\text{C}$ and $+25^{\circ}\text{C}$ to $+35^{\circ}\text{C}$. These ranges overlap one degree, with the upper end of each range overlapping the lower end of the next higher range.

Operating Characteristics

The following operating characteristics have been determined from laboratory tests. Calibration runs show an accuracy of absolute temperature measurement of better than $\pm 0.2^{\circ}\text{C}$. System electronic noise is equivalent to 0.05°C and it can be reduced further. Reference temperature (cavity) control drift is within $\pm 0.05^{\circ}\text{C}$.

INFRARED RADIATION THERMOMETER

The infrared radiation thermometer (IRT) was developed to provide a small, compact and portable radiometer where the size and precision performance requirements of the ART were not needed. Basically, the two instruments are identical in principles of operation.

The IRT differs from the ART in the following respects:

1. Smaller entrance aperture.
2. On-off cavity controller rather than proportional controller.
3. More rudimentary reference cavity structure.
4. AC signal panel readout instead of DC synchronous detection.
5. Calibrated to temperature range as desired.

These basic changes have resulted in a highly compact, simply operated unit having an accuracy of the order of 1°C and a sensitivity of 0.1 to 0.2°C .

A photograph of the IRT is shown in Fig. 7. As in the ART it consists of three units--radiometer, electronic unit and optionally supplied recorder. Operation consists of setting up the radiometer to view in the desired direction, turning on main power and reading panel meter (and/or recorder) after the reference cavity is up to operating temperature.

The IRT can be supplied with a filter similar to the ART (to pass only energy in the 8-13 region). The unit shown in Fig. 7 was calibrated on a black body and adjusted for a full scale panel meter readout of 15°F to 100°F .

FIELD TEST OF AIRBORNE RADIATION THERMOMETER

Field tests have been carried out by the Navy Oceanographic Office for which the instrument was developed. Test data have been obtained from 3 types of platforms under the conditions described below.

Static Tower Tests

In June 1962 the ART was mounted on ARGUS ISLAND, an oceanographic tower in 194 feet of water 22 miles southwest of Bermuda. The tower platform was easily adapted for mounting the ART. The instrument had an unobstructed view of the sea surface from a height of 65 feet and was operated continuously during daylight hours. Bucket temperatures were taken periodically. Comparison of ART temperatures and bucket temperatures are shown in Figs. 8 and 9. The trend of the curves shows a greater change in ART temperatures than in bucket temperatures with the maximum change occurring at 1400 hours. On 26 and 27 June skies were 0.8 obscured by clouds and air temperature reached a maximum value at about 1300 hours. The ART appears to be recording the temperature of the surface of the water accurately. This has been shown in the laboratory; however, methods remain to be devised for relating these values to water temperatures at depths of 5 to 10 feet. Future tests are being planned to repeat the ARGUS ISLAND tests on a more comprehensive scale. The ART measurement will be related to humidity, air temperature, wave height and albedo. A thermistor chain will make continuous recordings of water temperature at various levels in the upper foot of water.

Helicopter Flight Tests

Prior to acceptance of the prototype ART several flight tests of the instrument were made over Chesapeake Bay on 23 and 24 June 1960. The ART was mounted in a HUP-2 helicopter. A series of passes were made across the track of a small boat which towed a thermistor probe clear of the boat's wake. These instruments were calibrated under identical conditions; equal accuracies were indicated.

Fig. 7. Model 14-312 infrared thermometer.

Fig. 8. ART sea surface temperature comparison tests at ARGUS ISLAND, 26 June 1962.

Fig. 9. ART sea surface temperature comparison tests at ARGUS ISLAND, 27 June 1962.

Data from the 23 June test are shown in Figs. 10 and 11. Temperatures were recorded by both the ship and the aircraft. Sharp spikes appeared in the ART trace each time the helicopter crossed the ship's wake. Although the temperatures generally agree, an exact comparison is difficult because of the variability in surface thermal conditions shown by the traces. Meteorological conditions offer a possible explanation for the surface conditions; surface winds were light and variable and skies were clear.

On the second day, light winds were present at the surface, the water appeared to be more thoroughly mixed and the thermistor trace was steady. ART temperatures were lower than thermistor temperatures (Fig. 11). Analysis of the data shows a probable ART deviation of $\pm 0.31^{\circ}\text{C}$ from the reference sea surface temperature.

WV-2 Flights

The ART was shock mounted in the baggage compartment of a WV-2 aircraft. It views the water surface through an opening in the fuselage bottom. The aircraft is normally pressurized to allow air to exhaust around the sensing unit. This was found necessary to prevent instrument noise resulting from excessive turbulence around the lens. The recorder is separated from the console and mounted at one of the radiomen's stations. Continuous temperature records are manually noted at one minute intervals. During normal operations the aircraft was flown at an altitude of 1,500 feet at 190 knots. All flights to date have been conducted during daylight hours; however, night flights are being scheduled. Flight tracks do not usually exceed 1,400 miles; average flight duration is usually 6 to 8 hours.

Aircraft surveillance with the ART provides a quick method of obtaining sea surface temperatures over large areas. Accumulated data aid in the construction of sea surface temperature

charts. A sample of surface isotherms for 2 October 1962 is shown in Fig. 12. The data were collected off the North Carolina coast in connection with sea surface temperature studies in the Gulf Stream. During the flights skies were clear, the sea was calm and the air temperature was 23°C (73°F).

A series of flights was completed between 15 and 25 July 1962 over a triangular track centered at 39°N 70°W . The exercise was designed to determine time-space variability or persistence of sea surface temperature patterns. The aircraft was flown at an altitude of 1,500 feet at 190 knots. The range of the observed temperatures was 18° to 27°C . Temperatures compared over 2, 48 and 72-hour periods are shown in Figs. 13, 14 and 15 respectively.

CONCLUSIONS

The ART is becoming a valuable means of obtaining sea surface temperatures. Aircraft surveillance with the ART makes possible the collection of large quantities of data in relatively short periods over broad areas. When first put into operation, the instrument was subject to frequent failure of electronic components; however, this problem has been resolved and the instrument now has good operational reliability.

Instrument accuracy of 0.2°C has been shown in the laboratory. The ability of the instrument to detect horizontal temperature gradients at the surface has been of particular value. In field use the ART has not produced results comparable to those obtained in the laboratory. On several occasions ART temperatures have concurred with immersion temperatures; on other occasions significant differences have occurred. At present, these differences remain unexplained. Future temperature measurements with the ART are expected to increase in accuracy and become a valuable source of information.

23 JUNE 1960

WATER IMMERSSED THERMISTOR (YP BOAT)

23 JUNE 1960

AIRBORNE RADIATION THERMOMETER (AIRCRAFT)

Fig. 10. ART helicopter flight test data (normal sea), 23 June 1960.

24 JUNE 1960

WATER IMMERSSED THERMISTOR (YP BOAT)

24 JUNE 1960

AIRBORNE RADIATION THERMOMETER (AIRCRAFT)

Fig. 11. ART helicopter flight test data (mixed sea), 24 June 1960.

Fig. 12. Sea surface temperature pattern derived from ART flight test, 2 October 1962.

Fig. 13. Comparison of 2-hour temperature changes, 20 July 1962.

Fig. 14. Comparison of 48-hour temperature changes, 20-22 July 1962.

Fig. 15. Comparison of 72-hour temperature changes, 20-23 July 1962.

SESSION III

SYSTEMS

Chairman: W. F. BRISCH
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CABLE ASSEMBLY WITH INTEGRAL HYDROPHONES AND INSTRUMENTATION

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INTRODUCTION

The cable assembly described in this paper was developed as a result of the need for a long multi-element vertical acoustic array that could be raised and lowered in and out of deep water rapidly by remote control without human supervision. The location of the equipment limited the space available and required that a minimum of space and weight be added, that storage be automatic and that the entire array length change direction at least 90° . It was also important that the attitude and shape of the array be known at all times.

Many sophisticated storage and handling arrangements were examined including methods for Flemishing, spinning reel type storage, linear cable hauler, capstans, etc. All methods had serious faults for this application--too large, too expensive, too complex, too slow, etc. A simple arrangement with a large power driven storage drum and an overboarding sheave to accomplish the change of direction, appeared to be desirable if an array could be designed that could be stored under tension on the drum and flexed sufficiently to pass over a reasonable size sheave. A requirement that operation be remotely controlled eliminated the possibility of storing array sections in short lengths and assembling them as they passed over the side even if a system could be developed that permitted the rapid assembly necessary to meet the raising and lowering speeds specified.

DESIGN CRITERIA

The final approach decided upon required the development of an array in which the hydrophone elements, preamplifiers if required and attitude sensing elements although larger than the cable in diameter, became an integral part of the cable, without restricting the flexibility required for changing direction and storage on a drum. This approach itself immediately initiated many problem areas. The strain member and electrical conductors of the cable would have to be concentric with the instrument packages. The packages themselves must maintain as small a diameter and length as possible. An array of this length would be difficult to manufacture in one continuous operation. The break-out of individual leads to each array element

must not weaken or disturb the continuity of the strain member but the leads themselves must sustain frequent flexings without failure. Cable diameter, even with 96 leads, must be kept to a minimum but the strain member must provide a satisfactory safety factor for reliability.

The above problems required various solutions. To maintain the cable leads and armour concentric with the instrument packages, all units were designed with a hole around their center axis through which the cable could pass. A cylinder with a hole through its center does not present the most desirable volume in which to package a hydrophone, preamplifier, tilt sensor or magnetic bearing detector. The necessary components were fitted into packages with an external diameter of 2.5 inches and a maximum length of 3.5 inches with a hole 0.8 inch in diameter for the cable. An array of this type necessitated a hydrophone with a high degree of insensitivity to acceleration effects and the ability to operate at high pressures in addition to the necessary acoustic sensitivity and impedance.

A stabilized transistorized preamplifier with 40 db gain was fitted into the desired package configuration. Linear accelerometers, used in pairs to measure cable deviation from the vertical, were available that would fit the package configuration. Magnetometer probes measuring field strength by the even harmonic method were found small enough to be packaged as an integral part of the cable.

A system was conceived by which the array could be manufactured in short sections although the final assembly would have the appearance of one integral section. Although construction of the array was facilitated in many respects by assembling the entire length from short sections, the multitude of connections necessary to provide continuity of the leads from section to section presented a problem. A quick disconnect type connector was considered but none was available with the necessary small size, sufficient electrical connections and suitable strain member connection. The lack of a quick disconnect connector plus the other considerations resulted in the method described here.

Fig. 1. Terminal assembly.

Fig. 2. Cone and collar on cable.

THE CABLE SYSTEM

The cable to be used contained 48 twisted pairs in 7 bundles enclosed in a watertight jacket of neoprene. The conductors are solid copper to reduce cable diameter and facilitate design of an anti-hosing cable. The armor braid of flat stainless steel ribbons woven external to the neoprene jacket provided optimum flexibility with a minimum of added diameter and weight.

Flat stainless steel ribbons readily adapt themselves to a terminating scheme which produces reliable strain member connection easily and

quickly. Each terminal assembly consists of a cone and collar held together by three bolts (Fig. 1). The collar is slipped over the armour braid to the position the assembly is to occupy on the cable. The cone is slipped over the neoprene jacket with the partially unbraided armour ribbons ascending the cone. Each ribbon is inserted through the proper hole in the base of the cone as the cone is pushed toward the collar, clamping the armour between the two identically inclined surfaces (Fig. 2). The three bolts are tightened sufficiently to lightly clamp the ribbons in place. A slight pressure is applied to each ribbon by pulling easily where it exits from the back of the cone. After each ribbon has been positioned, the three self-locking bolts are torqued to 30 foot points to firmly entrap the armour in the terminal assembly. Numerous tests of this assembly on a tension testing machine produced breaking strengths equal to that of the uninterrupted cable.

Two terminal assemblies after being clamped to sections of cable, are joined by three stainless steel rope assemblies so that a flexible connection exists between the strain members of two cable sub-assembly sections.

The separation of 4 inches between the two terminal assemblies provides space for the electrical connections which present another problem. To keep the array diameter at a minimum and still connect the multitude of leads, each individual connection must occupy little more space than that required for a single lead. Connector

Fig. 3. Assembled instrument section before potting.

inserts, crimp type pins and other methods of joining two leads were investigated and rejected for various reasons of size, reliability or complexity. After many tests, it was decided that the connections would be made by soldering two leads together side by side without twisting and covering the joint with heat shrinkable plastic tubing. The tubing, in addition to adding mechanical strength, provided a watertight bond with the insulation of the cable leads. Numerous tensile tests proved that the above method resulted in a junction stronger than the copper lead itself.

During array manufacture the terminal assemblies of two adjacent array sections are mounted about 4 inches apart. All the necessary electrical connections are made, tubing shrunk on and then three wire rope assemblies are installed joining the two sections mechanically (Fig. 3). Each end of the rope assembly is terminated in a threaded steel fitting swaged to the wire. Self-locking nuts hold the assemblies in position after they are inserted through holes in the terminal assemblies. The volume between the terminal assemblies and around the cable leads and wire rope is filled with polyurethane which bonds to the neoprene jacket on the cable providing a watertight joint that will stand the pressures expected for this application.

SYSTEM TEST AND OPERATION

A serious problem was discovered, however, when the array junction was cycled repeatedly under simulated load conditions over a large diameter sheave. The individual leads in the cable did not stretch as a unit with the outer armour and watertight jacket. During repeated flexing under tension, the leads appeared to walk up the cable and eventually the leads that walked the fastest failed in tension. This type of failure did not show up during straight tension test. Repeated flexing under simulated load conditions was necessary to allow the cable parts to work sufficiently until differences in length of the various cable parts caused a break in a lead.

A number of different cable designs were manufactured and tested with varying success. Part of the slippage problem was traced to the insulation on each lead. Because so many leads had to be soldered in such a small volume Teflon insulation was originally used. Teflon, however, is very slippery and cannot be bonded easily, so it was replaced by polyethylene. Test evidence also indicated that the relationships of the lays of each twisted pair and the cabling lay of each bundle contributed to the amount the leads appeared to walk in the cable. No cable tested eliminated the problem but the effect was minimized by proper design of cable insulation, direction and amount of lay and jacketing thickness and hardness.

To provide protection against lead failure due to non-uniform cable stretch, a service loop was included at each electrical connection. The loop provides approximately 2 inches of slack to allow for non-uniform cable and lead stretch. To prevent the encapsulating compound from filling the interstices of the connector and capturing the leads thus negating the action of the service loop, the connector area before encapsulation is wrapped with tape. The polyurethane moulds around the wrapped area leaving a small void internally in which the lead joints may slide freely past one another as the elements in the cable are worked over the sheave.

As pressure increases on the cable in deep water, the connector area is compressed and the internal void volume is decreased tending to freeze the leads in place. This is not serious because slippage occurs primarily during the time the cable curves around the sheave when pressures are negligible.

It is necessary to bring leads out of the cable at every location of a hydrophone or instrument package. To eliminate breakouts through the cable armour all elements are located next to a terminal assembly and the required leads are broken out at the electrical joint section between the terminal assemblies. When the electrical connections are being made between two array sections the cable leads associated with the hydrophone located adjacent to the terminal assembly are selected and brought to the surface of the

Fig. 4. Instrument section after potting.

Fig. 5. Instrument section bent around 44-inch diameter.

group of connections being made. To each cable lead to be used at this point a special single conductor wire about 8 inches long is soldered and the joint covered with shrinkable tubing. This special wire is non-hosing and is insulated with material compatible with polyurethane. The diameter is sufficient to allow passage through a hole in the cone and collar to the area immediately adjacent to the terminal assembly where the preamplifier and hydrophone packages have already been positioned on the cable. This lead and a lead from the preamplifier package are soldered together. Two such leads are required for each preamplifier. Two leads from the opposite end of the preamplifier are soldered to two shielded leads from one end of the hydrophone. A service loop to provide stretch length during flexing is provided by rotating each lead 180° around the center cable. The volume between each component is filled with polyurethane. This encapsulation positions the units on the cable, provides a watertight seal and mechanical protection for the necessary connections and provides a flexible cushion between the units to prevent interference during the flexing that occurs as the assembly passes over a sheave or is wound around a storage drum. To facilitate the passage of the assembly over curved surfaces, a tapered section is moulded at each end of the package (Fig. 4).

Polyurethane was used for all moulding applications. Of the large number of materials tested it possessed, in addition to the desired physical and electrical properties, the greatest ability to bond to metal, rubber, fiberglass and PVC. It is easy to handle, particularly if the material is used in the frozen cartridge form, moulds can be simply made and low temperature or room temperature cures are reliable and easy to make. Tests on the instrument bundle over a sheave under load simulating the worst actual operating conditions have shown that these compounds have very good abrasion resistance in addition to their flexibility.

To provide array position information, tilt indicators and magnetometer probes were included in the array assembly. As many as five leads were required for these instruments so that as many as five holes were needed through the cone and collar. Assembly procedures, however, were similar to that used for the hydrophones and preamplifiers.

Instrument assemblies manufactured according to the above procedures have been tested under tensions of 1,200 pounds while flexing over a sheave 44 inches in diameter (Fig. 5). Minimum time to failure has been about 200 cycles with some sections surviving over 500 cycles before lead failure.

ACKNOWLEDGMENTS

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COMPUTERS AND TRANSDUCERS

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INTRODUCTION

In this paper, the term "transducer" is used in its broadest sense as the whole link between the natural phenomenon and digital results presented in interpretable form. It will be shown that this use is justified by the unique role the computer can perform in a particular data-acquisition cycle. In this case, that which is "plugged into" the environment is the Richardson current meter and that which is "plugged into" the computer is the film record from this current meter. The computer which provides the processed data is the PDP-1 (Programmed Data Processor-1), a single address, single instruction stored program machine built by Digital Equipment Corporation.

THE TRANSDUCER

The current meter (Fig. 1) uses fiber optic digital 16 mm film recording of 7-level encoding disc sensing of both vane and compass positions and a 1:1 and 10:1 light chopper sensing the Savonius rotor revolutions.¹ The resulting digital format is illustrated in Fig. 2 where a section of an original test film strip is reproduced along with high-contrast negative and high-contrast positive prints. Test films are made by operating the instrument on a revolving platform. A fan drives the rotor in air. Note that there is a continuous or reference channel in addition to the 16 data channels and, not shown, a read pulse channel for interval recording. A variety of films were tested, including sound recording stock, to determine the most satisfactory for reading. The high-contrast positive print proved best.

Prints of 3 sections of an actual record are shown in Fig. 3. The bit packing density is extremely conservative across the film and could easily be doubled without changing the optical fiber or film image size. Along the film there can be resolved approximately 200 bits per inch. Thus, there are 200 sets of three 1% numbers per inch or some 3,600 bits. When recording continuously, the 100 feet of film in the instrument

Fig. 1. Richardson current meter: left-complete unit, center-internal mechanism, right-pressure case and vane cage.

Superior numbers refer to similarly numbered references at the end of this paper.

Fig. 2. Test film and prints: top-original negative, center-high-contrast negative print, bottom-high-contrast positive print.

lasts slightly more than 7 days. When recording intermittently, approximately 10,000 1/8-inch blocks of data may be recorded.

THE COMPUTER

The staggering task of manual reading is obvious. For example, using a large-screen 16 mm film viewer with motor-driven advance and a prepared grid, it took one person more than one day to read 42 hours of recording sampling at hourly intervals. The approach taken to mechanize reading of the tape involved adaptation of the PDP-1 computer. One of the main reasons for the selection was that the computer is equipped with an X-Y CRT point plotter feature for both read-in and read-out. A specially designed computer-controlled reader has been attached that contains a film advance mechanism and a photomultiplier. Initially the photomultiplier sensed the absolute image density as seen through the film. A later and superior version compared the image density with the background on a differential basis, thereby enhancing the sensitivity and overall stability of the system.

A test computer printout is shown in Fig. 4. The computer was programmed to type out ones and

zeroes for validation by comparison with visual reading. Agreement was found, as it was also between repeat readings of the same film, and corresponding scans of the same block of data read both 16 and 128 scans per block. Fig. 5 shows the present printout. The binary numbers are converted to degrees, the compass and vane directions combined and corrected for the magnetic variation (in this case $15^{\circ}W$) to give the true current direction, the rotor revolutions converted to current speed in mm/sec and the day, hour and minute of the recording computed. The reading rate, while not yet fully optimized, is approximately 10 blocks of data per second, each block spanning 2.5 minutes. This provides read-in of 42 hours of data in approximately 1 1/2 minutes when the original recording was made at one sample per minute. Of course, there are other steps such as setup and splicing on an instruction leader. Also, the time quoted is for transferring the raw data to magnetic tape in the standard IBM low-density format. One roll of magnetic tape will hold about 90 current meter records.

Among the obvious advantages of so closely integrating the transducer and computer is the capability of performing in the computer many of the operations normally done by the transducer.

Fig. 3. Film record from G-185: two sections near current minimum and one section near current maximum.

$R \times 10 \rightarrow$ Vane Compass Continuous Reference
 0111101001010011
 1111101011010011
 1111101011010011
 1111101111110111
 0111101010110011
 0111111111010011
 0111101111110011
 0111111111010011
 0111111011000011
 0111111111000011
 0111001111000011
 0111101011000011
 0111111111010011
 0111101011000011
 0111101001000011
 0111100011000011

Fig. 4. Photo of test printout from computer-reader.

	50006	70070	61	50006	40076	67
d	0	t 1509	r10	274	r1 10000	
	60354	70079	58	60357	70079	61
d	0	t 1511	r10	246	r1 10000	
	60354	70079	58	40346	70082	53
d	0	t 1514	r10	189	r1 10000	
	70349	70079	53	40343	70079	47
d	0	t 1516	r10	200	r1 10000	
	70340	70115	80	40343	70115	83
d	0	t 1519	r10	147	r1 10000	
	60332	70101	58	70340	70122	77
d	0	t 1521	r10	153	r1 20000	
	70337	70115	7	70329	70124	78
d	0	t 1524	r10	122	r- 19	

Fig. 5. Photo of present printout from computer-reader.

Not only can the computer be programmed to read the film and type out results but it also can be programmed to analyze the original data including normalization, linearization and individual instrument calibration correction. This greatly enhances an effort to allow simplicity (and thereby reliability) of systems placed in the ocean. The result of this principle is that the computer becomes truly a functionary part of the transducer. In the analysis of the current meter film, the computer memory can store the characteristics of every instrument and the calibration curves of the Savonius rotor. In addition, because the CRT is under computer control, the computer can present the raw data and the computed results in graph form for immediate visual presentation.

APPLICATIONS OF COMPUTER CAPABILITY

Additional judgment making capabilities are built into the computer program to prevent grinding out meaningless data. For example, if there is a break in the reference channel, or too many channels, these facts are typed out. These algorithms or rules for rejecting or accepting results can be elaborated manifold to include, for example, that a direction of 121° is 7 ones and its absence in some pattern signifies unresolved bits. The question of unresolved bits and the measure of confidence one can assign to any given reading has already been approached in a simple and direct way with the computer. This is done by printing out the level of the least significant digit which was a zero in the 7-level binary vane or compass reading. The fifth place numbers in Fig. 5 preceding the 3 place compass and vane readings are these values. A zero occurs only when all bits are resolved. Thus, a 7 indicates the highest level (3^0) of confidence in the value. Obviously, any other digit down to 1 could be equally precise since all channels can legitimately be on, so this is only a qualitative indication.

The fact that up to 600 scans per inch of film may be made leads to an evaluation of the recording idiosyncracies and thence to improved reading judgment capability. These results are also fed back to evaluate the performance of the current meters themselves. In fact, a program has been written to test and calibrate every instrument using a short length of test film such as shown in Fig. 2. This program gives the percent each channel is on (theoretically 50%), the amount of noise on the film (i.e., images that are not intentionally recorded data), the density or width of each channel, the mean position of each channel, the maximum drift of each channel, channel width variations if they occur and the variance of the reference channel along the film.

Via the CRT plotter, a variety of data presentations can be made automatically by the computer. Some of these have been programmed including trajectory summations, compass rose

current diagrams and a chart of the ocean area under investigation with superimposed animated current vectors. The last presentation may even be done isometrically to give a 3 dimensional view. Standard plots such as power spectra are easily handled.

A PERFORMANCE ANALYSIS OF THE CURRENT METER

Some of these data presentations can be used for an analysis of the instrument performance itself as well as for a study of the ocean. An example is a histogram presentation of the current meter compass and vane indications which was used to evaluate several mooring and instrumentation methods tested during an experiment in Vineyard Sound off Woods Hole, Massachusetts. Five current meters were moored in an area of nearly uniform 65-foot depth where a fairly strong tidal current running parallel to the shoreline reversed approximately every 6 hours. The arrangements were as follows: (1) a standard mooring using an 800 pound cast iron block anchor connected with polypropylene line to a current meter (serial no. G-185) and a subsurface inflated polyvinylchloride float; all parts shown in Fig. 6, (2) a rigid mooring (Fig. 7) consisting of a 20-foot length of iron pipe with an 800 pound anchor block on an iron plate with 4 pipe legs on the bottom to the top of which was bolted a current meter (serial no. 302), (3) a current meter (serial no. G-190) with a fiberglass fin attached (Fig. 8) moored in an otherwise standard fashion, (4) a current meter (serial no. G-181) with grease packed ball-bearing swivels above and below it on an otherwise standard mooring and (5) a current meter (serial no. 299) with the recording film advance 10 times that of (1).

Histograms of the currents for meters G-185 and G-190 are shown in Figs. 9 and 10 respectively. Current direction is represented along the abscissa in 128 increments from 000° to 357° and the number of times each direction reading occurred is represented along the

Fig. 6. Mooring gear for current meter mooring comparison experiment.

Fig. 7. Rigid mount for current meter mooring comparison experiment.

Fig. 8. Current meter with fiberglass fin used in mooring comparison experiment.

Fig. 9. Current meter G-181 current histogram.

ordinate. Of particular importance is the significant difference between the peaks for meter G-185 (the standard mount) and G-190 (meter housing with fin). The smooth well distributed current peaks (Fig. 10) of the latter were found to correspond exactly to the coastline directions and presumed actual flow orientations. Analysis of the records has not been completed; however, it is already obvious that stabilizing fins improve the quality of the data and should be used.

CONCLUSIONS

The special case of the Richardson current meter coupled with an automatic data reading-computer system illustrates the many advantages that can be derived from a close alliance between instrument design and data system utilization. The feasibility of this complete system has been demonstrated and a wide range of analytical techniques can be implemented through use of computer capabilities.

Considerable effort is being devoted to exploitation of the expanding possibilities of this special combination of a transducer and a computer in the marine sciences. Its use is not limited to the Richardson current meter but also may be extended to wind, wave and temperature instruments that employ the same simple reliable film recording format.

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We wish to acknowledge not only the assistance of our colleagues at Geodyne and Information International, without whom this work would have been impossible, but also those at the Woods Hole

Fig. 10. Current meter G-190 current histogram.

Oceanographic Institution who joined us in the Vineyard Sound experiment. Special thanks is due W. S. Richardson whose advice, encouragement and criticism were invaluable.

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UNTENDED DIGITAL DATA ACQUISITION SYSTEM PHILOSOPHY

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INTRODUCTION

Data gathering in the ocean as well as in the air-land interfaces of the ocean has been approached in many different ways in the past several years. The prime method in the past has been to take the scientist to the scene of his problem via surface vessels and collect data in this manner. It is certain that this philosophy will never be replaced but the advent of new tools based on later developments are slowly coming to the aid of the thinly spread scientist. It is therefore a natural development for the oceanographic community to think in terms of untended data gathering systems placed in the areas of interest for the particular problem concerned. There is the very important economic factor concerning the logistics support that has to be given to the scientist while in the field. Another factor of concern is the speed with which present day oceanography would like to move ahead in methods of data collection and presentation. These general problems primarily seem to be responsible for the present tendency of the field to turn toward systems approaches to the collection of oceanographic data.

The system approach to be outlined here is merely the collection of several different talents and techniques to perform the aims of satisfying what we might consider as the latest methods of data collection. Marine Advisers, Inc. in association with Ocean Research Equipment, Inc. has designed the system for unattended operation for periods up to 4 months with a capacity of recording up to 1/3 of a million complete data samples from a variety of individual sensors.

GENERAL FEATURES OF THE SYSTEM

The underwater system is diagrammatically shown in Fig. 1. This is a 2-buoy taut-wire mooring system designed for relatively shallow work. Below the surface buoy with its included meteorological sensors is a slack painter down to the subsurface buoy. This subsurface buoy with included data logging system is moored between 30 and 60 feet from the surface. Below the subsurface buoy is the sensor chain down to the anchor assembly.

The entire data logging system and power supply are located in the subsurface buoy as

previously mentioned. The mooring lines and electrical cables are one and the same in that the strain members are located within the electrical cable from the slack painter down to the last sensor. On the first mooring attempt the system was placed in 150 feet of water with the subsurface buoy 30 feet below the surface.

Each underwater sensor unit in this diagram consists of a Savonius rotor current meter, a direction vane (referenced to a magnetic compass in each sensor) and a temperature probe. Each sensor is hard wire connected to the data gathering package on the subsurface buoy. In the present system there is an anemometer and a wind direction sensor on the surface buoy (Fig. 2) and these are also referenced to a magnetic compass. The buoys are foam filled fiberglass with an outer Gel-coat and a polyvinyl-chloride (surface unit) or aluminum (subsurface unit) central tube. Internally, the surface buoy contains only the batteries and flashing unit for the navigation lights. This buoy also serves as a junction box for the meteorological sensor wires going down to the subsurface package as well as a series of 12 data lines coming to the surface buoy from the subsurface buoy. With this arrangement a small readout box can be plugged into the surface buoy from a small boat to read the data at the same time and with the same precision as it is being fed to the magnetic tape recording unit in the subsurface buoy.

Three such underwater sensor units were used for the first series of tests. The system as it is presently designed has the capability of at least 10 such sensors in the chain. There is a length of polypropylene line between the last sensor and the anchor with a release mechanism below the last sensor. The release mechanism is a clock operated electrical firing squib that will release the anchor on a short stay of line and allow the buoy system to come to the surface. In the present system the subsurface buoy has approximately 500 pounds of positive buoyancy and the anchor weighs about 1,800 pounds.

The most difficult problem encountered in this mooring system is the slack painter. Fig. 1 shows the configuration selected after the surface buoy line parted after being subjected to a state 2 sea for approximately 2 hours. It is necessary to have an electrical swivel at the top of the subsurface buoy and a small submerged buoy

Fig. 1. Diagrammatic illustration of complete untended buoy system.

Fig. 2. Surface buoy in place during first field trials.

is located midway along the slack cable to prevent the bite in this line from dipping below the subsurface buoy. Also incorporated across this bite of line is a section of bungee shock cord to act as a shock mitigator on the mooring line. The surface buoy has approximately 2,500 pounds of buoyancy. An inverted cone was chosen because of its non-capsizable properties. The shape of the subsurface and surface buoys is the same simply because the surface buoy mold was inexpensively usable.

DATA ACQUISITION SYSTEM

The data system (Fig. 3) is designed to accommodate oceanographic sensors whose outputs are a variable resistance, voltage, current frequency or serial pulse train. The analog input signal is converted into digital form by logic processes in the buoy data system (Fig. 4) and then converted into 12 bit binary form and stored on magnetic tape. The magnetic tape recorder is a special type employing a static digital recording technique. The master sequence clock for the buoy system is developed from a transistorized Brailsford DC motor with a cam that drives a micro-switch to start the data cycle. There are 2 modes of operation; 2 minutes and 20 minutes. The DC motor is driven from a 120 cps standard frequency source that has been developed by Marine Advisers. It consists of a 120 Kcps crystal and several tunnel diode divider stages. The 120 cps frequency standard that draws 3 milliwatts of power and the Brailsford motor that draws approximately 300 milliwatts are the only components in the system that have a 100% duty cycle. All other parts are sequence operated as far as power is concerned.

Fig. 3. Data logging package from central tube of subsurface buoy.

SENSOR MEASUREMENTS

The digital clock in the system uses a 100 Kcps crystal and has an operation cycle of 2.63 seconds. Consider a Savonius rotor speed pulse input to the system of Fig. 2. When the stepping switch is in the proper position (determined by the digital clock) the sensor output will pass into a wave shaping circuit where the shape of the wave form is altered so that it will operate the digital logic. From there, the signal proceeds into an interval detector that produces a square wave out of the time interval occurring between switch pulses. This square wave is mixed with a standard frequency of 3,125 cps. The frequency burst from the interval detector passes through other portions of the stepping switch in the sequence of events and through the proper gating circuits before it is impressed upon the count accumulator from which

is formed the 12 bit binary. At the proper time the information is transferred from the count accumulator to the tape heads. The 12 bit lines are fed into each individual head through gates and determine the presence or absence of a signal on a particular head.

The tape is not moving when current passes through the tape heads. After the information is transferred a step function is sent to the stepping motor of the tape drive and the tape moves about 0.036 inch to be ready for the next data cycle. During the cycling time a pulse is sent back to the interval detector and the count accumulator for complete reset prior to the next sample sequence.

The method of measuring resistance differs slightly. A vane for measuring water current direction moves a microtorque resistance element which is referenced to a magnetic compass device. The resistance is proportional to the clockwise rotation angle between magnetic north and the vane direction. This input is put into an analog-to-frequency converter which is located in the buoy system. From here, the signal passes through portions of the stepping switch and through the proper gates and logic and is impressed on the count accumulator. The reset and stepping functions of the tape motor take place in the same manner as discussed above.

The stepping switch turns the system off on its last position and waits for the master timer to again activate the circuit. Twenty-five input channels are sampled in each data cycle but these are not all sensor channels as there is a 3-point calibration function for the direction measuring devices and a 5-point calibration function for the temperature devices. This internal calibration is to determine the stability of the data logging system over a long period of time when voltage variations are liable to affect the accuracy of the data.

The tape recorder of this system performs digital recording in a static or stationary mode, i.e., the tape is motionless when the heads are magnetized. There are several precautions that have to be taken in this type of recording to insure reliable noise-free data. All of these seem to have been overcome and the system produces extremely clean signals that are not difficult to program into computer format. Thus, a full data tape is acquired in the field system with decimal information that is calibrated and in readily interpretable engineering units.

DATA TRANSCRIPTION

A duplicate tape is made from the original that effectively increases the spacing between frames by a factor of 3. A scanning process is used during constant speed playback from which a punched paper tape is eventually produced. The punched tape is fed to the 1604 computer with calibrations in IBM format that produces a calibrated decimal output in the proper format.

SESSION IV

WAVE MEASUREMENT

Chairman: F. E. SNODGRASS
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A RESISTANCE WIRE WATER LEVEL MEASUREMENT SYSTEM

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INTRODUCTION

Resistance wire elements have long been used for measurement of water level variations. Because both amplitude and time response are normally degraded by biological growth most resistance wire transducers have been used in the laboratory. The transducers that have been used in oceanography have consisted of small diameter single wire elements, either enclosed in a protective slotted tube¹ or suspended tautly between two supports without protection.² The former configuration suffers loss of response and precision due to interference of the tube and the latter is susceptible to being broken by drifting objects or foulants. These elements have the additional disadvantage of a low full scale resistance range, thus making it difficult to achieve high sensitivity with relatively simple low power circuitry.

The measurement system described in this paper was designed to avoid or reduce the major disadvantages mentioned above. The initial set of requirements for this system was imposed by a particular application; namely, suspension on the exposed side of piers and offshore platforms. For this purpose a staff was needed that was light enough for easy installation and not too delicate to withstand normal rough treatment in the natural environment. Staff lengths up to 40 feet were required with a measurement precision of 0.2% of full scale or better over the frequency range of natural water motions from short chop (about 1 cps) to tides (about 1 cycle per day). It was further considered necessary that the system consume a minimum of power and be insensitive to wide fluctuations of line voltage and frequency. Transducer output was required to be high level at 0 to 5 volts DC full scale and directly proportional to water elevation.

SPECIFICATIONS REQUIREMENTS

The first consideration of specifications was the range of wave and tide heights that the instrument should accommodate. Maximum wave

height seems to be of the order of 100 feet in the open sea. In areas of minimum tide range and exposure as little as 4 feet can suffice for total staff length. To encompass multiple purpose use within this range an incremental length of 5 feet was selected for total lengths up to 100 feet. The greatest demand seems to be for a 40-foot staff. For the purpose of this paper, the 40-foot unit is applied to specifications of range and precision.

A second parameter is overall accuracy required. For purposes of adequately measuring short chop superimposed on low seiche or swell, resolutions of a fraction of an inch are necessary. This means the instrument system must have an overall precision of at least $\pm 0.2\%$ of full scale, including both the staff and electronics errors, if staffs ranging up to 40 feet are to be used.

A third parameter of importance is response. Since both tides and waves are to be measured, the instrument must respond accurately to long and short periods, ranging in the extremes from months to a fraction of a second. A nominal high frequency cutoff has been selected at 5 cps.

The fourth major design parameter is output signal characteristics. The most standard telemetry voltage controlled oscillator input is 0 to 5 volts DC so it seems expedient to make the output from the instrument fall in this range. The output resistance should be low enough to enable the instrument to drive most recorders, voltmeters and various devices that may be connected to its output terminals. This system was designed to drive its full 5 volt output into 10,000 ohms. To meet the preceding accuracy requirements, the ripple on the output should be less than 5 millivolts peak to peak. The power source for the instrument to accomplish the above mentioned tasks is most readily available from a 115 volt AC, 60 cps power line. Power consumption for the instrument is approximately 25 watts. For operation in areas without 115 volt AC power facilities, a static inverter with batteries may be employed.

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Superior numbers refer to similarly numbered references at the end of this paper.

Fig. 1. Construction of active element.

Fig. 2. Electrical and physical terminations.

Finally, the ambient temperature range over which the system will operate within its rated accuracy specifications is an important consideration. Once the output level is set, the system should retain its accuracy over a range of $\pm 25^{\circ}\text{F}$. The system should operate over a range of 0° to 140°F with a slight degradation of accuracy.

TRANSDUCER

The basic transducer, more commonly referred to as the staff, evolved in the process of achieving the previously described specifications. Several different configurations can be used for the active element that fundamentally consists of a continuous resistance wire. The particular staff described below is a polyethylene jacketed wire rope of suitable physical strength wound in a continuous spiral with a Nichrome resistance wire. The resistance wire is lightly embedded in the polyethylene giving a near smooth surface offering minimum interference with water runoff (Fig. 1). The out-of-the-water resistance for all staff lengths is 2,000 ohms. To accomplish this for staffs of different lengths, either the wire size or winding pitch of the wire on the staff is varied, or both.

The strength of the polyethylene jacketed wire rope can be selected for compatibility with in situ operational requirements. Cable sizes allowing tensions on the order of 2,000 pounds have been utilized; however, the fouling rate from marine organisms appears to increase in excessive proportion to the increase in wetted surface area of the staff. Polyethylene has been demonstrated to have excellent resistance to deterioration in sea water and fortuitously has the characteristic of "memory," which facilitates the assurance of a tightly wound resistance element. In addition, polyethylene is quite readily replaced in areas where exposure of the wire rope is required in the construction of the active element (Fig. 2). A small soldering iron fitted with a spatula shaped tip, solid polyethylene spaghetti as the "soldering" material, plus a simple technique similar to conventional soldering, is all that is required to accomplish completely homogeneous and leakproof restoration of the polyethylene jacket. The lower end of the staff

Fig. 3. Termination at top of active element.

Fig. 4. Section of wire resistance wave sensor.

is terminated in an eye through the use of a stainless steel thimble and cable clamp. The upper end is terminated with a simple device constructed of linen base phenolic material that meets both physical and electrical requirements (Fig. 3). A pair of single conductor waterproof connectors are used to provide electrical connection of the active element to the deck unit. A photograph of the active element is shown in Fig. 4.

provided by a constant voltage oscillator driving a constant current amplifier. The 1 Kcps oscillator, a twin "T" type incorporating a temperature compensated automatic gain control loop, generates approximately one volt rms of a low distortion, amplitude stable sinusoid. This voltage is amplified by 10 and made to approach a constant current source by the constant current amplifier. Since the sea water acts as a resistance short, the voltage developed across the staff will be linearly proportional to the length out of water only if the staff is excited by a constant current source. The constant current amplifier fulfills this requirement at the high excitation level of 10 volts rms with the staff out of water. High level sinusoidal excitation minimizes degradation of performance due to electrolysis, marine fouling, 60 cps line pickup and induced noises in general.

The voltage across the staff, which varies linearly with the percent immersion, need only be converted to a form compatible with existing telemetry, digitizing and recording equipment. An AC-DC converter working into a low pass filter performs this function. This converter consists of a high gain operational amplifier with silicon rectifier diodes enclosed in its feedback path. The low pass filter is a 2-stage LC type which acts to eliminate the pulsating effects of the diode rectification. The output voltage is a ripple free DC voltage which varies from 0 to 5 volts depending on the staff immersion. The conversion accuracy is better than $\pm 0.1\%$ of full scale. The output also can be DC isolated from sea water ground to eliminate common mode voltages from the output signal.

PRINCIPLES OF OPERATION

A block diagram of the electronics is shown in Fig. 5. Excitation for the staff is

Fig. 5. Block diagram of wave and tide monitor.

STAFF EXCITATION

Twin "T" Oscillator

The basic oscillator consists of an amplifier with approximately 40 db raw gain with a selective negative feedback loop and a positive feedback loop. The twin T network in the negative feedback loop results in a peaking amplifier, the frequency of peaking being determined by the twin T network. Stable components have been employed in the network to insure peaking stability with temperature and aging processes. The gain of the amplifier at the peaking frequency approaches its raw gain of 40 db. Therefore, care has been taken in the design of the amplifier with local feedback in the gain stages to insure good stability of the 40 db raw gain. The positive feedback loop adjusts the gain around its loop to unity at the frequency determined by the twin T network.

Incorporated in the positive feedback loop is a temperature compensated automatic gain control circuit. Without applying this technique, the oscillator would have to be severely overdriven to maintain oscillation over the operating conditions encountered. For the application at hand the oscillator has to meet a rigid amplitude stability requirement, better than $\pm 0.1\%$, while maintaining an overall distortion of below

0.5%. Since an overdriven oscillator cannot meet either one of these requirements, especially the latter, the use of an automatic gain control is mandatory.

The block diagram for the oscillator (Fig. 6) will be used to explain the operation of the automatic gain control circuit. The output, E_o , is rectified, filtered and applied to the control diode, CR1, by means of resistor R_2 . Since the DC bias current through a diode also determines its AC impedance the magnitude of the feedback

Fig. 6. Twin T oscillator

Fig. 7. Series resistance constant current source.

Fig. 8. Simplified diagram of operational amplifier.

voltage transferred through resistor R_1 will be determined by this bias current. The effect is such that if the oscillator output level increases the rectified level of the automatic gain control increases, thereby driving more bias current through the control diode and lowering its dynamic impedance. Less positive feedback voltage is applied to the front end of the oscillator restoring the oscillator output level to very nearly its original value. A thermistor-resistor network is used to compensate for the temperature shifts in the control and rectifier diodes. The oscillator maintains the required amplitude stability of less than $\pm 0.1\%$ over an ambient range of 50°F .

Constant Current Amplifier

This amplifier is used to drive a constant current through the staff independent of resistance. The excitation level of 10 volts rms results in a good signal to noise ratio. In Fig. 7 is shown a circuit configuration in which a resistance is interposed between the oscillator and the staff to approximate a constant current source. Full scale voltage of 10 volts rms will generate a current of 5 milliamps through the 2,000 ohm staff. Holding 5 milliamps constant to within $\pm 0.1\%$ as the staff resistance changes

Fig. 9. Actual constant current amplifier.

from zero to 2,000 ohms requires a series of resistance, R_s , of 2 megohms or greater. Under these conditions the oscillator output would have to be at least 10,000 volts rms which is not practical. By utilizing a high gain amplifier in the operational configuration, the needed current accuracy can be attained and the oscillator output level of 1 volt rms is multiplied by 10 which is needed to drive the staff.

A simplified diagram of the operational amplifier is shown in Fig. 8. If the raw gain, A_o , is at least 80 db and the closed loop gain is 20 db or less, there will be a net negative feedback of 60 db or more. Under these conditions as R_3 is varied over the 2,000 ohm range the output voltage of the amplifier, E_{oa} , changes from 2 volts to 10 volts as the current, I_2 , is held constant. This follows from I_1 being equal to I_2 within better than 0.1% as a result of the 60 db of negative feedback around the amplifier. As R_3 is varied downward I_2 tends to increase causing a slight decrease in amplifier sensing current, I_3 . The amplifier output voltage, E_{oa} , is in turn lowered and I_2 very closely restored to its initial value. It follows that the voltage, E_{os} , developed across R_2 is proportional to the value of R_3 since I_2 is maintained constant by the action of the operational amplifier. Again it may be important to state that the preceding is true only if E_o is constant to within 0.1%. Fig. 9 shows the scheme used in the actual circuit to arrive at a practical value of amplifier input impedance, the principle of operation being the same as for the simplified case in Fig. 8.

SIGNAL CONDITIONING

AC-DC Converter

The AC-DC converter consists of a high gain amplifier again connected in the operational configuration but this time including silicon switching diodes in the feedback path. This technique develops a proportional DC output voltage with relation to the rms value of the input voltage. With a pure sinusoid the average value is equal to 0.45 of the rms value. This clearly

Fig. 10. Simplified AC-DC converter.

Fig. 11. Actual AC-DC converter.

Fig. 12. Low pass filter.

Fig. 13. Converter output.

shows why the waveform distortion must be kept low in this instrument. With total harmonic distortion below 0.5%, a conversion accuracy of better than 0.1% can be obtained related to the rms value of the input voltage.

A diagram of a simplified AC-DC converter is given in Fig. 10. The open loop gain, A_o , of the amplifier is approximately 66 db insuring over 60 db of net feedback around the loop including the silicon diodes. The diodes are connected such that on the positive half of the output wave, E_{oc} , diode CR1 conducts and diode CR2 is biased off. The reverse occurs on the negative portion of the wave. The sum of currents I_2 and I_4 are equal to current I_1 since sensing current I_3 is reduced to below 0.1% of I_1 as a result of the 60 db of negative feedback.

Operation with diodes in the feedback is as follows. If there is no input signal to the amplifier and the amplifier output noise is below 1 volt peak-to-peak, the rectifier diodes are for all practical purposes open circuits allowing the amplifier to have its full raw gain of 66 db. The waveform appearing at the output of the amplifier will be that of white noise. If a positive voltage is applied to the input of the amplifier, a current I_1 will flow into the amplifier as sensing current I_3 since the diodes are still open. Sensing current I_3 instantaneously drives the output voltage, E_{oc} , negative causing CR2 to conduct. Input current will now flow through R_3 as I_2 . I_3 , the amplifier sensing current, will drop to a negligible value. At this time the forward gain of the amplifier has dropped to slightly greater than unity. Therefore, the voltage developed across R_3 represents one-half of I_1 and the other half is developed across R_2 . Further, the rectified voltage, E_{dc} , developed across R_2 is proportional to the input voltage, E_{os} , to better than 0.1%. In Fig. 11 is shown the actual AC-DC converter diagram used to obtain the 2 megohms input impedance required for the amplifier. This requirement is necessary since the amplifier input impedance loads the staff.

Low Pass Filter

The output voltage, E_{dc} , from the AC-DC converter, though being a precise conversion of the AC voltage across the staff, is still not in a form usable for most applications due to its pulsating nature. It is necessary to smooth this voltage to keep the ripple to less than 5 millivolts. The 2-stage LC low pass shown in Fig. 12 is employed for this purpose. The two inductors have a series resistance of approximately 1,000 ohms. This resistance limits the load resistance that may be connected to the instrument without appreciable loss of filtered output voltage, E'_{dc} . At a carrier frequency of 1 Kcps the filter has an attenuation of over 70 db. The filter has less than 0.2% attenuation at 5 cps giving additional useful data up to 20 cps. Fig. 13 shows both the unfiltered converter output, E_{dc} , and the filtered output, E'_{dc} . The final output voltage is in a

form useful for most analog recorders, telemetry inputs, digitizing devices, etc.

CONCLUSIONS

The instrument described herein is capable of directly measuring variations in sea water level over a nominal band from 1 cps to 1 cycle per day. Accuracy may be held to 0.2% of the length of the staff which can be readily manufactured in lengths from 5 to 100 feet. These specifications apply only so long as the surface of the staff is clean; in situ testing is in progress to determine degradation caused by marine fouling. The system is readily portable and the transducer is rugged enough to withstand rough handling and adverse environmental conditions common to oceanography.

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SHIPBOARD ULTRASONIC WAVE HEIGHT SENSOR

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ABSTRACT

This paper describes a self-contained, electronic wave measuring and recording system developed for the U. S. Navy Oceanographic Office. In waves up to 40 feet it measures relative displacement of the sea surface from mean sea level with an accuracy of better than 5%, while compensating for all significant ship motions. Vertical distance is measured by a box-mounted, pulsed ultrasonic echo ranging unit. Ship motion is measured by a doubly integrated, accelerometer-vertical gyro system. The two signals are combined with a fixed offset to produce true wave height.

GENERAL SYSTEM DESCRIPTION

A new approach to wave measurement is embodied in the shipboard wave height sensor developed by

RCA for the Navy Oceanographic Office. This instrument is capable of long-term, unattended operation in the normal shipboard environment of vibration, temperature change and poorly regulated primary power supply. Data in the form of displacement of the local sea surface from mean sea level is recorded on a strip chart at a sampling rate of 10 per second. Height resolution is 2 inches with maximum wave height of 40 feet or greater and accuracy of better than 5%. Long-term, stable integration of ship accelerations permits accurate recording of waves having periods of 2 to 25 seconds.

The mode of operation of the wave height sensor is shown in the block diagram of Fig. 1. The rugged, watertight, stabilized housing shown in Fig. 2 is mounted at the ship's bow projecting over the surface of the water. This housing contains and protects the vertical gyro, accelerometer and roll and pitch stabilization drives.

Fig. 1. Block diagram of wave height sensor.

Fig. 2. Stabilized transducer housing.

The ultrasonic transducers are mounted on the bottom of the housing.

The vertical gyro, which has a low erection rate after spinup, acts as a long-period pendulum and provides a vertical reference accurate to 1/8 degree in spite of normal motions of the ship's bow and independent of the accuracy of the mounting surface. The housing is roll stabilized and the inertial quality, temperature regulated accelerometer is additionally stabilized in pitch. It is mounted on a small servo driven pitch cradle that is erected to synchro signals received from the vertical gyro.

The output of the accelerometer is a direct current proportional to the true vertical acceleration including gravity. The current is converted to voltage by means of a precision pick-off resistor located in the interior electronic package shown in Fig. 3. The gravity component is removed and the signal doubly integrated to produce a voltage proportional to the vertical displacement of the instrument housing. Distance from the housing to the local sea surface is obtained by means of a pulsed, ultrasonic, echo-ranging height sensor previously developed by RCA for hydrofoil craft control applications. The two signals are subtracted and combined with an adjustable bias to give the instantaneous displacement of the local sea surface from mean sea level. Correction for the variation of the velocity of sound with temperature is accomplished by means of a single dial setting. This could be made completely automatic, if desired, by addition of a thermistor temperature sensing circuit.

TRANSDUCER BEAMWIDTH

Most of the problems encountered in developing the wave height sensor arose, naturally enough, from such properties of the ocean surface as its local slope, reflectivity, displacement and velocity. The first two properties primarily affect the design of the echo-ranging part of

Fig. 3. Interior electronic package.

the wave height sensor. As shown in Fig. 4, the apparent profile of a wave is distorted by an excessively wide beamwidth. Fig. 5 shows quantitatively the error due to beamwidth in the presence of sloping wave surfaces. The lower group of curves corresponds to the shortest range within the beamwidth and the upper group to the longest range. For pulsed operation the lower group represents the first return. The extreme curve of the lower group shows the return for specular reflection, which is necessarily from perpendicular incidence. It implies operation

Fig. 4. Effect of excessive beamwidth on height error.

Fig. 5. Error in height due to beamwidth and wave slopes.

on sidelobe reflections or, alternatively, loss of signal when the wave slope is greater than one-half the beamwidth.

It is apparent from Fig. 5 that very narrow beamwidths would minimize the errors due to wave slopes but a compromise must be made if loss of signal is to be kept within allowable bounds. Such loss occurs when the slope of the entire surface in the area encompassed by the beam exceeds one-half the beamwidth. Fortunately, large slopes are statistically improbable under conditions of light wind and smooth surfaces. Moreover, the presence of wind roughens the surface and diffuses the return reflection thereby causing an effective increase in beamwidth without an attendant loss of accuracy.

Statistical measurements of the slopes of waves have been made.^{1,2} The distributions are approximately Gaussian with parameters shown in Table I. Since the measurements were made from photographs taken at substantial altitude compared with wavelength, the slopes represent the superposition of ripples and chop on the larger

Table I. Distribution of inclinations of reflecting facets.

Direction	Crosswind		Upwind-Downwind	
Wind velocity, knots	10	20	10	20
Bias, degrees	0	0	-0.5	-1.0
Standard deviation, degrees	5	7.5	7	10

waves. From Table I it is apparent that a slope of $\pm 20^\circ$, corresponding to sinusoidal waves of length-to-height ratio of 9:1 or greater, would include all the statistically significant cases. However, a half beamwidth of 20° would produce a range error of about 6%.

In practice it is feasible to operate at a frequency of 38 Kcps and reduce the beamwidth to $\pm 8^\circ$ between nulls, a value which can be obtained with commercially available transducers of 5 inches diameter. The RCA hydrofoil ultrasonic height sensor has undergone many hours of successful testing with such transducers. Sea conditions ranged from glassy calm to white caps with waves up to 5 feet. Relative winds from zero to 50 knots were encountered. Although receipt of 80% of return pulses is sufficient for proper operation, usually more than 90% and often more than 98% were received.

SELECTION OF TYPE OF MODULATION

Of the types of modulation applicable to distance measurement two of the simplest are short pulse and sinusoidally modulated CW. The measures of range are respectively the time interval between transmission and reception and phase shift of the sinusoidal envelope. For a maximum range of 40 feet the total transit time is about

Superior numbers refer to similarly numbered references at the end of this paper.

0.1 second and the highest non-ambiguous envelope frequency is about 10 cps. A carrier frequency in the neighborhood of 35 to 40 Kcps is suitable for either type of modulation since it is high enough to avoid machinery noise interference and low enough to avoid the effect of the rapidly increasing attenuation in the region of 50 Kcps and above.

For a relative horizontal velocity of 2 feet per second, the 38 Kcps transmitted frequency is shifted by ± 19 cps for a half beamwidth of 8 degrees. A continuous spectrum is generated by echoes from various points within the beam. The envelope of such a signal approaches 100% modulation at noise frequencies up to 19 cps and interferes with the necessary signal modulation of 10 cps. Pulse modulation was chosen for the RCA height sensor to avoid this source of noise and to obviate the necessity for heavy filtering with attendant low time response. Operation on the leading edge of the return pulse eliminates the effects of doppler shift.

MINIMIZATION OF THE EFFECTS OF SPRAY

The effect of spray on the distance measurement is minimized by the action of a slow automatic gain control loop. Spray droplets are generally small compared to the transmitted wavelength and, therefore, tend to scatter the energy incident upon them. If a sheet of spray is sufficiently dense the true echo may be so reduced in intensity that it will not exceed the automatic gain control threshold and hence will be

lost. To provide for this case the previous correct range must be held. Since the height sensor measures range by counting clock pulses, the previous count can be held exactly for any desired period of time. If the spray persists, the automatic gain control loop gain is automatically adjusted, within limits to pass the true signal. It is unlikely that a persistent wind-borne spray would produce a sharply defined echo at sufficient intensity to exceed that of the true echo because the particles of such a spray are necessarily finer and more uniformly distributed than those which occur momentarily in dense sheets near the surface of the water.

SHIP MOTION COMPENSATION

Ocean waves further affect the design and performance of the wave height sensor by causing motions of the ship's bow upon which the wave height sensor is mounted. The principal motions are pitch, roll and the attendant translations of the housing. It is required that the ultrasonic transducers and the input axis of the accelerometer be maintained approximately vertical but the necessary accuracy for the accelerometer is much greater than for the transducers. It is for this reason that the accelerometer is pitch stabilized while the transducers are not. Surge and sway accelerations are eliminated by keeping the accelerometer vertical and heave acceleration is used to derive the heave displacement height component which is subtracted from the echo ranging height.

Fig. 6 shows the Neumann spectrum for a fully developed state 6 sea and also the rough relative

Fig. 6. Neumann spectrum of state 6 sea.

response curves for pitch and roll of a typical oceanographic ship. To the right of the appropriate natural frequency the ship response is 180° out of phase with the slope of the waves and to the left it is in phase. Maximum amplitude of pitch response is expected to be less than 8° and roll response will not ordinarily be of much greater magnitude because the ship is required to be hove to and headed into the sea during wave measurements. Since the major portion of the pitch response is in phase with the wave slopes, the incidence of the echo ranging beam will usually be near perpendicular and signal loss will be minimized. For higher frequencies, corresponding to pitching that is out of phase with the wave slope, the pitch amplitudes and wave slopes are smaller.

To provide the necessary accuracy of roll stabilization at the frequencies near the peak of the spectrum, the servo bandwidth has been set considerably higher than the frequency of peak wave response. The accelerometer pitch cradle servo bandwidth is several times that of the roll servo.

CONCLUSIONS

The shipboard wave height sensor has been designed for accurate wave measurement at sea. It is believed that this design provides capabilities far exceeding those of existing systems, particularly with respect to measurement of large waves in deep water.

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EQUIPMENT FOR TELEMETERING OCEAN-WAVE INFORMATION

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INTRODUCTION

Wave measurements in mid-ocean have been plagued by three main obstacles: (1) observers generally do not agree on wave height (and also tend to ignore wave period), (2) in heavy seas the main emphasis of a ship captain is on survival rather than on measurements and (3) instrumentation for shipborne wave measurements is not generally available. Further, survey vessels that are equipped with wave-measuring instruments are not likely to provide sufficient data to describe the wave climate. An unmanned buoy that could measure ocean waves, particularly if it could do this on a currently-reporting basis, would seem to be a valuable asset to oceanographic instrumentation.

THE WEATHER BUOY

The United States Naval Research Laboratory has developed a weather-telemetering buoy (shown in Fig. 1) designed to transmit wind speed, wind direction, barometric pressure, air temperature and water temperature at 6-hour intervals. The messages are sent in Morse Code with numerous "repeats." Provision has been made to add up to 5 information channels without modifying the equipment and an additional 5 channels after minor modification. These added channels have been provided for telemetering outputs of oceanographic sensors that may be available in the future.

The buoy case is 36 inches in diameter and 30 inches high. A telescoping ballast structure extends 15 feet below the buoy. A telescoping superstructure with an 18-foot whip antenna extends above the buoy. All external instrumentation is mounted in a single assembly on top of the antenna. A UHF beacon is provided to permit aircraft to locate the buoy or, if the buoy is moored, permit its use as a navigational aid. The buoy weighs 600 pounds and carries batteries for 12 months of unattended operation.

Inside the buoy case a lower compartment houses the batteries. The instrumentation for coding, programming and measuring barometric pressure, station direction and average wind speed are located in the upper portion. Also in the upper compartment are a dc-dc convertor, 2 transmitters, 2 command receivers for remote turn-on. On clock-control one frequency is used in the

Fig. 1. The weather buoy.

Fig. 2. Weather buoy instrument package.

daytime and the other at night. If the station is operated on demand it will respond on the frequency used for interrogation. The two methods of control are completely compatible. The main instrument package is shown in Fig. 2.

MEASUREMENT OF SEA CONDITIONS

The first additional oceanographic sensor to be investigated is a sensor to obtain some measure of the sea condition. One description of the sea surface is that of an energy spectrum which gives estimates of wave energy as a function of frequency. Energy spectra are usually obtained by digital computer processing of a time series of data of the surface elevations taken over a time interval of the order of 20 minutes. The area under such a spectrum is a measure of the total energy of all the waves.

Since the weather buoy cannot be equipped with a complex computer, nor is it practical to supply the power required to transmit 20 minutes of wave-height data to a shore station for analysis, the possibility of obtaining the integrated value of the mean square of the surface deviation over a 20-minute period using a pressure transducer suspended below the buoy and working into an

integrating device was explored. The fact that this integrated value is a measure of the total energy of the measured waves added to the desirability of this arrangement.

Further study indicated that a vertical array of sensors could provide a certain amount of wave period information and this will be discussed.

Wave Measurements

Trochoidal wave theory depicts ocean waves as circular motions of water particles which decrease exponentially with the depth expressed in wave length. If one prefers to consider the ocean surface as an infinitely broad distribution of sinusoidal waves, the variations in pressure due to the waves decrease with depth, the rate of decrease being a function of the wave length. For water depths of the order of a few wave lengths either concept results in virtually the same rate of decay of wave effects with depth.

Because the wave effects diminish with depth as a function of wave length and because wave length is directly related to the square of the wave period, there is available a means of

sensing and telemetering some estimates of the energy spectrum. A vertical array of pressure sensors suspended at various depths below a buoy on an effectively rigid cable would follow the vertical motion of the buoy provided the weight of the array is sufficient to insure that (a) the array remains essentially vertical in the presence of current shear and (b) the weight is greater than the hydrodynamical drag so as to force the sensors to descend as rapidly as the buoy.

Consider the suspended vertical array of pressure sensors indicated in Fig. 3. A 5 unit array is shown with the buoy at the trough (a) and at the crest (b) of a surface wave. A sinusoidal wave is used for simplicity. The constant-pressure surfaces shown at the various depths in the figure were computed by using the exponential decay in wave activity derived from trochoidal wave theory and also by using the hyperbolic cosine ratio resulting from the concept of a sinusoidal wave on the surface which is infinite in extent. Both methods resulted in essentially the same configuration of constant-pressure surfaces.

Fig. 3. Wave sensor configuration schematically displayed relative to constant pressure contours for a wave period of 9.34 seconds.

The following equations were used:

$$K = e^{-2\pi Z/L} \quad (1)$$

$$K = \cosh [2\pi d/L(1-Z/d)] \quad (2)$$

where d is the water depth, Z is the mean depth of the pressure surface, L is the wave length and K is the factor by which the amplitude of the constant-pressure surface at depth Z is reduced compared to the constant-pressure surface at the water surface.

One can see from Fig. 3 that the shallow sensors cross fewer constant-pressure surfaces as the wave passes than do the deeper sensors. The pressure change to which each sensor in the array is exposed is proportional to the difference in amplitude between the constant-pressure surface at the water surface and the constant-pressure surface at the depth of the sensor. Therefore, the response of each sensor is proportional to $1-K$.

Integration of Wave Measurements

To obtain an integration of the output of a wave sensor over a period of time (for example, 20 minutes) the concept of an electrical calorimeter is used.¹ If a voltage which is at all times proportional to the deviation of the pressure from a mean value as measured by any one of the pressure transducers in the vertical array (Fig. 3) is applied across an appropriate resistance, whose heat capacity is known and which is highly insulated, the rise in temperature of the resistance over a given period of time is a measure of the energy introduced into the resistance during that time. This temperature change can be telemetered as a measure of the mean square of the amplitudes (also the total energy) of the pressure variations to which the wave sensor responds.

Such an "electrical calorimeter" has been constructed and is illustrated in Fig. 4. The unit consists of a copper bobbin on which are wound a heater winding and a resistance-thermometer winding. The calorimeter is insulated from its surroundings by foam plastic. A 30-gram copper bobbin in the center of a 3-inch cube of foam plastic has a thermal time constant of about 20 minutes and averages over a 20-minute period with good accuracy. With the full scale output of the wave sensor described above, the calorimeter would show a temperature rise, above ambient, of 70°F. The coding system of the weather buoy has a resolution that corresponds to about 0.4°F so that overall system accuracy should be adequate.

¹Superior numbers refer to similarly numbered references at the end of this paper.

Fig. 4. Typical electrical calorimeter.

Calculation of Energy Spectrum Estimates by Use of a Vertical Array

Assuming that the sea surface can be approximated by a combination of sine waves having 5 different periods, one can compute (1-K) for each of the 5 sensors as illustrated in Fig. 3 for each of the 5 different wave periods. Each sensor will respond to the 5 waves but with different sensitivities due to the different depths of the sensors below the buoy. The squared and integrated output over an interval of time of each sensor in the array is a linear combination of such response to the 5 waves having different periods. Thus one can form a set of linear equations describing the outputs of the 5 sensors as follows:

$$R_i = (1-K_{ij})^2 E_j \quad (3)$$

where R_i is the output energy over a given interval from the i^{th} sensor, K_{ij} is the depth attenuation for the i^{th} sensor for the j^{th} wave period and E_j is proportional to the energy associated with the j^{th} wave period. These equations can then be inverted to obtain the E_j in terms of the R_i which is the data telemetered.

The inverted set of equations for an array with the gages located at the 95% response depths for periods of 4, 8, 12, 16 and 20 seconds are:

$$E_{20} = +0.393R_{39} - 2.80R_{157} + 12.39R_{352} - 28.5R_{626} + 18.56R_{978} \quad (4)$$

$$E_{16} = -1.000R_{39} + 7.12R_{157} - 29.8R_{352} + 53.6R_{626} - 30.0R_{978} \quad (5)$$

$$E_{12} = +1.46R_{39} - 10.03R_{157} + 28.12R_{352} - 38.61R_{626} + 19.20R_{978} \quad (6)$$

$$E_8 = -2.67R_{39} + 7.11R_{157} - 12.19R_{352} + 14.28R_{626} - 6.79R_{978} \quad (7)$$

$$E_4 = +1.84R_{39} - 1.56R_{157} + 2.26R_{352} - 2.71R_{626} + 1.35R_{978} \quad (8)$$

The subscripts on the E's indicate period; those on the R's indicate depth.

Since a short appendage to the buoy might be much more convenient in field operations than a long one, an array of gages located at the 10%-response depths was also considered. The inverted set of equations for the short array are:

$$E_{20} = +18,271.R_{4.9} - 5,102.R_{19.8} + 1,766R_{44.6} - 405.9R_{79.4} + 31.4R_{124} \quad (9)$$

$$E_{16} = -32,870.R_{4.9} + 8,814.R_{19.8} - 2,689.R_{44.6} + 400.0R_{79.4} + 37.4R_{124} \quad (10)$$

$$E_{12} = +14,474.R_{4.9} - 3,783.R_{19.8} + 1,064.R_{44.6} - 111.5R_{79.4} + 2.86R_{124} \quad (11)$$

$$E_8 = -1,721.R_{4.9} + 430.5R_{19.8} + 109.2R_{44.6} + 94.1R_{79.4} - 2.86R_{124} \quad (12)$$

$$E_4 = +43.3R_{4.9} - 75.9R_{19.8} + 15.7R_{44.6} - 0.15R_{79.4} - 3.06R_{124} \quad (13)$$

Obviously the coding-system resolution required to use the short array would be far greater than that required to use the long array.

Once the equations for 4, 8, 12, 16 and 20-second periods have been solved to obtain 5 estimates of the energy spectrum the location of any maximum might or might not be indicated. If a maximum is indicated another set of equations for a more narrow range of periods can be determined and solved to locate the energy maximum in more detail.

FIELD TRIALS

Preliminary field trials of suspended pressure transducer arrays were carried out during September and October of 1962. Long period waves were encountered in only one test when a 2-unit array was in operation with sensors at a depth of 88 and 245 feet respectively. Connections to the pressure transducers were by means of cables to recorders mounted in a small boat.

The water depth was well over 2,000 feet. The wave records indicate that the sensors did not follow the downward motion of the buoy as accurately as they did the upward motion.

For this experimental setup the output of the pressure transducers was recorded on strip recorders rather than feeding into the electrical calorimeter as would be done for telemetering. Digital data taken from the 2 gages in the array were subsequently processed to obtain a power spectrum of the energy as measured at the particular depth of each gage (not corrected for depth). The areas under each of the plots of these spectra (as shown in Fig. 5) are equal and the respective normalizing factors required to reduce the area to the particular value are shown. Since the area under a non-normalized plot would be proportional to the total energy, the normalizing factor is proportional to the energy and would therefore be directly related to the rise in temperature which would occur in the electrical calorimeter. The ratio of the

normalizing factors is 5.8. The single wave period which would give this particular ratio for two gages at the depth used is about 23 seconds. The actual spectra have maxima around 10 seconds, thus giving a rather large discrepancy. These preliminary tests have pointed up a number of changes which must be made in the experimental setup for future experiments to evaluate the overall feasibility of this approach to sea-state measurement.

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Fig. 5. Energy spectra from suspended wave sensors.

SESSION V

FLUID MOTION

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SOME DYNAMICAL PROPERTIES OF THE SAVONIUS ROTOR CURRENT METER

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ABSTRACT

A series of steady state and acceleration experiments has been performed with the Savonius rotor current meter in a tow tank. From the several models tested an evaluation has been made of some of the effects of size and configuration on rotor performance in the range of 0.05 to 3 knots. Rotor response to changes from zero to a steady current speed and vice versa has been shown to be significantly different and dependent on current speed. Notable changes in performance have also been found due to change of rotor surface roughness by biological fouling.

INTRODUCTION

A commonplace failing in research is use of a measurement device without complete understanding of its characteristics. Whether this be by necessity or neglect, the danger exists that subsequent misinterpretation or overevaluation of data may contribute to confusion rather than enlightenment. Such could be the case in the realm of ocean current measurement and it is evident that at least one device, the Savonius rotor, deserves some attention in this regard.

A major motivation for the studies summarized herein has been the unprecedented rise to popularity of the Savonius or "wing" rotor since its introduction as a current meter in 1952.¹ Several commercial firms have become involved in manufacture of the several hundred rotor meters that have been widely used for oceanographic and limnological research. It is interesting to note that all of these meters employ the same rotor design that was rather arbitrarily selected for the first experimental model. There has been a dual objective for our tow tank experiments: (1) to quantitatively evaluate the measurement capabilities of the "standard" Savonius rotor and (2) to generate criteria for possible design improvements.

BACKGROUND

The Savonius rotor is not new. S. J. Savonius devised the "wing rotor" in the early 1920's as an improvement over ocean-going sails² and subsequently as a wind and water driven power generator for a variety of applications.³ In the early 1950's J. M. Snodgrass began experimenting with the rotors as an ocean current sensing device.¹ By 1958 at least two U. S. companies were beginning to manufacture rotor meters and W. S. Richardson at Woods Hole Oceanographic Institution was using rotors in instruments for a major ocean current study. From that time to the present application of the meters has steadily broadened. Little has been published about these applications; still less about characteristics of the device itself.

A series of tests was initiated jointly by the authors in 1961 after earlier spot checks had failed to explain the reasons for discrepancies between calibrations of rotor meters. Details of many of the initial studies have been given in a previous report.⁴ This present paper is limited mainly to results obtained during the latest test period in July 1962.

EXPERIMENTAL APPROACH

The rotor models shown in Fig. 1 were used for the July 1962 experiments. The 2 rotors on the left are "standard" models consisting of 3 circular flat plates 6 3/8 inches in diameter that enclose 2 tiers of 2-inch radius half-cylindrical vanes placed in pairs with the horizontal axis of symmetry rotated 90° between tiers. Rotor CS-2 is a Hytech production unit made of molded high impact polystyrene and ST-1 was individually fabricated from cyclocac at Scripps Institution of Oceanography. Rotor ST-2 is scaled down to one-half size, ST-3 is standard diameter and height overall but has 4 tiers of standard diameter vanes. Rotor ST-4 has 2 tiers

¹Superior numbers refer to similarly numbered references at the end of this paper.

Fig. 1. Savonius rotor models used for calibration experiments in July 1962.

Fig. 2. Rotor unit CS-2 used in experiments of July 1962.

Fig. 3. Rotor test unit ST-1 mounted in support assembly used for tests of "ST" rotor models.

and is standard diameter but each of the vanes is double height. Rotor HT-1 (not shown) is another production model identical to CS-2. Both of these rotors were tested in a meter housing (Fig. 2) and the 4 "ST" rotors were mounted in the special assembly shown in Fig. 3.

Experiments were run in the Hytech tow tank facility in San Diego, California. The tank is 150 feet long by 7 feet wide and has a fresh water depth of 6 feet. The carriage system is hydraulically driven with high tension steel cable and is considered to maintain an acceptably small amount of transverse vibration and variation in speed at tow rates above 0.05 knots.⁵

Normally the rotors were towed in pairs suspended from the tow carriage as shown in Fig. 4.

Fig. 4. Rotor units CS-2 and ST-4 ready for calibration run in Hytech tank, July 1962.

Earlier tests failed to reveal any measurable influence of one rotor on the performance of the other with this tandem setup compared to towing one rotor at a time.

It is important to note that all of these tests are restricted to still (non-turbulent) water. Evidence that results under this condition may be significantly different from those obtained under natural conditions was first offered by Savonius² who found some 10% to 15% increase in rotational frequency for the same air speed in the natural wind compared to the wind tunnel. It follows that performance is probably dependent mainly on the frequency and scale spectra of turbulence superimposed on the mean flow.

THRESHOLD AND ANGULAR SPEED VARIABILITY

The threshold of a current meter, i.e., the minimum current speed it is capable of detecting, is of major importance. Unfortunately, the

Savonius rotor has no clear-cut threshold that fits this definition because the rotor turns non-uniformly due to a dependence of torque on vane position relative to orientation of flow past the rotor. Fig. 5 is a polar torque diagram for one of Savonius' early rotors. This is "static" torque; its magnitude relative to other torque components decreases as rotational speed increases and the rotor gains inertia. Therefore, if the rotor gains enough angular momentum while being driven in its high torque region it can stay in motion even though the torque would be insufficient to start it from stall in the low torque position. It is rather difficult in the presence of variations in tow carriage speed and residual turbulence in the tank to accurately establish threshold. With good bearings, clean surfaces and moderate manufacturing care the threshold for any flow orientation should not exceed the range of 0.02 to 0.05 knots.

The exact value of threshold may be somewhat academic since the rotor continues to turn non-uniformly for flow speeds considerably above the

Fig. 5. Polar torque diagram for an early Savonius rotor.

starting point. Experimental equipment has not yet been obtained to quantitatively evaluate rotor performance much below 0.05 knots. However, some notion of the significance of rotational variability can be drawn from Fig. 6 which represents considerable averaging from an early set of rotor tests. These results indicate that for speeds greater than 0.05 knots the rotational variation is not large, perhaps less than 10%. This has been generally borne out by tests with other rotors although, as might be expected, the tolerances and condition of bearings becomes significant at these low speeds. Obviously the effect of rotational variability can be largely eliminated if output is calculated in multiples of one revolution of the rotor.

REFERENCE ROTOR PERFORMANCE

Rotor unit CS-2 (Fig. 2) was treated as a reference for model comparison. CS-2 was towed in tandem during practically all of the runs made with the other models. Steady state analysis of records was quite uniform, being based on the time required for 5 to 10 revolutions taken at least 15 revolutions after the carriage had been

Fig. 6. Sample of angular speed variation during one revolution.

Fig. 7. Calibration for rotor unit CS-2.

started or its speed changed. Steady state calibration results derived from 60 runs are shown in Fig. 7. Standard deviations of rotational frequency relative to the estimated best fit smooth curve have been calculated for various speed ranges and are noted in Fig. 7.

COMPARATIVE PERFORMANCE OF ROTOR MODELS

Steady state calibration results for each of the rotor models are shown in Fig. 8. Not shown are data for ST-1 (standard size) which, within

limits of experimental error, corresponded to the reference curve of CS-2. On this basis it is assumed that the remaining models may be validly compared to CS-2 for performance features associated with rotor geometry.

The following observations seem pertinent concerning the curves in Fig. 8. The half scale model (ST-2) rotates about 60% faster over the range from 0.1 to 3.5 knots. Visual observance of ST-2 indicated that the threshold speed was much lower than for CS-2 which qualitatively supports an extrapolation of the curve with the

Fig. 8. Comparative calibration curves for rotor test models.

same offset as for CS-2, to 0.05 knots or less. Deviation of the data points from the smooth curve is relatively large and is attributable to the close proximity of the signal pickup to one of the rotor plates. It was also noted during the response tests that the rotation rate of ST-2 decayed much more gradually than CS-2. The 4-tier model (ST-3) is significantly less efficient than CS-2. At 0.35 knots the output of ST-3 is 13% below CS-2 and at 0.1 knots it is down 50%. This seems to indicate that retarding fluid stress on the drag area (tier separators) of the standard diameter rotors is significant at speeds less than about 1 knot.

The calibration curve for rotor ST-4 (double height) corresponds closely to CS-2. However, the longer rotor is consistently more efficient by about 10% above 0.1 knots and less efficient as the threshold is approached. This is consistent with the slight reduction in drag area compared to torque area; the reverse of the 4-tier rotor.

SURFACE ROUGHNESS

One of the most pertinent and least investigated aspects of current measurement with rotor or impeller devices is the degree to which meter performance is affected by change in surface roughness, especially by marine fouling. The nature of biological fouling precludes very definite or quantitative answers but orders of magnitude are important. Prior to the experiments in July a production meter, HT-1, of the same design as CS-2, was suspended in San Diego Bay for about 4 weeks. It accumulated a very even coat less than 1/8-inch thick of natural fouling that was left undisturbed for part of the calibration experiments. Fig. 9 is a picture of the unit after being in the fresh water tank overnight. Much of the fouling had deteriorated and sloughed off the vertical surfaces but the original fouling coat can still be seen on the horizontal plates.

The dashed curve of Fig. 10 is for HT-1 with the light coat of fouling. Unfortunately, the bearings of HT-1 apparently were affected by fouling or corrosion so the calibration curve for the rotor with cleaned surfaces deviated markedly from the CS-2 curve below 0.15 knots. From these 2 curves it is found that the thin coat of fouling caused a 40% reduction in rotor efficiency at 0.25 knots. Perhaps more interesting is the decreased slope of the curve in the low speed range, indicating that the fouled rotor operated more efficiently at low speeds and had a lower threshold than after cleaning.

Also shown in Fig. 10 are calibration results for CS-2 after the rotor was lightly coated with petroleum jelly. Although this clearly improved rotor efficiency, the increase was only 5% at 0.1 knots and became less significant as speed was increased. Petroleum jelly was selected to

Fig. 9. Rotor unit HT-1 with coat of biological fouling present during calibration tests in July 1962.

simulate an anti-fouling aerosol coating that has proven moderately successful.

RESPONSE

The dynamic response of an instrument in most cases is as important as the steady state output and much more difficult to evaluate experimentally. The necessity for a quantitative knowledge of rotor response to shifts in mean flow is obvious; more subtle is the probable dependence of mean output on the spectrum of turbulent flow.

Three kinds of still water acceleration-deceleration experiments so far have been attempted: (1) approximate step change from stop or low speed to higher speed, (2) approximate step change from a steady speed to stop and (3) harmonic cycling. It is apparent that techniques (2) and (3) involve relative movement of the rotor through its own wake each time a deceleration or travel direction reversal occurs. During

Fig. 10. Calibration curves showing influence of rotor surface roughness.

an acceleration step change the rotor is not anomalously affected in this manner so results are likely to be more consistent. Harmonic cycling experiments have been performed by Marine Advisers⁶ with a maximum lateral displacement of about 4.5 feet and a period of 10 seconds. Output failed to return to zero and the output oscillation was modulated with a period twice that of the forcing function.

Besides being convenient to perform, the step function is useful as a standard response test which allows interpretation in terms of the well known "time constant." The time constant strictly applies only to non-inertial systems that respond exponentially. In such cases the

time constant is independent of the magnitude of the step change and is equal to the time required for approximately 63% response. The Savonius rotor is definitely inertial but for convenience and uniformity rotor response to the first 63% of a step change in towed speed is taken as its "time constant."

It must be emphasized that the response tests described were for a step change between zero and a steady speed. The results of anemometer tests⁷ indicate that rise and decay characteristics may be radically different when step changes are between steady speeds rather than between zero and a steady speed. This is especially true for the negative step (meter

Fig. 11. Rotor response to abrupt change between zero and steady speed.

deceleration). Therefore, the test results given below may be applicable only to the limiting conditions of the special case; this possibility is quite definitely supported by preliminary results of tests in progress at the time of this writing.

Results of response tests employing a near step change, i.e., one requiring a small but finite length of time for the transition, from stop to a steady towed speed (positive step) or vice versa (negative step) are given in Fig. 11. Mechanical difficulties of accelerating the tow carriage limited the number of usable positive step runs. The positive response deviates from exponential and there is some overshoot (not shown). Several rotor revolutions are required for the rotational frequency to settle down to a reasonably steady value.

From the response curves shown for negative step changes it is obvious that the rotor decays towards zero much more slowly than it accelerates and that the decay rate is a function of step change magnitude as is characteristic of so strongly an inertial system. Time constant values are compared in Table I. The times for

Table I. Rotor CS-2 response to step changes of towed speed.

Step Magnitude	Time for 63% Response (sec)	Time for 90% Response (sec)	t_{90}/t_{63}
+0.247	3.3	6.5	1.97
-0.084	27	>60	----
-0.247	11.8	43	3.65
-0.680	3.4	12.7	2.68

90% response are also given. In a non-inertial system these values would be 2.3 times that for 63% response.

Another feature of the deceleration curves of Fig. 11 is of interest. Immediately after stopping the tow carriage it is noted that the response factor goes above unity before falling off as it should. This is due to the wake that has been generated by the meter as it travels by the stopped rotor, thus giving an additive component to the omnidirectional sensor. The greater the flow speed before the negative step the more rapidly the wake moves past the meter, consequently shortening the time during which the rotation rate is significantly influenced, as seen in Fig. 11.

Fig. 12 gives the flow speed indicated by the rotor as its speed through the water is varied in a somewhat irregular fashion. Some of the characteristic response features described above are readily discernible. Note that when the speed varied almost sinusoidally with a period of roughly 4 seconds (between time of 160 and 170 seconds in Fig. 12) the indicated speed followed the mean trend but failed to indicate the variations. The plotted points represent single rotor revolution averages; somewhat better response might have been obtained by shorter averages, but at low speeds the previously discussed angular rotor speed variability due to non-uniform torque would introduce considerable error.

Fig. 12. Response of rotor CS-2 to irregular changes in tow carriage speed.

CONCLUSIONS

We consider it presumptuous to assume that there is such a thing as the "best" current meter. A current meter, just as any other instrument, must be evaluated on the basis of the user's requirements. It is a good instrument if it satisfies the particular needs with high reliability and within the user's allowable limits of accuracy, cost, time and manpower. It is certain that the Savonius rotor current meter is a good instrument for many applications. In practically all cases its characteristics and limitations must be recognized if not accounted for at the data analysis stage.

With reasonable manufacturing control the standard Savonius rotor current meter should operate reliably in the range of 0.05 to 3 or 4 knots. Turbulent flow encountered in the natural regime may be expected to bias rotor performance; much yet remains to be done before this bias can be quantitatively estimated. Normally, measurement of highly turbulent or rapidly varying flow with the rotor probably should be avoided. Rotor output is likely to be greater in the natural environment than in a tow tank so the meter will register a higher mean current speed than actually present.

Marine fouling has a marked effect on rotor output even when not very severe. The rotors should either be kept clean or a correction factor greater than unity applied. Presence of

an anti-fouling aerosol similar to petroleum jelly has little effect on performance causing a slight increase of output.

Above about 0.2 knots steady state performance is essentially unaltered by changing the length or number of tiers of vanes in the rotor. At speeds approaching the threshold output will be altered inversely proportional to surface area of the rotor plates. Reduction of rotor diameter increases efficiency, presumably due to reduction of surface area, particularly of the tier separators.

The Savonius rotor is a highly inertial device. Response to acceleration can be several times faster than to deceleration (when the flow past the meter is stopped) and response factors are strongly dependent on the magnitude of speed changes.

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A DOPPLER CURRENT METER

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ABSTRACT

A Doppler current meter designed and assembled at the Institute of Marine Science, University of Miami, was tested in model tanks and in the ocean. The output signal under representative oceanographic conditions was recorded and analyzed.

INTRODUCTION

An acoustic current meter based on the Doppler shift principle was designed and assembled early in 1961 and tested in order to study characteristics of the output signal and evaluate the limitations of this meter. Doppler shift meters are of interest because they have high sensitivity, are inherently self-calibrating, have good transient response and have no moving parts. During a period from June 1961 to June 1962 tests were conducted in a towing tank and in representative oceanographic environments.

The instrument consists of a transmitting and receiving transducer operating on a 5 Mcps acoustical signal. The receiver is a single conversion superheterodyne type which provides a good signal to noise ratio. The intermediate frequency passband was shifted upwards to uniquely select the upper sideband signals derived from flow towards the receiver. Addition of double conversion and double sideband detection could provide instantaneous data on flow direction and magnitude.

THEORY

The Doppler shift or frequency change that results when a transmitted wave is reflected from a moving object may be expressed as:

$$f_1 = \frac{fK(c+v)}{c-v} \quad (1)$$

where c is velocity of sound, f is transmitted frequency, f_1 is transmitted frequency shifted by the Doppler effect, c is positive when movement is towards the receiver and K is unity if the transmitter and receiver heads are identically located and the reflecting object moves in directions parallel to the transmitted wave. For other angles, the angular relationship of the transmitting and receiving heads to the direction of the reflecting object must be recognized in the formula. In the interest of simplicity, K combines these angular functions since our objective was not to prove the Doppler theory but study the meter characteristics.

The instrument is self-calibrating if f is held constant, K is accurately determined and c is known. Frequency is held to a 0.002% tolerance using a precision quartz crystal and instability is not a significant source of error. If a vane arrangement is used to align the instrument into the direction of current flow and the relative head angles are accurately measured, K becomes a known constant.

At a current speed of 2 fps an error in sound velocity determination of 5 fps results in an error of less than 0.002 fps in speed indication. When sound velocity is determined indirectly¹ the resulting errors introduced are shown in Table I.

Table I.

<u>Measurement Error</u>	<u>C Error</u>
Temperature: 0.036°F	0.18 fps
Salinity: 0.02 parts per thousand	0.086 fps
Depth: 5 feet	0.091 fps

The error magnitudes are in excess of those generally incurred in oceanographic tests.

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Superior numbers refer to similarly numbered references at the end of this paper.

Fig. 1. System block diagram.

INSTRUMENT DESIGN

The transmitter section consists of a crystal controlled oscillator driver whose output is matched to a barium titanate transducer. The receiving system consists of a broadband crystal controlled superheterodyne receiver, transducer, frequency meter (Model 41-7991, Airpax Electronics, Inc.) and tape recorder (Fig. 1).

Both the transmitting and receiving transducers were mounted on a head fixture which permitted variation of the "interocular" distance between the 2 units and experimental changes in the cross-over point. The rear surface of the 1-inch diameter transducer discs are air-loaded to eliminate back radiation. Theoretical beamwidth at $1/2$ power points at the operating frequency is given as 2°

$$\alpha = 1.22 \frac{\lambda}{D} \text{ radians} \quad (2)$$

where $\lambda = c/F$ and D is transmitter diameter. For the test instrument λ is 3.08×10^{-2} and α is 0.836° . The beamwidth measured in a tank has been found to be somewhat less than theoretical and minor lobes are at least 60 db down in amplitude.

A frequency of 5 Mcps was selected as a best compromise between achieving narrow beamwidth, ability to resolve small reflecting particles and high Doppler sensitivity vs. increased attenuation by the medium with high frequency. The 2 units of channellite 100 (barium titanate, Channel Industries) were found to have resonance peaks 30 Kcps apart and more careful frequency matching could undoubtedly improve the signal to noise ratio and further reduce the transmitter power requirement. A transducer spacing of 8 inches with a crossover point of 10 inches (Fig. 2) was

Fig. 2. Transducer positioning.

THE EXPERIMENT

Fig. 3. Receiver bandpass characteristics.

found to optimize the signal to noise ratio and minimize the effects of head turbulence.

Adequate frequency stability was obtained by use of 0.002% tolerance quartz crystals in both the transmitter and receiver. A drift of the receiver's local oscillator causes a shift in the received signals with respect to the IF bandpass but does not affect the instrument accuracy. Transmitter frequency drift effect is discussed in the section on theory.

The receiver is a 7-transistor circuit employing an RF stage, mixer, oscillator (crystal-controlled), 2-stage IF strip, diode detector and 2 audio stages. AVC was not incorporated in an effort to maintain system linearity. The IF amplifier was tuned as shown in Fig. 3 so that the carrier and upper IF sideband only were passed. This limited the instrument response to read current flow toward the transducer faces and reduced response to turbulent flow in one-half of the possible directions. A receiver sensitivity of 1 microvolt at 0.15 VPP output for a 12 db (S+N)/N ratio was achieved by the use of 70 Mcps cut-off PADT transistors (post alloy diffused. Amperex, Inc.) in the critical circuits. The receiver was powered by a 12 volt mercury cell.

The transmitter utilized a conventional crystal controlled vacuum tube oscillator. A variable voltage regulated power supply provided control of transmitter power input from 15 watts to less than 10 milliwatts. In practice, a power input of 45 volts at 6 milliamps to plate and screen of the oscillator tube was found to be optimum. The low impedance of the barium titanate transducer ($-j = 2$ ohms, $R < 2$ ohms) made it necessary to place it in series with the final tank circuit in order to transfer sufficient driving power.

No environmental housings were fabricated and the heads were fed remotely by means of coaxial cable. Under average sea reflectivity conditions, audio outputs of 0.1 to 0.35 VPP were obtained with a signal to noise ratio of 10:1. Higher signal to noise ratios can be obtained by closer transducer frequency matching and/or higher sensitivity crystals.

Several experiments during a one year period were conducted at the Institute of Marine Science laboratory dock in 8 feet of sea water. The head assembly was tripod-mounted 4 feet off the bottom and aligned parallel with the current flow. The heads faced toward the Bear Cut bridge 1,000 feet away and were 4 feet to one side of the dock pilings. Various head angles and crossover points were tried as well as positions parallel and normal to the current flow.

A series of tests was run in the towing tank at Stevens Institute of Technology and the output was tape recorded. The tank was 80 feet square with damping beaches and was filled to a depth of 4 feet with still fresh water in an air conditioned room.

Further tests were conducted off the west shore of Bimini, Bahamas, in 20 feet of water during slack tide when wind and current were nil. The transducer head assembly was tripod mounted 4 feet from the bottom and heads were successively positioned in all 4 quadrants, starting normal to the shoreline facing seaward. Various head spacings and angles were tried. The meter output was monitored and tape recorded.

Tests in the bay at Bimini off the Lerner Marine Laboratory dock were conducted with the transducers 8 inches from the surface in 2 feet of water. The heads faced into the current well forward of the dock pilings but 2 feet from an anchored barge. The water was clear and the surface was smooth. A small drifting wood chip was carefully timed over the length of the barge to get an approximate flow velocity. Tapes were made of the meter output. The head spacing was 8 inches with a crossover of 10 inches.

ANALYSIS

Three principal types of equipment were used for readout. An Airpax magmeter read frequency of the Doppler shift. Integrating time constants were varied from 0.25 second to 4 seconds in 0.25 second steps. A 4-second integration gave the most stable readings. A Panoramic sonic analyzer, Model LP1A, was used for spectrum analysis using one second duration and 0 to 20 Kcps log frequency sweeps at linear amplitude settings. Relative amplitude relationships were studied. A Tektronix oscilloscope, Model 535, was used to display output wave shape and frequency.

Tests were recorded on magnetic tape and analyzed. A 4-second tape loop was made of a representative portion of each test. Successively 1, 20 and 40 sweeps were recorded on the analyzer. Single sweeps at rates of 1 and 2 cm per second were recorded on the scope and magmeter readings at 4 seconds integration time were noted. In addition, 15 and 60 consecutive one second sweeps were taken of continuous segments of the

a.

b.

c.

d.

Fig. 4. Tests at Institute of Marine Science dock May 1961 to February 1962: (a) oscilloscope, single sweep, 1 ms/cm, (b) Panoramic, 20 sweeps, 4 second tape loop, (c) Panoramic, 16 sweeps, continuous segment and (d) Panoramic, 60 sweeps, continuous segment.

original tapes. In general, the audio output of the Doppler meter fluctuates considerably due to flow velocity variation and the number of scatterers in the reverberation volume. Under violently turbulent conditions the frequency meter reading was fairly stable.

Examples of extremely turbulent flow can be observed in the records taken from the Institute of Marine Science dock. Many local eddies were observed visually around the pilings and large swirling patterns from the Bear Cut bridge extended to the dock. The Doppler shift frequency, converted to an audible signal, sounded complex and resembled wind in blizzard conditions. When the transducer heads were positioned normal to the general current flow appreciable

Doppler shift was still produced, signifying turbulent conditions. With head parallel to current flow a complex wave structure was generated (Fig. 4a) and the frequency spectrum was broadband with no well defined "peak" (Figs. 4b, 4c and 4d).

The current meter output was recorded during tests at the Stevens Institute tow tank. No Doppler shift was produced until the transducers were mounted 2 inches from the surface and the towing arm crossed its own wake on its second and subsequent revolutions. Low frequency fluctuations modulating the sinusoidal output were caused by the motion produced wavelets (Fig. 5a). The frequency spectrum of the signal is narrow after a 1-second signal sweep (Fig. 5b). There

a.

b.

c.

d.

Fig. 5. Tests at Stevens Institute towing tank on 3 June 1962: (a) oscilloscope, single sweep, 0.2 ms/cm, (b) Panoramic, single sweep, 4-second tape loop, (c) Panoramic, 16 sweeps, continuous segment and (d) Panoramic, 60 sweeps, continuous segment.

is no appreciable broadening after 16 consecutive sweeps (Fig. 5c) and there is still a sharp frequency spike after 60 consecutive sweeps (Fig. 5d).

An interesting phenomenon was noted in the offshore Bimini tests where the sea was essentially still. The meter output was zero except when long gentle swells produced a Doppler shift output coincident with the below surface orbital motion. There was a poor signal to noise ratio (Fig. 6a). A broad plateau contains the entire forward range of the orbital water motion caused by the swell (Fig. 6b, 6c and 6d) except for the frequencies below 50 cps which were cut off by the combined tape recorder and spectrum analyzer response.

Frequency meter indications were generally lower than those of the Panoramic analyzer because the instantaneous "peak" frequency is not as well defined or densely distributed in time as appears on a well integrated record.

Tests at the Lerner Marine Laboratory dock, where near zero wind speed and seemingly low turbulence conditions prevailed, show a more complicated wave structure than produced in the tank (Fig. 7a). Note the broader structure and some sidebands of Fig. 7b in contrast to Fig. 6. The sidebands were caused by turbulence and/or instantaneous variation in flow velocity (Fig. 7c). Additional integration time produced a somewhat denser version (Fig. 7d) and the low frequency peak is due to reflections from a barge riding at

a.

b.

c.

d.

Fig. 6. Tests offshore from Bimini on 27 June 1962: (a) oscilloscope, single sweep, 2 ms/cm, (b) Panoramic, 20 sweeps, 4-second tape loop, (c) Panoramic, 16 sweeps, continuous segment and (d) Panoramic, 60 sweeps, continuous segment.

anchor a few feet from the current meter. Very little Doppler was noted when the heads were placed normal to the current flow. Magmeter readings were reasonable compared to the current velocity measured by timing a floating chip.

CONCLUSIONS

The Doppler current meter described will provide a sensitive and accurate sinusoidal output for measurements of a unidirectional, turbulence-free current containing particulate matter such as would exist in a properly designed flow tube. A meter based on the Doppler shift principle was described in a paper by Chapulnik and Green.³ Their experiments indicated that this instrument

was well suited for measuring unidirectional, constant-velocity current flow.

Since this meter is non-inertial, it responds to rapidly changing irregularities or turbulence in the medium. Most mechanical meters read the average or integrated gross water movement past them and smooth out these irregularities. It is possible by analytical or electronic means to effect integration of the output Doppler meter; however, to do so suppresses the capability of this device to resolve instantaneous turbulent flow. In a highly turbulent flow where complex sidebands are produced, flow determination becomes difficult, but there is reason to believe that with a proper choice of integration time constants

a.

b.

c.

d.

Fig. 7. Tests at Lerner Marine Laboratory dock, Bimini, on 28 June 1962: (a) oscilloscope, single sweep, 1 ms/cm, (b) Panoramic, 20 sweeps, 4-second tape loop, (c) Panoramic, 16 sweeps, continuous segment and (d) Panoramic, 60 sweeps, continuous segment.

this instrument will produce no greater error than do other integrating types.

Analysis of the frequency spectrum exhibits a predominant frequency which corresponds to the primary or average flow component and other side-band frequencies that are proportional to the product of the direction cosines and velocity of turbulent flow. The major contributing component is comparable to a carrier frequency and the turbulence to modulation sidebands. In order to exploit the instrument's sensitivity to turbulence it could be designed to operate in three planes with simultaneous velocity and direction sensing sections, suitable for tape recording, that would give the mean and turbulent components of motion in each coordinate direction. High

sampling rates can be used for obtaining an extremely fine structure.

Tests in the towing tank, which represented an apparently homogeneous particle-free environment, confirmed the requirement for the presence of particulate matter for reflection of the acoustic beam. Tests in the ocean off Bimini demonstrated the ability of this instrument to respond to water particle motion induced by swells in an otherwise currentless environment. Another application to be explored is a 2-plane instrument mounted on a free drifting neutrally buoyant float. It would read only turbulence components because current flow would be cancelled by the float drift.

Future investigations will include consideration of the characteristics of the reflecting particles and a rigorous mathematical analysis of the output signal.

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PRACTICAL PROBLEMS IN THE DIRECT MEASUREMENT OF OCEAN CURRENTS

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ABSTRACT

The motion of water in the sea is a complex of turbulent, oscillatory, sporadic and steady movements with wide scales of size, velocity and period. All of these vary with wind, season and year and generally decrease in magnitude from the surface downward. Attention may be concentrated on various aspects of the motion by taking measurements which are time-integrated with appropriate time constants. In many situations the integrated mean vector is much smaller than peaks of the instantaneous velocities and may have little correlation with the instantaneous direction. Attempts to deduce mean velocities from measurements having too short a duration may lead to large errors. The current meter of most general utility would be one which can be kept in place continuously to record continuously on as short a time scale as is feasible.

Current meters are subject to many errors due to undesired motions of the flexible supporting cable and the supporting platform. These errors are described and estimated. Existing current meters are of severely limited value for any but the grossest measurements when the suspensions must be long, relatively flexible or disturbed by waves. Periodic stray motions could be removed by vector-integration either in the meter or at a later date on the record, but with consequent serious deterioration in the representation of real changes of similar period. Small systematic errors accumulate to such important magnitudes in long integrations that meters having accuracy, rapid response and faithful integrating characteristics in a high degree are required.

INTRODUCTION

The direct measurement of ocean currents appears simple, perhaps because current meters are relatively simple and because current meters are described in text books and in the literature well dissociated from any mention of practical field problems. It is to dispel this fallacious idea of simplicity in the minds of the many new instrument designers entering the field of oceanography that this paper is written. It will be shown that the measurements of currents by means of conventional meters suspended from ships, buoys or other platforms are

seriously distorted in many ways due to the stray motions induced by the platform and supporting cable as well as the imperfect response of the meter to the resulting transients and to the real transients which exist in the sea. Some of the information to be presented has appeared incidentally and in a qualitative way mostly in scattered papers describing successful series of current measurements at sea. It is hoped that the present more unified and semi-quantitative discussion will be a stimulus to the design of equipment and techniques which will be useful in the era of unattended instruments which is now beginning.

The discussion will treat specifically those current meters whose velocity element is a rotor but it may be applied with little modification to other types, such as those having pressure plates, tilting bodies or acoustic paths as sensors. The emphasis will be on depths and velocities typical of the open sea but will apply also to estuarine motions in which the problem has not become grossly simplified by the shallowness of the water.

The problem of current measurement cannot be attacked in the abstract. Instead it must be faced in relation to conditions which exist in the sea and to that aspect of the complex motion which it is desired to study. For this reason the discussion will begin with a general description of the types of motion in the sea in relation to the portion of the motion which the experimenter may wish to extract.

DISCUSSION

Types of Motion in the Sea

The net motion of water in the sea may be considered as a system of average established currents upon which are superimposed transients that may be slowly changing and with a size scale of thousands of miles. At the other extreme is the random motion of turbulence of a size scale smaller than we care to deal with now and a time scale correspondingly short. There are motions which are periodic, such as those of tidal period, inertial rotations and currents associated with surface and internal waves. Others are more or less random, such as the wind driven transients and the various scales of turbulence.

There are regions of strong currents, such as the Gulf Stream, in which mean surface velocities rise to several feet per second (fps). The superimposed macro-turbulence has velocities with magnitudes a large fraction of the mean and directions vary through the full rotation of the compass. In much of the ocean, established currents have mean velocities of the order of a few tenths of a foot per second and there are large areas in which the mean may be measured in hundredths of a foot per second. In areas of weaker surface current the winds are often the chief disturbing influence and, since wind-driven water velocities may approach 2% or more of the wind velocity, a situation can exist in which the instantaneous velocities are many times larger than the mean and the direction of flow has little relation to the mean direction.

Surface waves commonly have periods in the region of 4 to 25 seconds and heights reaching 50 feet or more. Heights of 6 to 12 feet are common. The particle velocity in the wave is quasi-sinusoidal and, at the surface, has a peak velocity equal to the velocity of a particle rotating uniformly in a circle of diameter equal to the wave height and making one complete rotation during one wave period. In a 12-foot wave of 10 seconds period, the particle velocity is then 1.2π , or 3.77 ft/sec. This motion may affect near-surface meters directly or may introduce stray motion into the surface-floated supporting system. The particle motion decreases rapidly with depth in proportion to $e^{-2\pi Z/L}$ where Z is the depth and L the wavelength.¹ Thus, for a decrease in depth equal to 1/9 of a wavelength, the orbital diameter decreases by one-half. For the 10-second wave in deep water the computed wavelength is 512 feet; the particle velocity would have decreased to one-half at 57 feet of depth and to 1/512 at 512 feet of depth. Under these conditions a meter or buoy even at a depth as shallow as 228 feet (4/9 of the wavelength) would experience an orbital velocity of only 0.23 knots. In the presence of a long high swell this would not be true.

Water velocities are generally considered to decrease with depth, at least down to some depth at which velocities are relatively small. This is a plausible conclusion where the driving forces are the winds at the surface. However, there are circumstances in which the decrease with depth is followed by a reversal and an increase to velocities comparable to those at the surface. Two such cases are the Cromwell Current in the Equatorial Pacific and its counterpart the Atlantic Equatorial Undercurrent. Some driving forces, such as the tides, the moving atmospheric pressure disturbances or the long waves of tsunamis, make their relatively small contributions nearly equally at all depths with magnitudes of the order of 0.1 fps. There is always the possibility that such deep-acting forces may cause more important velocities by convergence into deep narrow channels between islands or

between seamounts. Sporadically, in some areas having sufficient bottom slope, turbidity currents will flow along the bottom with velocities reaching 15 fps or more.

Then there are the massive, but extremely slow, thermohaline circulations of the deep ocean water generated in the Antarctic and Arctic by the sinking of surface water made more dense by cooling and partial freezing. The velocities of these flows average at most a few hundredths and perhaps a few thousandths of a foot per second, but the few direct measurements which have been made in deep water have shown transient velocities of as much as 0.7 fps and directions having little relation to the indirectly deduced mean.

The Need for Direct Current Measurements

For many years the velocities and patterns of average ocean currents have been deduced by two principal methods: (1) the statistical treatment of the reported deviations of naval vessels from their courses and (2) indirect computation by application of the geostrophic equation to the experimentally (and indirectly) measured density field. The first method is inaccurate and yields only surface currents. The second gives some information about mean velocities at all depths in deep water but fails near shore. The determination of flows at great depth is strongly dependent on the choice of a depth of no net motion which still must be determined by methods which are theoretical and not well supported by experiment. Both methods produce means with a summing period of one or more weeks and give little or no information about transients of shorter period.

A determination of mean velocities is useful and the geostrophic method has advantages but it is now necessary to check its validity by experiment and supplement the findings where the method is known to be weak. In the vast regions where transient velocities in the sea are many times greater than the mean it can be seen that many processes probably have little relation to mean velocity. Examples of such processes are the transport of sediments, the mixing of water masses and the transport of plankton and fish. The understanding of these processes awaits an adequate description of the transients.

The Experimental Problem

With the above outline of the complexities of motion in the sea it is now possible to look at the practical problems in current measurement. These will be considered in two senses: (1) the design of the experiment and (2) the design of measuring equipment and suspensions.

The two elements in the design of a current measuring experiment which are most often poorly done are: (1) design of the experiment to

¹Superior numbers refer to similarly numbered references at the end of this paper.

extract from the complexities of motion those components which are of interest for the purpose at hand and (2) sufficient distribution of the measurements in time and space. Attention often must be concentrated upon a particular component of motion because the entire field of motion is too complex for present understanding or because a current meter designed for one range of velocities may not function in a range which is grossly greater or smaller. A current meter designed for measuring the particle velocities of waves may be of little use for general purposes and one which might measure the low velocities in deep water may not serve at higher velocities. Furthermore, one must understand what he wants. When near-surface measurements are made, either by drift bottles or with the GEK, the result obtained is sensitive to a few feet difference in the depth of immersion of the measuring device. There has been a tendency to dismiss as inaccurate those measurements made quite near to the surface, explaining the errors as due to "windage." The writer believes that such differences likely represent real gradients in velocity with which we are not yet prepared to deal. We are more comfortable describing currents which represent greater volumes of flow or which are representative of the forces acting on more deeply immersed objects like ships or buoys.

If a mean is desired then the period of measurement must be long enough to obtain a good mean and if the result is to represent a volume rate of flow over a large section, the complete section must be investigated in width and depth with due regard to the variations caused by weather and other variables. Too much wishful thinking has been done of the type which purports to describe a sine curve by means of one point measured at random.

Exploration, of course, is legitimate and necessary. What is objectionable is any tendency to assign wide validity to isolated measurements.

THE ERRORS IN CURRENT METERS HUNG FROM A SHIP OR BUOY

To again clarify the limitations placed on this discussion it is emphasized that attention is being concentrated on current meters which can be suspended from a ship, buoy or other platform. For convenience, considerations are limited to meters whose velocity sensors are rotors but the same principles apply, almost without exception, to other types of meters similarly suspended. Other devices such as the geomagnetic electrokinetograph, parachute drogue and Swallow float are omitted. These still have their spheres of usefulness but at present they appear too slow, inaccurate or expensive (in terms of ship time) to solve the problem of measuring transient flows in the detail which will be necessary in the future. No attempt will be made to catalog the various types of current meters as this has been done by a variety of investigators.^{2,3,4}

It is scarcely necessary to point out that the current meter, even in ideal behavior, measures only the water motion relative to it so relative motion of the meter introduces an error. If the direction element fails to respond precisely another error results. These errors are discussed under two somewhat overlapping headings: (1) those errors which can occur without any motion of the supporting platform and (2) those due to motions of the support in company with failures of the meter and its suspension when exposed to rapidly changing flows. The latter have been called "dynamic errors."

ERRORS WHICH CAN OCCUR WITHOUT MOTION OF THE PLATFORM

The errors in current meters hung from a ship or buoy arise mostly from the motions of the platform but there are at least 5 sources of error even if the platform is fixed. These are: (1) distortion of the near-surface flow by the platform, (2) deviations of a magnetic compass in the meter by iron on the platform, (3) elasticity and hence distorted response of the long suspension, (4) dynamic errors of the current meter itself and (5) indirect error which results from the error in depth due to wire-deflection when the meter carries no depth element.

The first error may readily be demonstrated by simultaneous comparison of current meters near the bow and near the waist of a vessel, or of meters on opposite sides of a vessel, at depths less than perhaps 2 or 3 times the ship's draft. It requires little imagination to picture a variety of distortions due to the large body of the ship at various angles relative to the current. Such effects may extend laterally for distances of the order of one ship's length as one quickly discovers when using a drift-pole paid out on a measured line from the stern. The effects are particularly serious in small currents (less than one knot) when wind and the yawing of the vessel may make the vessel lie at a sizable angle to the current. In measurements made from a freely drifting vessel the distortions may be less serious unless there are important velocity gradients in the sea between the surface and twice the depth of the keel or the vessel is drifting rapidly with respect to the water.

The deviations of a magnetic compass by iron on the ship are well known. Yet, meters containing magnetic compasses have been used blithely, close to the vessel, with no determination of the errors. Errors up to 12° in the indications of a current meter hung near the surface at the stern of the wooden vessel BROWN BEAR have been demonstrated.⁵ On steel ships the errors are much more serious. The writer has found errors of the order of 100° at a depth of one-quarter ship's length and 2 keel depths below the surface on a 275-foot ice-breaker.

The effects of a long suspending cable are a time lag in the response to changes in current

and an attenuation in the peaks of the recorded flow. A more important contribution to the same effect is introduced by the elasticity of the moorage. This subject as well as the dynamic behaviors of current meters will be discussed below under "Dynamic Errors."

The problem of error in depth is more or less self explanatory. Its importance depends upon the gradient of velocity with depth and would be especially serious in situations where there are relatively sharp changes, as in the region of the Cromwell Current.

DYNAMIC ERRORS

The dynamic errors associated with current meters have been classified into 5 types: (1) those due to slow, more or less random movements of the platform, (2) those due to the elasticity of long suspensions and the elasticity and slack in moorings, (3) those due to dynamic failures in the meter itself which prevents the accurate following of rapid transients, (4) those due to pendulous or elastic-cord types of oscillation of the suspension excited by the rolling and heaving of the platform or by turbulence and (5) those due to vertical motions of the meter.

Effects of Slow Movements of the Platform

The effects of slow movements of the platform will be discussed first. Platforms anchored on the surface on relatively long and elastic anchor lines undergo a complicated cycle of motions even in constant currents. There is the oscillation about a center near the bow, called yaw, oscillation about a center near the anchor, called swinging, both superimposed upon a fore-and-aft (riding) movement due to cyclic tightening and relaxing of the anchor cable. The platform moves with each change of current and with each gust of wind. The current meter dangling below on a wire experiences these motions with some time delay and attenuation due to the elasticity of the suspension.⁶ In depths of 100 meters or less, on small vessels the writer has found yaw, swinging and riding nearly small enough to ignore at velocities of one knot. In deep water with larger ships and different weights and scopes of anchor wire this conclusion might well require modification. A long series of observations has been made on the ARMAUER HANSEN in depths of 1,800 to 4,000 meters. cursory examination of these data shows fluctuations in the bearing of the anchor cable of the order of one or two degrees at water velocities approaching one knot, whereas in more common conditions when velocities were about 0.5 knot the scatter is about $\pm 5^\circ$. More extreme fluctuations occurred at lower velocities.

Consider the spurious error due to yaw alone calculated on the assumption of a swing of $\pm 5^\circ$ during a period of about 2 minutes at a point 100 feet from the bow of a 140-foot vessel and

assuming a sinusoidal variation in the velocity of yaw. It is found that the amplitude of yaw is ± 9 feet and the spurious velocity at the middle of the yaw is 0.25 fps. The use of a buoy as a platform will reduce the yaw greatly. Swinging and riding still remain, however, and it is likely that their combined effects are at least comparable to the velocity calculated above. A strong and gusty wind blowing across the direction of current flow can severely accentuate the motion of the ship at low water velocities.

Reduction in Dynamic Response Due to the Elasticity of Long Suspensions

The discussions of this section apply equally well to the effects of rapid stray motion at the top of the current meter suspension and to the dynamic response of the meter and its long suspension to real transients in the flow. It will be shown that long suspensions buffer the current meter against short rapid movements of the platform but diminish the ability of the meter to record transients in the velocity at depth. The response of a current meter to a step-change in velocity is derived first.

Table I shows the time required to attain 90% response to a sudden 20% increase in velocity for a typical current meter suspended on a light wire under a number of conditions. The initial wire angle also is shown to give some feeling for the depth error involved. The velocity of 3.0 fps at 10,000 feet is admittedly unrealistic, but the reciprocal situation of currents being measured from a ship drifting at 3.0 fps is quite a real possibility.

Table I has been calculated by a gross simplification of a complex problem. The meter area and weight have been lumped together with the area and weight of the lower third of the wire and assumed concentrated at the resulting center of area, at which point the water is presumed to act. The remainder of the wire is assumed weightless and without drag. The waterforce has been taken proportional to the square of the slip velocity and the drag coefficient as unity. The meter and terminal weight together are taken to have a frontal area of one square foot and a weight in water of 150 pounds. The supporting wire is assumed to have a diameter of 0.1875 inch. Inertial forces are neglected and the velocity of the meter at any time is taken as the difference between the new water velocity, v_2 , and the slip necessary to maintain the wire angle, θ , at that instant.

The slip is given by

$$v = \sqrt{\frac{k \tan \theta}{\cos \theta}} \quad (1)$$

Table I. Wire angle and times for 90% response in current meter subjected to a step increase in velocity of 20%.

Initial Velocity ft/sec	0.3		1.0		3.0	
Wire Length ft	θ_0 Degrees	t Sec	θ Degrees	t Sec	θ_0 Degrees	t Sec
100	0.05	1.6	0.6	6	5.0	17
300	0.09	9.	1.0	28	8.5	83
1000	0.2	59	2.0	193	16.5	420
3000	0.4	450	4.8	1420	32.3	1340
10000	0.8	2600	8.6	8500	44.5	3120

and the horizontal velocity of movement of the meter by

$$\frac{dx}{dt} = 1.2 \sqrt{k \frac{\tan \theta_0}{\cos \theta_0}} - \sqrt{k \frac{\tan \theta}{\cos \theta}} \quad (2)$$

where $k = \frac{2gW}{\rho C_D A}$

W = weight of meter + terminal weight
+ lower third of cable in water, lbs,

ρ = density of sea water, 64 lb/ft³,

C_D = drag coefficient, assumed 1.0,

A = area of meter + weight + lower third
of cable, ft²,

θ = angle wire makes with vertical,
radians, and

θ_0 = initial wire angle.

The current meter is able to sense only the slip, which at time zero is the initial velocity, v_0 , and approaches 1.2 v_0 asymptotically.

To solve the above equation for time, t, dx is replaced by its equivalent $L \cos \theta d\theta$ where L is the wire length. The time to attain a given wire angle is

$$t = \frac{L}{\sqrt{k}} \int_{\theta_0}^{\theta} \frac{\cos \theta}{1.2 \sqrt{\frac{\tan \theta_0}{\cos \theta_0}} - \sqrt{\frac{\tan \theta}{\cos \theta}}} d\theta \quad (3)$$

For 90% response, θ is chosen as the value corresponding to $v = 1.18 v_0$. This equation is integrated numerically for angles greater than 10°, but at smaller angles it may be approximated by the equation

$$t = \frac{L}{\sqrt{k}} \int_{\theta_0}^{\theta} \frac{d\theta}{1.2 \sqrt{\frac{\tan \theta_0}{\cos \theta_0}} - \sqrt{\frac{\tan \theta}{\cos \theta}}} \quad (4)$$

which, on numerical integration, gives

$$t = \frac{5.4 L \sqrt{\theta_0}}{\sqrt{k}} \quad (5)$$

The times for 50% response are about 0.27 as great and for 95% response are 1.3 times greater.

From Table I it may be concluded that there are severe restrictions on the ability to detect short term transients when using long suspensions. For placement of deep current meters one would prefer to fasten the meter in the span of a taut-wire mooring with a stiffness much greater than that corresponding to 150 pounds of buoyancy. The buffering offered to deep current meters against short term fluctuations of the surface platform is evident.

It is of interest that the most important contribution to the area in the preceding calculation comes from the wire itself. Table II shows the areas and weights of wire used in the preceding problem. Since the times increase in proportion to the wire diameter, every effort should be made to keep the suspending wire as small as possible if excessive lag times and wire angles are to be avoided.

Table II. Cable weight and area contributing to the time constant of a current meter suspended on 3/16-inch wire rope.

Length, ft	100	300	1,000	3,000	10,000
Weight lower 1/3 of cable, lbs	1.6	4.9	16.3	49	163
Area lower 1/3 of cable, ft ²	0.5	1.6	4.7	15.6	46.8

Fig. 1. Conventional mooring features of surface vessel platform.

Effect of Elasticity and Slack in the Mooring

The mooring inevitably has elasticity; often by design in order to absorb shock loadings. When the mooring line is heavier than water the elasticity is in the catenary. If the line is synthetic fiber rope it is mostly in the elasticity of the material. Typical situations are shown in Figs. 1, 2 and 3 for 4 types of mooring: (1) a ship or buoy anchored in 300 feet at a scope (ratio of line length to depth) of 3:1 shown in Fig. 1(a), (2) a surface platform in 6,000 feet of water at a scope of 1.1/1 shown in Fig. 1(b), (3) conventional taut-wire moor in the same depth (Fig. 2) and (4) the taut-rope moor now being used by W. S. Richardson at Woods Hole Oceanographic Institution (Fig. 3). The diagrams for the first two are self-explanatory.

In the taut-wire moor, the deviation of the submerged buoy will vary with the constants of the system. The wire angle has been estimated at 1° for a buoy of 500 pounds net lift and

12 square feet cross-section on 3/16-inch wire rope at an assumed velocity of 0.5 fps when negligible drag is contributed by the surface float. This is a conservative assumption since it is often difficult to keep the drag of the surface float as small as that of the submerged float. Actual knowledge of the instantaneous velocities at 150 feet depth is sparse indeed. Frequently at some locations, and perhaps occasionally in many, the velocity certainly will exceed 0.5 fps. The degree of restraint on the motion of the surface float with respect to the buoy depends upon whether or not the upper mooring line is heavier or lighter than water. If distinctly heavier, a catenary forms and there is a corresponding restraint shortly after the surface platform moves away from vertical alignment with the submerged buoy. If the line is nearly neutrally buoyant there is little restraint until it is stretched taut.

To obtain a feeling for the kind of distortion in the measured current due to slack and elasticity, the simple case of a purely sinusoidal

Fig. 2. Platform moored to submerged buoy at 150 feet in 6,000-foot water depth with upper mooring scope of 3:1.

Fig. 3. Richardson toroidal buoy on taut elastic propylene rope.

Fig. 4. Distortion of surface tidal current by elasticity and slack in the moorage.

reversing current of semi-diurnal period has been considered. To suit the shallow water case the peak velocity has been taken as 1.0 fps while for deep water the more reasonable value of 0.5 fps is taken.

Fig. 4 shows the kind of distortion to be observed for the two simple moorings. In the shallow water case the analysis is simple. Shortly after slack water the elastic extension of the mooring has been relaxed and the platform is free to move with the current for a distance equal to twice the slack in the mooring. In the simplified case there is no relative motion between platform and water during this period and the current meter registers zero. Rather abruptly the mooring line begins to tauten and the apparent velocity rises sharply. The rise is sharp because the elastic extensibility of the moorage is small compared to the total excursion of the water during one half-cycle (252 feet versus 13,770 feet). The measured velocity never does reach the peak velocity because some elastic extension of the moorage is continuing at this point. When peak velocity is past, the moorage begins to relax and moves the platform against the current to maintain the apparent velocity higher than it should be until after the true velocity has reached zero. The cycle then repeats in the opposite direction.

In the deep water moorage the total water transport in one half-cycle is 6,885 feet and the elasticity amounts to 2,750 feet in addition to the 1,200 feet of unrestrained motion. The result is to attenuate the apparent peaks quite severely. The 1,200 feet of slack contributes its period of apparently zero velocity as before. The degree of attenuation and phase lag depend greatly on the stiffness of the mooring so the diagram in this case must be regarded as illustrative rather than in any degree quantitative.

No attempt has been made to derive the more complex response of the taut-wire mooring since there has been so little standardization that it is more difficult to put plausible values on the constants of the system. However, the response will differ only in degree from those illustrated. If the submerged buoy has a large buoyancy compared to the drag forces on the lines and surface float, it is likely that it may be the most rigid system, even for a meter near the surface. For a meter at the submerged buoy or in the span of the taut wire it definitely has an advantage. No analysis of Richardson's system is offered since the extensive experimental results now forthcoming from current meters on this moorage will form a better basis for an analysis of errors. This system may compare favorably with the taut-wire mooring.

It can be seen from the above that phenomena occurring when the moorage is slack are completely lost. Those velocities which occur during the elastic stretching of the moorage are attenuated and shifted in phase to a degree directly related to the ratio between the effective extensibility of the moorage and the linear transport of water during a half-cycle.

Rotary motions also are subject to similar distortions. If the radius of the streamline of rotary motion is less than that of the stretched moorage the motion is lost, except for any effect of the drag of the cable on the bottom. If the radius of the true motion is somewhat larger only a fraction of the velocity and transport will be observed.

A more hopeful situation exists if there is a relatively steady current, involving large transports, upon which the fluctuations are superimposed. If the moorage is stretched so as to remove most of its elasticity it will yield relatively little to fluctuations along the line of the moorage and these fluctuations may be fairly faithfully represented. Lateral components involving small transports, however, will be severely attenuated or absorbed. It is easily demonstrated that a moorage stretched to a radius of 1,000 feet under a current of 1.0 fps will respond to a small change of direction at a rate which will attain 90% of the change in 2,300 seconds or 38 minutes, during which time the direction record in the meter changes correspondingly slowly.

All of the stray motions which have been described in this section are slow enough for the meter to accurately register the relative velocity with the consequent advantage that the integral of all cyclic transports is zero over one cycle so that the distorted velocities at least can be removed from the results. In the next sections effects will be treated which do not sum to zero and which can contribute to spurious determinations of long term transports or average velocities.

Meter Response to Rapid Changes in Horizontal Motion

Rapid transient horizontal motions, real and artificial, are presented directly to the current meter by wave motion or indirectly by wave induced platform movement or natural turbulence of the water. Current meters are subject to a number of spurious responses and response failures which can lead to some confusion. Again the effects are the most serious when the real currents or their means are small compared to the real or artificial transients.

When a surface-floated platform rides in the waves it undergoes complex motions due to the waves. It is subject to the particle motion of the waves which moves the platform back and forth with wave period. This motion, combined with the restraint of the moorage and the rolling of the platform moves the current meter suspension back and forth or, more generally, in a small highly irregular loop, usually elongated. The effect is amplified if the meter is suspended from a boom extending far from the metacenter of a ship. This motion, insofar as it is transmitted to the current meter, is undesirable. If the meter responded accurately the motion could be recorded and integrated to zero. For various reasons the current meter does not respond accurately. The errors may be classified as due either to failure in directional response or non-ideal velocity response. Both will be treated as though the suspension were fixed and the water fluctuating but the treatment applies equally well to the reciprocal situation. Failure in directional response will be illustrated by reference to two general types of current meter. One has a propellor-like rotor intended to be exposed to the current from the front only and it carries a tail fin or other orienting device to turn the entire meter to face the current. The other has a rotor presumed equally sensitive to flow from all orientations, e.g., the Savonius rotor. Direction, if obtained, is derived from a light vane, of short time-constant, rotated with reference to an internal compass.

In the first type of meter there is a definite limitation in directional response. Take for example a meter with a flat tail fin and the center of the fin at a radius, r , from its center of rotation. This meter is subjected to a step-wise reversal of velocity at magnitude, v , and lies with an angle between the source direction of the current and the projection of the meter axis through the tail fin. On a flat fin it may be assumed that the component of the velocity normal to the fin turns the current meter with no slip and no inertial forces. The normal component, of course, is zero when the meter is at 0° and 180° incidence, which is unreal because it leads to an infinite period of rotation, whereas the tail fin is certainly started on its way in these indeterminate regions by stray motion or turbulence. A more realistic estimate may be obtained by integrating the equation between limits of 3° and $\arccos 0.632$; the latter a not

Fig. 5. The Ekman current meter.

Fig. 6. Response of current meter with tail fin to rapidly reciprocating current.

strictly justifiable simulation of a condition of 63.2% response. Then

$$-\frac{r}{v} \int_0^{129^\circ} \frac{d\phi}{\sin\phi} = \int_0^t dt \quad (6)$$

and

$$t = \frac{r}{v} \log_e \tan \frac{\phi}{2} \quad \left| \begin{array}{l} 129^\circ \\ 3^\circ \end{array} \right. = 3.8 \frac{r}{v} \quad (7)$$

If we use a velocity of 1.0 fps and a radius, r , of 20 inches, corresponding to the Ekman current meter shown in Fig. 5, we obtain a time constant of 6.3 seconds. During part of the period water flows through the meter backward. In the Ekman meter reverse turns are subtracted but in most electrically registering meters the rotor has no directional discrimination and the registration of velocity is always positive. Current meters with small radii of rotation and those with hydrofoil sections for tail fins will have better characteristics. Particularly good is the Von Arx current meter⁶ which uses two Garbell fins on either side of a cylindrical body and probably the most satisfactory device is a small sensitive direction vane such as used in the Snodgrass meter.⁷

A practical problem is to inquire what happens to a meter like the Ekman meter in the continually oscillating currents in waves near the surface, which is similar to the case of a rapidly fluctuating suspension. The calculation requires only minor modification to that above but is sensitive to the boundary conditions. Here it is assumed that the meter will carry out a symmetrical rotary oscillation reaching a maximum conformity to the current direction at the end of each half-cycle.

The results of this calculation are shown in Fig. 6 for the Ekman current meter in a reciprocating current corresponding to the particle velocity of 5-foot sinusoidal waves at the

surface. It is interesting that the result is independent of the period of the wave and depends only on the ratio of wave height to the radius of rotation of the meter fin. In Fig. 6 the apparent velocity is shown as negative when the water flows backward through the rotor. In this idealized case the Ekman meter would sum current flow to zero in one cycle whereas electrically registering meters would count all the flows as positive although the independently registered direction, if it were registered continuously, would give indication of a spurious result. Discrete registrations of direction could lead to confusion, depending on the frequency of sampling. Unfortunately, the real situation is worse since most meters are not equally sensitive to forward and reverse flows and the time-integral of velocity will not be exactly zero even if direction could be properly incorporated. Rapidly responding meters will behave much better. The negative excursions of the apparent velocity will be smaller and the orientation of the meter will be near 0° and 180° during a larger fraction of the cycle. Such meters, however, will not be immune to the accumulation of apparent flow registration due to their front-to-back asymmetry and the many times repeated oscillations.

Integration of such cyclic fluctuations to zero over an integral number of complete cycles theoretically is possible if the velocity sensor is equally sensitive from all directions, the direction sensor extremely rapid in response, and the sampling sufficiently frequent. In the general case, in which fluctuations are rotary, it is necessary to carry out vector-integrations continually, either in the current meter itself or from the record at a later date. This requires that the velocity and direction be associated as vectors. If they are dissociated, it generally is impossible to integrate.

Of existing current meters, the Snodgrass meter (Fig. 7) in its continuously recording form is closest to having the desired characteristics

Fig. 7. The Snodgrass current meter.

although the actual integration from the velocity and direction records would be impossibly tedious in practice. Richardson's modification of the Snodgrass meter, with its digital recording system, may provide a solution but it remains to be proved that the discrete sampling is being done at a sufficiently high frequency. No suitable internally-integrating meters are known.

Errors Due to Pendulous, Elastic-Cord and Rotary Types of Oscillation

Pendulum action is an effect which is not well documented. One worker reported observing unexpectedly high apparent currents at depths of the order of 100 to 200 meters which he believed due to such resonances. A calculation of resonant lengths shows a suspension 100 meters in length resonant to a 20-second period. However, the period of ship's roll is in the region of

5 to 10 seconds, corresponding to lengths of 20 to 80 feet, and one would anticipate a greater likelihood of resonances in this region. The increased damping of greater wire lengths also diminishes the likelihood of long-period resonances. Meters mounted in the span of a taut wire generally will be more stiffly supported and responsive to shorter periods. Experimental work would be desirable to detect such phenomena.

Another form of error due to a short rapid pendulous motion is "jitter," a situation occurring when an electrically registering rotor is stalled or almost stalled on the contact. The pendulous motion causes the rotor to oscillate back and forth across the contact, producing rapid contact closures which are seen as rapid forward motion by the registering mechanism. Richardson has pointed out that a related but not so serious behavior occurs with current meters in his mooring system.⁸ Apparently there is a rotary oscillation of the cylindrical current meter body about the rotor caused by surges which induce torque gradients in the helically-laid supporting rope. Fortunately, the register that counts turns is in a form which permits the excess counts to be detected. There is a suspicion that such rotations may affect the reference compass and cause errors in direction. Richardson also points out that the Russian practice of mounting current meters on an arm projecting from the supporting cable must exaggerate errors due to cable rotation.

Errors Due to Vertical Motion

The errors due to up-and-down motion of the current meter arise from 4 causes: (1) asymmetrical water flow about the rotor generated by the body of the current meter, (2) direct sensitivity of unhoused rotors to vertical motion due either to front-to-back asymmetry in the propeller blades or to a form of turbine action which occurs in horizontally oriented bucket wheels, (3) porpoising and (4) constant tilting of the current meter due to water drag which exposes a projection of the face of the meter to vertical motion.

The first cause is difficult to avoid. In the Ekman current meter the propeller has been housed in a horizontal tube which undoubtedly removes much of the effect. However, the writer has directed tests in which meters of the Ekman type were cycled up and down through a 5-foot motion every 5 seconds to simulate the rolling of the BROWN BEAR. Under these circumstances the rotor ran backward at a rate corresponding to about 0.25 fps. The Ekman-Merz meter similarly treated ran forward at the equivalent of 0.61 fps.

The Price current meter (Fig. 8) which has an unhoused bucket-wheel ran forward at about 2.2 fps in a similar test. A fraction of the effect probably was due to porpoising. One would expect the Snodgrass current meter to be relatively insensitive to vertical motion since all aspects of the rotor and housing are nicely symmetrical with respect to such motion.

Fig. 8. The Price current meter.

The term "porpoising" refers to the tendency of the meter to nose upward when rising and downward when falling. This action occurs most severely on current meters which are mounted in trunnions and carry improperly designed horizontal tail fin surfaces. One meter that porpoises is the Price meter but it already is so sensitive to vertical motion that the additional effect is unimportant. Another in which the effect can be most serious is the modified Roberts current meter, one model of which both horizontal and vertical fins have several times the area of those in the standard meter of Fig. 9. Some horizontal fin is necessary in this instrument to balance the pressure moments of the large rotor during vertical motion but the writer has observed the meter to turn its nose nearly vertically downward and upward during moderate heaving of the vessel. The standard Roberts meter also exhibits porpoising to a significant degree.

It is important to recognize that heaving motions may be transmitted along the supporting cable to much greater depths than are horizontal disturbances.

Fig. 9. The standard Roberts current meter.

CONCLUSIONS

A pessimistic picture has been painted of our ability to measure ocean currents on a continuous basis with suspended current meters and existing techniques. The problems of stray motion and limited dynamic response are extremely serious. Generally speaking, small short period fluctuations will be difficult to find. The large, long period transients may be measured with fair accuracy but probably not well enough to determine mean currents in those areas where the transients far exceed the means. There is a great need for a current meter of rapid response in both direction and velocity which is insensitive to stray motion and will integrate accurately to zero all of the undesired cyclic motions.

Of existing current meters the most promising is the Snodgrass current meter, in its continuously recording form, although it is far from perfect. Something will have to be done to convert the form of the record into one which either internally integrates or is easy to integrate later from the record. Richardson's modification of the Snodgrass meter appears to be producing useful information and solving many of the problems.

Of existing mooring systems the stiff taut-wire moor with a small surface float serves fairly well the region from the submerged buoy downward, but not the upper section. A close competitor may well be the Richardson moor. It may be that early work with continuously moored systems in the more difficult areas may have to be done with bottom mounted meters.

The present discussion has tended to emphasize situations which are serious because they are easier to illustrate. It is readily granted that in particular experiments much less serious conditions may exist. In such cases the experimenter must accept the burden of proving that his results are real and meaningful.

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A FAST RESPONSE CUP ANEMOMETER FOR MEASUREMENT OF TURBULENT WIND OVER THE OCEAN

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ABSTRACT

A fast response cup anemometer suitable for measuring turbulent winds over the ocean is described. The electrical characteristics of this instrument are suitable for use at remote observing stations where low power drain and telemetry are desirable. Dynamic response characteristics of the cup anemometer are discussed together with an ingenious method for dynamic calibration.

INTRODUCTION

It should be remarked at the outset that measurement of wind is a proper concern of the oceanographer since the wind serves to transmit considerable mechanical energy into the ocean and strongly influences other processes such as evaporation and mixing. In fact, wind driven phenomena such as large current systems and wind generated waves are certainly among the most spectacular features of the ocean.

Before discussing the details of the cup anemometer it is worthwhile to examine some aspects of the measurement of dynamic variables in oceanography, particularly since it is becoming increasingly fashionable to deal with dynamic measurements by use of digital computers. It should be apparent that meaningful measurement of a variable implies a rather long term observation of its time history. If the time history is interpreted in terms of its corresponding frequency spectrum it is found that oceanographic variables rarely contain frequencies above 10 cps. A more usual upper frequency limit would be 2 cps for phenomena near the surface, while the practical low frequency limits for many phenomena may be measured in cycles per day or month.

Obviously, low frequency data of this sort may be processed conveniently and economically on a general purpose digital computer as contrasted with, say, acoustic data which may be analyzed with so-called analog devices. On the other hand, new technological capabilities have so vastly expanded the capabilities for acquiring large quantities of oceanographic data that the digital computer becomes an essential element in the interpretation, cataloging and analysis of data.

Now, once the commitment is made to use a digital computer in data analysis the computer becomes, essentially, a part of the "instrument" itself. This fact can be important in the design and evaluation of the transducer and data acquisition system since it is frequently possible to incorporate instrument corrections into the computer program. Thus it is possible to apply corrections for nonlinearity, temperature compensation, etc., to the data in the digital computer. This procedure may serve to vastly simplify the transducer design or (because extremely complex corrections may be made using a digital computer) it may be possible to use transducers that would otherwise be unsuitable.

Cup anemometers have been a standard device for measurement of wind speed for many years. In recent years, however, their use has been extended to the measurement of turbulent wind in micro-meteorological research. While the cup anemometer is a rugged and reliable device, serious questions have been raised regarding its suitability for accurate dynamic measurements in turbulent wind regimes. In particular, the linearity of response to increasing and decreasing wind speed has been questioned.

The anemometer described here was designed for use in conjunction with a study of wind generated ocean waves. Since it was intended to subject the wind speed data to power spectrum analysis, the dynamic characteristics, particularly in regard to linearity of response, had to be known. This is particularly important since any instrument nonlinearity must be removed before calculating the covariance function and the power spectrum. However, as will be shown, the actual performance of the cup anemometer did not exhibit the anticipated difficulties. Nevertheless, it seems worthwhile to point out the necessity for careful evaluation of transducers intended for dynamic measurements and the possible means of compensating for undesirable transducer characteristics.

DESIGN SPECIFICATIONS

The following criteria and specifications were used in the design and construction of the anemometer:

1. Wind speed range of 1 to 30 mph.
2. Fast dynamic response which requires minimum inertia and friction of all moving parts. Frequency response to 1.5 cps.
3. Design should be rugged, weatherproof and capable of withstanding winds up to 60 mph in the presence of rain and salt spray. The electronic circuitry in particular should be stable over a wide range of environmental temperature with an extreme range of -20° to $+60^{\circ}\text{C}$.
4. Electrical characteristics:
 - (a) Minimum current drain since anemometers may be battery operated.
 - (b) Output should be compatible with standard IRIG FM subcarrier oscillators, preferably 0 to 5 volts DC.
 - (c) Provision should be made for automatic field calibration of all electronic circuitry.

Consideration of these specifications led to the construction of a compact anemometer, completely self-contained except for a 24 volt power source and field calibration equipment. In order to minimize inertia and friction the moving parts were reduced to the shaft which supports the cups and a slotted cylinder which acts as a light beam interrupter. Several slots are cut in the light "chopper" to give better resolution at low wind speeds and to enhance the dynamic resolution.

Mechanical Construction

The mechanical layout of the anemometer is shown in Fig. 1. The entire assembly is 13 inches overall and the main instrument case is 2 inches in diameter. The anemometer cups are press fit into a hole in the upper cap. No retaining screw is needed. The upper cap is locked onto a stainless steel shaft which is supported by two miniature precision ball bearings. The upper cap, which rotates with the shaft, forms the outer portion of a double weather seal. There is an inner cap, fixed to the case, inside of which is a spinner which in turn rests on the inner race of the upper bearing and which makes a loose contact with the shaft. A second cap is locked with set screws to the shaft at the lower bearing, just inside the instrument case. This is the light chopper which projects downward and over the lamp housing. It has 30 slots 0.01 inches wide milled parallel to its axis. The lamp housing consists of an aluminum tube surrounding a low voltage incandescent bulb and having a single slot 0.02 inches wide. A plastic ferrule fastened to the lamp housing serves to mount a solid state photoelectric switch. The photo-switch is placed in line with the slot in the lamp housing about $3/32$ inch distant, while the chopper rotates between the lamp housing and the photodetector mount. Thus as the shaft rotates, light passing the lamp housing slit is alternately

interrupted and passed by the slots in the chopper causing the photoelectric switch to alternately open and close an electric circuit.

The instrument case is fabricated from aluminum tubing. The lower end plug and the case extension which supports the shaft and bearing assembly, are machined from aluminum and are fitted with "O" ring seals, being secured to the tubular case with small machine screws. The lamp housing, photo-detector mount and the electronic circuit boards are mounted on 3 small rods which are in turn fastened to the lower end plug. A 4-pin hermetically sealed MS type electrical connector is threaded into the lower end plug. The assembly is finished with 2 coats of white epoxy paint which not only provides corrosion protection but also acts as a reflective coating to prevent the electronic components from becoming overheated when exposed to sunlight.

ELECTRONIC CIRCUITRY

The essential features of the electronic circuitry are shown in the functional diagram of Fig. 2 and Fig. 3 illustrates one of many workable circuits capable of performing the basic functions. The photo-sensitive switch manufactured by Solid State Products, Inc. of Salem, Mass., and called a Photran, is of special interest since it functions much like a switch with high conductivity when exposed to light but with very high resistance when dark. Once the device conducts, however, it continues to do so until the source of current is nearly spent. This accounts for the high value of 1 megohm in the Photran circuit. The pulses derived from the Photran charging the 0.001 mfd capacitor appear on the one-shot multivibrator as differentiated pulses of a couple of microseconds duration. The one shot shapes these into pulses of constant width and amplitude, the amplitude being determined by the zener diode. Since the pulses are of constant amplitude and width and only change in frequency, they may be integrated to produce a voltage proportional to the incident wind velocity.

Field calibration of the electronics is made by extinguishing the lamp and introducing standard frequency square waves which correspond to the light chopper frequency for a given wind velocity. The temperature environment limits of the instrument are essentially those of normal transistor tolerances when used in a one-shot multivibrator and the Photran, being a silicon device, is capable of equal or better performance over a wide temperature range. Power consumption of the instrument is approximately 170 milliamperes, the rated current of the No. 313 lamp. The rest of the circuitry adds very little to this drain and depends somewhat on the frequency of the pulses generated.

Fig. 1. Anemometer assembly.

STATIC CALIBRATION

Wind tunnel tests were conducted at the Round Hill Field Station of the Department of Meteorology, Massachusetts Institute of Technology, to evaluate the performance of the Beckman-Whitley cups and the mechanical portions of the anemometer. The results that were used in the circuit design are shown in tabular form. They are averages for the 4 anemometers tested.

<u>Miles/hr</u>	<u>Meters/sec</u>	<u>Pulses/sec</u>	<u>Rev/min</u>
30	13.411	260.00	520.00
10	4.470	86.67	173.34
1	0.447	8.66	17.30

No departure from linearity could be detected on wind tunnel tests. However, allowance had to be made for a certain amount of background noise

Fig. 2. Functional diagram of anemometer circuitry.

in the wind tunnel which required taking rather long term averages to determine mean pulse rates. Average pulse rate is 19.38 pulses/sec per meter/sec or 0.646 rev/sec per meter/sec. Since the distance from the center of rotation to the outside edge of the cups is 9.0 cm, the ratio of cup tip speed to wind speed is 0.366. This means that the outside edge of a cup will travel 0.366 meters while the air moving past the cup travels 1 meter.

The threshold velocity for four anemometers varied from 0.5 to 0.9 meter/sec. The lowest threshold velocity was observed on an anemometer which had been in outdoor service for over a year.

Assuming that the cup rotation rate is linearly proportional to the wind speed, as indicated above, the remainder of the electronic circuitry may be evaluated by substituting a square wave generator for the photoswitch output. The integrating circuit (Fig. 2) is an essential

part of the anemometer circuitry since the pulse output of the one-shot multivibrator must be smoothed somewhat before it can be used to modulate the subcarrier oscillator (VCO). Both the integrating circuit and the VCO are nonlinear circuit elements in this application. The VCO output frequency is normally a linear function of the input voltage. However, since there is considerable ripple present on the integrator output voltage and because the magnitude and frequency of the ripple also vary with the pulse rate, the output frequency of the VCO is not strictly proportional to the average input voltage. The RC-integrating circuit is, of course, inherently nonlinear. Fortunately, the two effects tend to oppose one another so that the frequency output of the subcarrier oscillator is a linear function of the pulse repetition rate with a maximum deviation from the least squares straight line fit of $\pm 0.5\%$ of full scale. The voltage output across the integrating circuit as measured with a DC voltmeter has a maximum deviation of $\pm 2\%$ of full scale from the least squares straight line fit.

Fig. 3. An electrical circuit design for converting anemometer output.

DYNAMIC CALIBRATION

When observing a cup anemometer in the laboratory it is immediately noticeable that the cups will accelerate rapidly in response to a sudden draft of air but will continue to coast for a relatively long time in still air when the driving force has been removed. This raises the possibility that the angular acceleration of the cups in response to an increasing wind velocity differs from the deceleration in response to a decrease in wind velocity of the same magnitude. Furthermore, it can be expected that the angular acceleration of the cups will be larger; that is, the cups will respond faster to the same magnitude of velocity change at higher mean wind velocities. Thus, it is at least possible that the dynamic response of the cups is dependent on both the mean wind velocity and the sense of velocity change.

One way to evaluate the overall response of any transducer is to subject it to a step change of the variable to be measured while observing the output from the transducer. The technique is highly developed for purely electrical measurements and much of the existing technique may be applied directly in evaluating transducers of various kinds. The apparatus for simulating a step function in the wind tunnel is shown schematically in Fig. 4. A variable speed motor mounted on a hinged support drives a circular puck on the end of a long shaft. The puck may be engaged against the anemometer upper cap by forcing the motor to swing upward by means of a push bar extending through the floor of the wind tunnel. The angular velocity of the cups may now be regulated by adjusting the motor speed to be either greater or less than the wind speed. Upon release of the push bar the motor and puck assembly is pulled rapidly back to its retracted position. Thus, so far as the anemometer is concerned, it experiences a realistic step change

Fig. 4. Apparatus for producing simulated step function response in a wind tunnel.

in wind speed as soon as the puck loses contact with the anemometer cap.

This procedure was carried out for several values of mean wind, for increasing and decreasing step functions of various amplitudes. The surprising result was that the response characteristics were uniform for all wind speeds from 2 m/sec to 10 m/sec for both increasing and decreasing step functions. The observed response was, in fact, an exponential function with a time constant identical to the RC time constant of the integrating circuit, which is 0.27 sec. This result holds true, even at the extreme condition, for a mean wind of 2 m/sec with a ± 2 m/sec step function.

This result is both encouraging and disappointing. If the pulse output had been recorded as well as the integrated output much more could have been learned about the cups themselves. The requirement for a smoothed voltage into the telemetry system forced the inclusion of the integrating circuit in the anemometer. While the integrator has masked the response of the cups themselves this is not entirely without virtue since the observed dynamic response of the anemometer is uniform over a wide range of mean wind speeds. Hence, within the limits imposed by this relatively slow response, the instrument has a single and simple dynamic response. The only question remaining is whether

or not the response is adequate for investigation of turbulent wind.

FREQUENCY RESPONSE

As mentioned earlier, one of the more useful means of presenting turbulent wind data is the power spectrum. The reason for desiring to use a frequency scale in preference to a time scale for data presentation is that certain manipulations of the data are easier to perform in the frequency domain and frequency data are almost always easier to interpret. The time constant when transformed into the frequency domain becomes the frequency response function. If then, the time constant can be experimentally determined and if the response to a step function is (approximately) exponential the frequency response function $W(f)$ may be written

$$W(f) = \frac{U_o}{U} = [1 + (2\pi f k)^2]^{-1/2} \quad (1)$$

where f is the component frequency in cycles per second of the turbulent wind, U_o is the observed amplitude at frequency f , U is the "true" amplitude at frequency f and k is the time constant. This shows that the amplitude, U , is attenuated proportionally to $1/kf$ so that at higher frequencies the observed amplitude, U_o , becomes smaller. For power spectra the quantity of interest is $W^2(f)$ and this function may be used to correct the observed power spectrum for the attenuation due to the instrument's time constant by the formula

$$U(f) = \frac{U_o^2(f)}{W^2(f)} \quad (2)$$

Fig. 5 shows a plot of $W^2(f)$ for $k = 0.27$ superimposed on a portion of a typical power spectrum $U_o^2(f)$ calculated from observation of wind over Buzzards Bay, Mass. Wind velocity was measured with one of the anemometers described here over a period of about 10 minutes. The velocity signal was sampled 5 times per second so that the highest frequency computed in the power spectrum is 2.5 cps (only a portion of which is shown in Fig. 5). Since the observed power spectrum attenuates very much more rapidly than the frequency response curve it can be assumed that the frequency response of the anemometer is high enough so that important high frequency components in the wind are not cut off. However, if the observed spectrum is corrected for the effect of the time constant according to Eqn.(2) some modification of the spectrum does occur with the possibility of a secondary peak occurring near $f = 0.4$ cps. Whether or not such a peak has real meaning can only be determined by careful consideration of the statistical reliability of the power spectrum reinforced by the experimenter's own prejudices and preconceived notions as to what he is looking for.

Fig. 5. Typical power spectrum of wind speed measured over Buzzards Bay, Mass.

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SESSION VI

COMPONENTS AND SPECIAL DEVICES

Chairman: D. D. KETCHUM
Ocean Research Equipment, Inc.
Vineyard Haven, Massachusetts

WIDE BAND TRANSDUCERS FOR SOUND VELOCIMETERS

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ABSTRACT

Some influences and considerations which play a significant role in the accurate measurement of underwater speed of sound are presented. An inaccuracy of "sing around" circuits used in the measurement of the speed of sound due to variations in the measurement of the acoustic pulse travel time is discussed. The contribution to the development of an accurate velocimeter by the use of proper amplifier bandwidth, pulse rise time, transducer "Q" and threshold triggering level is emphasized.

INTRODUCTION

The accurate measurement of sound speed is the keystone of efforts to describe the various acoustic paths in the ocean by ray plotting techniques. The importance of sound speed measurement is well recognized in qualitative terms but the degree of accuracy required and the quantitative effect of measurement error is not fully appreciated. There is a real and immediate need for sound speed measurements with a repeatability of 1 part in 10,000 over the entire spectrum of ocean environment.

Several years ago the National Bureau of Standards developed the "sing around" type velocimeter. This development was an excellent example of the kind of imaginative instrumentation which is required if we are to make real improvement in our oceanographic measurement capability. On the other hand, there are basic considerations with regard to measurement accuracy that need to be reviewed with the objective of improving this instrument to its ultimate capability. The paper discusses the capability of current instruments, the factors which limit their accuracy and the areas in which improvement is necessary.

BASIC DESIGN CONSIDERATIONS

Pulse Travel and Rise Time

The basic principle of operation of pulsed velocimeters is measurement of the time required for an acoustic signal to travel a fixed distance. In the "sing around" system each received pulse triggers a succeeding pulse so that the time

Fig. 1. Pulse time measurement.

measurement is accomplished by counting the number of pulses occurring in a given time interval.

Now just how does one measure the time of occurrence of a transient event? Fig. 1 shows a typical level shift function which is initiated at time t_0 and stops at time t_f . The determination of the time of the pulse is made by observing the time at which the transient voltage exceeds a threshold voltage, E_t .

The design of a velocimeter for any specified accuracy puts a minimum requirement on the permissible error in the fundamental factors involved in the time measurement. These are the rise time, the threshold level and the loop gain of the system. In Fig. 1 it should be noted that any shift in the gain of the system will result in a shift in the time indicated. The dashed curve represents the function reduced by a loss of 3 db and the point, t'_m , represents the new time indicated. The difference between the time, t_m , and time, t'_m , is the resulting error, t . By similar reasoning it can be shown that any shift in the threshold level likewise produces a change in the indicated time and therefore an error in time measurement. One way to escape from this limitation is the use of a level shift that is so rapid that measurement at any place on the wave front yields the desired accuracy.

A design based on this philosophy could be based on a path length of 7.6 inches and a maximum design error of ± 0.5 feet per second (fps). Here it is assumed that the path length is the same as in the original "sing around" developed by the National Bureau of Standards, and the accuracy desired is equivalent to roughly 1 part

in 10,000. Applying the time-worn rule of thumb which states that the bandwidth required to pass a pulse is the reciprocal of the rise time, it is found that the bandwidth required in the system is 40 Mcps. From these assumptions the acoustic delay is 127×10^{-6} seconds giving an allowable time error of 12.7×10^{-9} seconds and an allowable rise time of 25.4×10^{-9} seconds. This requirement is so staggering that one instinctively casts about for some way of reaching a more reasonable answer. The rule used by oscilloscope manufacturers is less stringent and says that the frequency band required is equal to 0.35 divided by the rise time between 10 and 90% amplitude. On this basis the bandwidth required is only 20 Mcps or so. Perhaps this figure is more practical. The main point here, however, is to emphasize that a considerable bandwidth is required if such a fast rise is necessary. It should further be noted that a decrease in path length, or in the allowable error, requires proportionately greater bandwidth.

There is a fundamental limitation which must be evaluated before such a system is developed. The attenuation in sea water is inversely proportional to temperature. At 15 Mcps, for example, the attenuation in the 7.6 inch path is almost 10 db greater at 20°C than at 30°C , while at 30 Mcps the difference in attenuation between these temperature limits is over 30 db. It follows that a pulse front containing energy over a wide, high frequency range will be altered in shape by this selective attenuation.

From these considerations it seems unlikely that freedom from systematic errors can be achieved by this means. Referring again to Fig. 1, it can be observed that one way out of this dilemma would be to compensate for the loop gain of the system in some way. Since an increase in loop gain causes a shortening of the time interval and since an increase in the threshold level causes a lengthening in the time interval, it would seem that the threshold could be controlled to produce an error compensating for the gain changes which must be accommodated. It can be observed that if the function reaches a maximum in the same rise time, regardless of the loop gain, then it reaches any given percentage of its maximum in the same time. If then the threshold is caused to change so as always to equal some fixed percentage, say 50%, of the maximum there would be no time error introduced by changes in the loop gain. Such a circuit (compromising a simple peak rectifier) would permit the use of rise times longer than would otherwise be tolerable and consequently would require less bandwidth.

Other Pulse Characteristics

Fig. 2 illustrates the type of pulse delivered to the amplifier input from the acoustic circuit in the Bureau of Standards type meter. The "Q" of the transducers is so high that 5 cycles at the resonant frequency occur before a maximum is

Fig. 2. Standard acoustic circuit behavior.

reached. In practical use of the instrument a loss in amplifier gain, an increase in acoustic path attenuation, a mis-alignment of the transducers due to pressure effects, and/or a change in the beam patterns of the transducers due to frequency, pressure and temperature changes as well as aging of the components, causes the signal to change in level. Under such conditions the instrument will continue to function in apparently normal fashion but will measure the time to the wrong half-cycle. The resulting error with the standard 3.6 Mcps crystals is about 270 nanoseconds and produces an error in the indicated sound speed of about 9 fps. This effect has been observed on many occasions by various laboratories and considerable effort has been expended in critical readjustment and recalibration in order to avoid this error. While it is possible to prevent this shift by painstaking adjustment, the fact remains that this is proof that the errors discussed previously are in fact present. It might further be observed that since the velocimeter is normally calibrated by using distilled water at various temperatures, the error is compounded in the actual calibration process.

The pulse shape shown in Fig. 2 presents other difficulties. Some of the energy arriving at the receiving crystal is reflected back to the transmitting crystal. Some of this reflected energy is likewise reflected back to the receiving crystal. The difference in energy level between the direct and the reflected energy is approximately equal to the difference in attenuation (including spreading losses) experienced by the 2 signals. This value is approximately equal to twice the loss in a single pass through the system. With the type pulse shown, however, the signal from the central portion of the pulse is much stronger than the first or second pulses (either of which may be used for the triggering pulse) and consequently the reflected interfering signal is very strong compared to the "signal" cycle of the pulse. In addition, since these interfering pulses occur very soon after the signal cycle and since the electronic time delay is small, the reflected pulse arrives at the receiver at essentially the same time as the desired pulse causing interference effects.

PULSED TRANSDUCER
 SIZE .250" DIA.
 THICKNESS .013"
 MATERIAL LEAD ZIRCONATE

RECEIVING TRANSDUCER
 SIZE .250" DIA.
 THICKNESS .026"
 MATERIAL LEAD METANIOBATE

IMPULSE

OUTPUT

Fig. 3. Acoustic current with carrier null.

PULSED TRANSDUCER
 SIZE .250" DIA. CEMENTED
 TO .5" SQUARE WEDGE
 THICKNESS .013
 MTL. LEAD ZIRCONATE

RECEIVING TRANSDUCER
 SIZE .250" DIA.
 THICKNESS .026"
 MTL. LEAD METANIOBATE

IMPULSE

OUTPUT

Fig. 4. Acoustic behavior with wedge backed transducer.

Table I. Comparison of three acoustic systems

Acoustic System	Conventional	Lead Zirconate Lead Metaniobate	Lead Zirconate (Wedge) Lead Metaniobate
Pulse shape	Unsatisfactory	good	good
Rise time	100 microseconds	100 microseconds	90 microseconds
First peak voltage	6 mv	10 mv	8 mv
Voltage rate	60,000 v/seconds	100,000 v/seconds	90,000 v/seconds

APPROACH TO DESIGN IMPROVEMENTS

Various methods for improving the transducer system were considered. The results sought were that the pulse should have (1) a fast rise time and (2) a first rise which exceeds all successive transients. It appeared that the transmitting transducer should be "damped" as much as possible from the electrical side. For this purpose it was felt that lead zirconate having a high electro-mechanical coupling coefficient would perform well. In addition some method of destroying the resonance of the transducers, such as by cementing a ceramic wedge to the back of the crystal, seemed probable of success. On the receiving end it appeared that a material with a low electrical Q should be used and in addition it might be useful to design the receiver crystal to be anti-resonant at the resonant frequency of the transmitting crystal to overcome the buildup of carrier frequency energy.

Fig. 3 shows the behavior of such an acoustic circuit in which a transmitting crystal of high coupling coefficient is driven from a very low impedance source. The receiver is made of a low Q material and is twice as thick as the transmitting crystal in order to be anti-resonant. Specifically, the transmitting crystal is of lead zirconate titanate resonant at about 8 Mcps while the receiving crystal is of lead metaniobate resonant at about 4 Mcps. The pulse has a rise time of approximately 100 nanoseconds, a voltage rise rate of 100,000 volts per second and possesses the desired characteristic, viz.,

that no portion of the pulse exceed the first rise. The amplitude of the first rise is 10 millivolts and is approximately equal to the second half-cycle in the standard system shown previously.

The carrier energy in this pulse is of no value in the operation of the velocimeter and some effort was made to further reduce it. For this purpose a lead zirconate transducer was cemented to a wedge shaped backing block and substituted for the transmitting transducer. This configuration gave a slightly faster rise time with slightly lower output but very much less "carrier" energy as shown in Fig. 4. Here the rise time is about 90 nanoseconds with a voltage rise rate of 90,000 volts per second. For direct comparison the characteristics of the three acoustic systems discussed are shown in Table I.

All of the results shown here have been observed with a direct water path from the transmitting to the receiving transducer. As previously noted, reflections within the acoustic path result in an interfering signal which arrives at about the same time as the desired signal. For example, assume we use a yardstick as a time base and consider the acoustic delay to be 11 inches and the electronic delay to be 1 inch. It can easily be seen that a signal reflected by the receiver reaches the transmitter after "22 inches" and reflects from it to arrive at the receiver (for the second time) at "33 inches." The third succeeding pulse after passing through the system only once arrives at the

Fig. 5. Multiple reflections.

Fig. 6. Pulse shape with nonparallel transducers.

receiver at "35 inches." In other words, a reflected signal passing through the system 3 times arrives at the receiver 2 electronic time delays before the third succeeding transmission. This reflection must be minimized and the threshold adjusted well up on the pulse front to avoid errors due to this reflection.

Photographs of these reflected signals are shown in Fig. 5. The top line shows the attenuation with the path length reduced to one-third the normal length for purposes of illustration. It can be seen that the reflections are only about 6 or 7 db less than the desired signal. In the bottom line the normal path length is used and it is seen that the signal is roughly 18 db below the desired signal. With the conventional pulse shape the reflections from the large center portion of the pulse are a serious source of interference to the smaller "signal" cycle which came earlier in the pulse. With either of the improved pulses shown, reflections should not be a serious problem.

The preceding illustrations have been prepared with the transmitting and receiving transducers accurately aligned. If angular misalignment is introduced, a change in the pulse shape will result as shown in Fig. 6. The effect of even a very small displacement is seen to produce

Fig. 7. Effect of temperature.

Fig. 8. Pressure effect.

a considerable lengthening of the pulse rise time as well as causing a serious reduction in signal amplitude.

Considerable stress has been given to the fact that the attenuation in the acoustic path increases as the temperature is lowered. This problem is illustrated in Fig. 7. We see, however, that the pulse amplitude was reduced by about 3 db as the temperature was reduced from 27°C to 3°C. It should also be noted that no significant change in the rise time occurred.

Similar tests were made to determine the effect of hydrostatic pressure. Photographs taken of the waveforms observed during this test are shown in Fig. 8. Unfortunately these tests were made in paraffin oil, about which our knowledge as to the acoustic attenuation as a function of pressure is even more nebulous than for sea water. There is, however, no indication of any change whatsoever in the pulse shape or amplitude. This test was carried to 10,000 psig with no change noted.

THE WIDE BAND AMPLIFIER

With these facts in hand it appears that we now have the basic knowledge required to effect

GAIN = 10 db/STAGE
BAND = 0 TO 30 mc

Fig. 9. Amplifier circuit.

a major improvement in the accuracy and reliability of pulsed velocimeters. These ideas are now being applied to a new instrument incorporating all of these improvements. The amplifier circuit shown in Fig. 9 was designed to pass any of these pulses without distortion. The bandwidth of this amplifier can easily be adjusted by changing the feedback network values. Present indications are that the bandwidth required is only about 10 Mcps with the pulses shown. The use of the wider amplifier bandwidth does however yield a smaller electronic time delay and, therefore, reduces the nonlinearity of the calibration. The amplifier shown has a delay of less than 100 nanoseconds.

CONCLUSIONS

A pulsed type velocimeter requires an acoustic pulse with a fast rise time and one in which the first rise is greater than any succeeding cycle. The attenuation caused by changes in water temperature and other factors introduces a time error in measurement which limits the accuracy obtainable unless a means of compensation is introduced. Methods for generating suitable wide-band pulse forms and for making loop gain compensation have been discussed. Unfortunately there are no adequate standard testing facilities available for determining over environmental extremes the success of these corrective measures. Until such facilities become available, the only way to estimate the accuracy of these instruments is by careful quantitative consideration of all the individual factors which control the accuracy of the instrument.

ACKNOWLEDGMENTS

Mr. Paul West performed all the physical tests and took the excellent photographs which contribute so much to the understanding of the various phenomena.

SOLION ELECTROCHEMICAL DEVICES

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ABSTRACT

The solion is a new class of electrochemical devices which act as current limiting diodes, signal processing elements, pressure or flow detectors, etc. Of particular interest is the solion linear pressure transducer or linear flow detector, with its wide range of possible application at the lower frequencies normally associated with oceanography and geophysics. A discussion of the principles of solion operation will be presented along with some of the practical applications of solions in the field of oceanographic instrumentation.

INTRODUCTION

The science of electrochemistry began around 1800 when Galvani noticed that if two dissimilar conducting materials were placed in contact with a freshly prepared frog's leg, the leg twitched as if alive. Although the solion does not utilize a freshly prepared frog's leg, it does utilize some of the principles noticed in Galvani's experiment.

The solion is a very low power consumption electrochemical device, commonly known as a redox system. With a redox electrode the reaction occurring at the electrode is completely reversible. Furthermore, the electrodes consist of an unattackable metal, usually platinum, which will not enter into the reaction itself. The electrochemical system consists of an electrode set immersed in a solution containing soluble forms of the same chemical in two different oxidation states. For the case of the solion this is generally an iodine/iodide electrolyte system.

The name solion is derived from the phrase "ions in solution." Electric current is transferred via ion flow in a solution as opposed to ion flow in a gas or solid. The redox electrochemical system is discussed in this paper, but other solions utilize different electrochemical principles such as electrokinetic transduction.

THE SOLION ELECTROCHEMICAL DIODE

Consider the case of a solion diode. This will illustrate the basic characteristics of the

Fig. 1. The basic electrochemical diode system.

solion, not including those effects due to hydro-acoustic flow. Fig. 1 is a schematic of the basic electrochemical-diode system. The diode consists of a pair of platinum electrodes sealed into an airtight chamber that has been filled with an iodine/potassium iodide/water solution. One electrode, the anode, is chosen with an effective surface 10 times that of the other electrode, the cathode. The chamber is constructed of a chemically inert plastic material such as Kel-F. The external electrical circuit consists of a variable low voltage, DC supply, a DC milliammeter and a high impedance DC voltmeter.

With the circuit connected as in Fig. 1, the voltage between the electrodes is increased and the current through the cell is monitored. The voltage-current relationship is shown in the concentration polarization curve of Fig. 2. Maximum voltage is about 0.9 volts DC; any substantial increase above this value will tend to cause hydrogen evolution at the cathode. This curve illustrates one of the basic features of the solion--the output current is independent of the applied voltage over the range 0.1 to 0.9 volts. Typical value of the slope of the plateau is approximately 1 megohm. Over the region of the plateau, the limiting current is given by the following relationship:^{1,2}

¹Superior numbers refer to similarly numbered references at the end of this paper.

Fig. 2. The concentration polarization response of a simple solion diode.

$$i_d = \frac{AD}{\ell} n FN \quad (1)$$

where A is effective area of cathode electrode, N is iodine concentration or normality, ℓ is effective thickness of diffusion layer, n is 2, number of electrons involved in reaction and F is Faraday constant, 96,500 coulombs/g-mole.

The diffusion coefficient, D, is given by

$$D = \frac{KT}{\sigma} \quad (2)$$

where T is absolute temperature in degrees Kelvin, σ is viscosity of the solution and K is a constant for the particular system. Therefore, for a solion diode the limiting current is primarily determined by the cathode area (a cathodic controlled reaction), the iodine concentration and the absolute temperature.

The electrochemical reactions occurring at the electrodes consist of reducing iodine at the cathode and oxidizing iodide back to iodine at the anode. The process is illustrated by the following:

The electrode material itself has not entered into the reaction and the completely reversible process can continue indefinitely. The shape of the "knee" of the curve can be adjusted by varying the potassium iodide concentration but

Fig. 3. Solion flow detector.

the shape illustrated makes greatest use of the constant current feature.

Another unusual feature of the solion is the "double" source impedance characteristic. Although the "signal" output appears to originate from a 1 megohm source, the cell appears as a 100 ohm source to any 60 cps "pickup" that might appear in the external electrical circuit.

"Reverse" voltage characteristics of the diode are very similar to those shown in the curve of Fig. 2. The anode and cathode leads are now interchanged with the cathode becoming an electrode of 10 times the previous area. The polarization curve will again have a similar shape except that the limiting current will be approximately 10 times the "forward" limiting current, due strictly to the increased area of the cathode electrode. The "front to back" ratio is therefore primarily determined by the ratio of the electrode areas. Values in excess of 100:1 have been obtained.

THE EFFECTS OF HYDROACOUSTIC FLOW

The diode has been discussed to illustrate some of the basic principles of the electrochemical system utilized in the solion. The assumption was made that hydraulic flow was absent. By proper design, the solion can be utilized as a hydraulic flow or pressure detector.

Consider the design of a solion, similar to that indicated in Fig. 3. The rigid plastic body of the diode has been replaced with a cell of different design. The cathode element is now mounted in a solid web at the center of the plastic housing so that any fluid flow between chambers is possible only through the cathode electrodes. The electrolyte solution is constrained by compliant diaphragms which permit limited volume flow between chambers.

Since the cathode structure tends to obstruct any flow of fluid between chambers it is considered as an acoustic resistance, R, measured

in acoustic ohms. Since the diaphragms are compliant, this effect is considered as an acoustic compliance, C , measured in acoustic farads. The product of the acoustic resistance and compliance determines the low frequency response of the transducer.

If the flow detector is connected to the external electrical circuit shown in Fig. 3 and if flow through the cathode elements is assumed to be zero, the individual cathodic currents will tend to a quasi background current as the iodine ions in the neighborhood of the cathodes are depleted. The background current is then determined by Eqn. (1). If the two cathode electrodes indicated in Fig. 3 are identical, their background or "no flow" currents will be identical. The differential "output" will then read zero or near zero volts, depending upon how nearly identical the cathodes actually are. The iodine ions contained in the volume in and around the cathodes are reduced to near zero except for the small amount of iodine diffusing into the region.

Assume now that, with the cell connected to the external bias, a net differential pressure is developed between the compliant diaphragms. A net hydraulic flow of the electrolyte solution will commence from one chamber to the other chamber. The amount of volume flow is determined by the net differential pressure and the acoustic resistance through the cathodes. This is illustrated by the classical relationship³

$$\Delta p = R \frac{dv}{dt} \quad (5)$$

where Δp is the net differential pressure, R is the acoustic resistance of the cathode and $\frac{dv}{dt}$ is the volume flow rate. The volume flow rate is related to the pressure by R and can be a linear or a nonlinear relationship depending upon whether R is constant or some function of $p[R(p)]$. At low frequencies ($f < 1$ cps), pressure and volume flow rate are related by R , but at higher frequencies the relationship must become $|Z|$ so as to include the acoustic inertance of the fluid in the flow path. A linear flow detector has a useful upper frequency response in the 30 to 50 cps region.

As flow commences through the cathode electrodes, electrolyte at the bulk iodine concentration is forced into the region of the cathode electrodes. The output current is not limited to the diffusion currents of Eqn. (1) but increases in relationship to the number of iodine ions per unit time arriving at the cathode. If the cathodes behave as linear detector electrodes, all the iodine arriving at the cathodes is reduced. The linear detector cathode, therefore, furnishes an output current which is linearly proportional to the volume flow rate. This is shown by

$$I = FN \frac{dv}{dt} \times 10^{-3} \quad (6)$$

Fig. 4. Output characteristics of a typical solenoid linear pressure detector.

where I is the electrical current in the external cathode circuit. From Eqn. (5) a substitution for the volume flow rate gives

$$I = FN \left(\frac{\Delta p}{R} \right) \times 10^{-3} \quad (7)$$

During the flow cycle discussed the electrolyte passing through the "upstream" cathode has been depleted of its iodine ions and only dilute electrolyte arrives at the "downstream" cathode. The downstream cathode has its small background current reduced even further since the dilute solution flowing through this cathode tends to overcome the iodine diffusing in from the bulk solution on the downstream side. The net effect is to cause an increase in the external electrical current associated with the upstream cathode, while the electrical current associated with the downstream cathode remains small or even decreases.

The resulting voltage developed across the 2 resistors in the external load is such that one output lead becomes positive with respect to the other and, in the case described, this differential voltage is proportional to the applied differential pressure and preserves the phase as well as the amplitude. A return to zero difference pressure lets the output difference voltage return to zero volts. A reversal of the pressure causes a reversal in the polarity of the output difference voltage.

Output characteristics of a typical linear detector are illustrated in Fig. 4. The load line has been adjusted so that at some hypothetical maximum pressure the voltage between the cathode and anode is always greater than 0.1 volts. In this manner, the solenoid always operates in the proper region as a constant current device. For

Table I. Range of parameters of solion linear flow detectors.

<u>Parameter</u>	<u>Range of Values</u>	<u>Units</u>
Cathode acoustic resistance	10^4 - 10^7	acoustic ohms
Current sensitivity	0-300	microamp/dyne/cm ²
Pressure threshold	0.01 to 100	dynes/cm ²
Frequency range	0.0001 to 30	cps
Dynamic pressure range	1:1 to 30,000:1	--
Background power consumption	10 to 1,800	microwatts
Maximum signal output power	up to 27	milliwatts
Operating temperature range	-10 to +30	°C
Maximum temperature coefficient of sensitivity	+2.5	%/°C
Maximum size - diameter	3.0	inches
thickness	0.75	inches
Maximum weight	8.2	ounces

a typical solion linear detector, operating in the linear region, it is interesting to note the volume flow sensitivity. If an iodine concentration of 1.0 normal iodine is used, from Eqn. (6) it can be seen that a flow of 10^{-6} cc/sec will produce an output current of 100 microamps. This offers an extremely sensitive flow detection capability.

A comment should be made regarding one other characteristic of the linear flow detector. If an excessive differential pressure is applied to the transducer the flow rate exceeds the linear ion reduction capacity of the cathode electrode. This does not cause the output current to "clip," but causes the output current to increase as the square root of the flow above the linear range. The flow signal is not "lost" but simply modified. In this manner pressures far in excess of the linear range can be monitored and even measured with proper corrections of the output signal.

Linear flow detector transducers have been built with a wide variety of parameters. These parameters are given in Table 1. Although a wide range of values is indicated, all combinations of extremes are not obtainable in a single detector.

NONLINEAR TRANSDUCERS

The flow detector just discussed is a so-called "linear" flow detector transducer. It operates on two principles: (1) linear hydraulic flow and (2) linear electrochemical response. By proper design of both the acoustic (flow)

system and the electrochemical system, various nonlinear relationships can be obtained.

Eqn. (7) indicates an output current that is linearly related to pressure. If the acoustic circuit is modified to become nonlinear with pressure, say by inserting an orifice of proper design, then R is not constant but becomes a function of pressure: $R = R(p)$.

Eqn. (7) also assumes that the cathode electrodes are behaving as linear detectors. By proper design of the cathode electrode structure, various nonlinear ion reduction responses, such as the square root response mentioned, can be obtained. With a combination of both acoustic and electrochemical nonlinearities, a wide range of pressure-current relationships can be obtained such as square root, linear, exponential, square and higher powers (powers up to 4 have been measured). By removing an anode from one bulk fluid chamber and replacing it with a scavenger cathode electrode, an output current sensitive to flow in only one direction can be obtained. Therefore, it becomes a rectifying pressure or flow detector.

Other unusual effects and responses can be obtained although some of these effects are undesirable and difficult to remove from a desired response.

APPLICATION OF SOLIONS

Because of its extreme sensitivity at low frequencies, along with the stable properties of a redox electrochemical system, the solion is

well suited for application to the low frequency problems associated with geophysics and/or oceanography. A few examples of how solions have been utilized in these fields are listed here.

Microbarograph

By choosing a "backup" pressure reference chamber with the proper acoustic "leak," very minute atmospheric pressure changes (of the order of 0.01 microbar) can be detected within the frequency limits of the system. If this sensitivity is excessive, a less sensitive transducer should be chosen or an acoustic resistor should be inserted in series with the transducer. A linear operating range of 10,000:1 would place the maximum pressure limit around 100 microbars in the case described.

Measurement of Vertical Pressure Gradient in the Atmosphere or Ocean

By coupling the solion flow detector to a long rigid wall pipe, mounted in a vertical (or any angle desired) position, dynamic differences in pressure within the frequency and pressure response of the transducer can be measured. Again, 0.01 microbar of pressure change is detectable. Although changes in pressure (the dynamic pressure) can be detected, static pressures cannot.

Oceanographic Bottom Pressure Transducer

Again, by choosing a proper backup chamber (pressure changes must be measured with respect to some constant reference pressure), extremely small changes in bottom pressure can be detected. Pressure changes of the order of 4×10^{-6} inches of water are theoretically detectable, so long as the changes lie within the limits of the system's frequency response. Housings have been designed which physically protect the solion and allow pressure measurements in the 1.0 cps to 0.001 cps frequency range.

A Solion Seismograph

If the solion linear flow detector is coupled to a long, horizontal column of fluid, say mercury, and if the column is equally divided about the solion (the same amount of column length on each side of the transducer), there is no net differential pressure across the solion and its output is zero. Output will be obtained when a shock signal, containing acceleration components within the frequency response of the solion system, is directed along the length of the column. The pressure developed (and, by Eqn. (7), the output current) will be proportional to the length of the column of fluid, the density of the fluid and the acceleration component along the length of the column. Detection of accelerations of the order of 10^{-8} g is readily possible.

Detection of Small Oscillatory Water Currents in the Ocean

A device to detect small oscillatory water currents has not been constructed but limited investigation indicates the possibility of designing such a transducer. Fluid flow through a Venturi tends to create a pressure effect that is proportional to the velocity of fluid flow. A compound Venturi system coupled to a solion transducer, with one Venturi "pointed" 180° away from the other, could furnish a directional, low velocity water current transducer. The same effect also appears possible with the pitot tube, but a "full wave" response would be more difficult.

CONCLUSIONS

These are only a few of the many possible applications of the solion. Solions have been used extensively to measure ocean bottom pressure signals in the study of the harbor seiche problem. These transducers have been in operation for approximately three years. Solions are also being used in the study of low frequency atmospheric noise. Reliability and stability have been excellent.

Some of the unusual characteristics of the solion are: (1) low power consumption, (2) remote operation capabilities, (3) high sensitivity, (4) low pressure threshold capabilities, (5) very low frequency response, (6) broad-band response at low frequencies, (7) a reasonable temperature coefficient that can be corrected with thermistors, (8) excellent stability and reliability and (9) surprisingly rugged construction, except for diaphragm puncture.

ACKNOWLEDGMENTS

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INFLUENCE OF HYDROSTATIC PRESSURE ON COMPONENTS

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ABSTRACT

After a cursory investigation into the effects of high hydrostatic pressure upon components used in electronic circuitry, a more thorough look has been made in certain areas. Components which are satisfactory for short term tests have succumbed after longer periods under pressure.

In the last reporting¹ it was shown that a test block of thin-walled aluminum cylinders embedded in plastic withstood a short term test. In the present test series the same block was subjected to 6 months duration. One cylinder failed and the second was reduced in diameter along its length. This test indicates the "cold flow" effect upon plastics which in turn can be transmitted to components.

The pressure tank used for these investigations has been modified to vary temperature as well as pressure. It is capable of lowering temperature to approximately 0°C.

LONG TERM PRESSURE TESTS

In the earlier report of pressure tests¹ it was mentioned that a long term test was in progress. This test was devised to determine the thickness of potting material necessary to protect components such as transistors and capacitors which have internal cavities and voids. Fig. 1 shows 4 very thin walled aluminum tubes cast

into a plastic block. The specimens were placed at 1/32 inch increments from the surface of the block. The two closest to the surface (1/32 and 1/16 inch from the surface) imploded at about 2,500 psig; the other two, more deeply embedded, successfully withstood the full 10,000 psig pressure. The end of the test block containing the two tubes that had not been crushed in the original pressure test was placed in a small pressure tank where the pressure of 9,000 psig was maintained for 6 months.

The samples were removed from the tank at the completion of the long term test and its condition was observed to be as shown in Fig. 2. The most obvious change was the failure of the cylinder situated 3/32 inch from the surface. Considerable damage occurred, however, at other places in the sample. The remaining cylinder (situated 1/8 inch from the surface) was reduced in diameter over a portion of its length. In addition, a depression immediately over the axis of the cylinder had occurred and was measured to be 0.025 inch deep (averaged). When the sample was first removed from the tank a bubble noticed prior to the long term test was almost invisible and on the underside of the plastic casting was a depression 0.046 inch deep. In the first few hours after removal from the tank, the tiny bubble increased in size and forced the oil out through a crack in the plastic. The photograph shown in Fig. 3 was taken 5 days after the test block was removed from the pressure tank.

Fig. 1. Hollow aluminum cylinders in plastic and exposed to short term hydrostatic pressure of 10,000 psig.

Superior numbers refer to similarly numbered references at the end of this paper.

Fig. 2. Hollow aluminum cylinders in plastic as photographed 2 hours after removal from pressure tank following 6 months exposure to 9,000 psig.

From this test we know that long term pressure tests must be integrated into the overall environmental simulation tests. It is essential to determine the characteristics of various resins and fillers with respect to cold flow if successful operation of potted circuits without heavy metallic pressure housings is to be achieved.

In a 2-week test a number of resistors and capacitors were placed in the tank under 10,000 psig and at room temperature. The resistors tested were of a type in which a glass encapsulation is fusion sealed around a tin oxide resistance element. Sixty percent were unaffected by the test, 20% leaked but still read correct resistance, 10% developed encapsulation cracks but still read correct resistance and 10% broke and were completely unusable.

The capacitors tested were of a ceramic type and their capacitance, in most cases, had decreased enough to cause concern at the conclusion of the 2-week test. These same capacitors were placed into a long term pressure container and the pressure held for 2 months. When the capacitors were removed from the test most of the capacitors had increased their capacitance. What seems most unusual is that the capacitance increased more in the 2-month test than the capacitance decreased in the 2-week test. Measurements were again made after the capacitors had 2 days in the atmosphere to recover. The larger valued capacitors returned almost to their original value but the lower values were still reading high although they did show some recovery.

An important discovery in this test is that all components must be tested carefully under many conditions. An instrument designed and constructed with certain of these ceramic type components would have become unreliable sometime after lowering.

Fig. 3. Hollow aluminum cylinders in plastic as photographed 5 days after removal from pressure tank following 6 months exposure to 9,000 psig.

HOLLOW VESSEL TESTS

A typical test method for determining the external burst pressure of an air filled vessel is to place it in a fluid filled pressure tank and build up the pressure until the test vessel implodes. This technique does give the desired answer but usually cannot show how or where the failure began.

A method which is now being used at the Naval Research Laboratory does not take the test vessel to complete destruction. The unit is filled with fluid and a small, say 0.025 inch inside diameter tube is inserted into the vessel (Figs. 4 and 5) and led out of the pressure tank. This tube is led into an upright or inclined manometer tube, open at the top. As pressure is applied on the test vessel, it will shrink slightly, forcing the fluid up the glass tubing. This gives a dynamic, instantaneous and accurate measure of the test item's deflection. If the deflection is measured and plotted against pressure as the test proceeds then material yield points are easily recognized and the test stopped if desirable. On the other hand, if carried to burst pressure, the resulting implosion is stopped far short of complete collapse, due to the back pressure occurring within the test vessel, since the thin 0.025 inch tubing will not allow the inside fluid to be squeezed out fast enough. A view of the deflection in an aluminum sphere is shown in Fig. 6. Other samples have been tested using this technique and analyses conducted. Figs. 7 and 8 are pictures of

Fig. 4. Aluminum sphere with manometer needle attached.

Fig. 5. Fiberglass cylinder with manometer needle attached prior to testing in pressure tank.

Fig. 6. Aluminum sphere of 0.094 inch wall thickness and 3.0 inch diameter crushed at 5,300 psig (deformation began at 4,900 psig).

Fig. 7. Fiberglass cylinder crushed at 10,200 psig.

Fig. 8. Fiberglass cylinder segmented for inspection after failure at 10,200 psig.

segmented sections of fiberglass cylinders which were stopped short of complete implosion. Inspection of these segments have shown where and how the failures occurred and where the designers should give added attention in building a more reliable container.

TEMPERATURE CONTROLLED PRESSURE TEST FACILITY

To simulate more fully the deep ocean environment one of NRL's pressure facilities has been modified to include the capability of cooling the tank and the enclosed fluid. The tank is cooled by a small unit with a 3500 BTU/hour capacity. The cooling coil is tightly wrapped to the outside of the pressure tank as is the thermal control bulb. Flexible hoses connect the cooling unit (mounted on the pressure tank enclosure) to the cooling coil. The cooling unit of this system is capable of lowering the temperature of the pressure vessel from 75°F to 32°F in about 1 hour and 40 minutes. The pressure tank is 5 1/16 inch ID and 6 7/8 inch OD with an inside length of 20 inches. The volume of the tank is 410 cubic inches and usually contains paraffin oil.

A tank heating unit is also incorporated to bring the pressure tank temperature from its cooled state to room temperature in a reasonably short period of time. The heating unit is a 750 watt surface heating element from a domestic electric range. The element is firmly in contact with the base of the pressure tank. The surface heating element can return the temperature of the tank from 35°F to 55°F in 2 hours and 50 minutes. Both the cooling and heating elements are thermally insulated from the surrounding atmosphere.

The temperature of the contained fluid is sensed with an iron-constantan thermocouple. The thermocouple junction is located on the longitudinal axis of the pressure tank 1 inch above the bottom. A thermoelectric device maintains the thermocouple reference junction at 32°F.

At present, the fluid used in the 15,000 psig pressure system is paraffin oil. This oil becomes sluggish near 32°F. It is desirable to use an oil whose viscosity is fairly constant from 32°F to 85°F. Some synthetic oils exhibit this desirable trait but their coefficient of compressibility is too great. The fluid which embodies both of the above desirable characteristics is water but some other features are not so advantageous.

DISCUSSION AND CONCLUSIONS

With every instrument discussed at this Symposium there is probably a common unknown; namely its accuracy when operating in the real ocean environment. The program at NRL is aimed at testing and evaluating oceanographic sensors in a simulated deep ocean environment. At this time only the parameters of pressure and temperature are considered. Unless there is an organized and concentrated effort to design and produce secondary standard instruments and test instruments under controlled simulated parameters it seems apparent that some doubt must be associated with any measurements taken in situ.

A wide range of tests have been undertaken to learn more of the influence of hydrostatic pressure on components. Many of the tests described deal with areas of the utmost concern to instrument designers--criteria for selection of electronic components to be used in long term submergence and effectiveness of encapsulating materials used to contain electronic circuits and seal them from hydrostatic pressure. System designs could be improved and production of prototypes accelerated if a clearing house for this kind of information was readily available and taken advantage of. This would minimize duplication of experiments and component manufacturers could also improve product design through application of this knowledge.

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NUCLEAR DIGITAL TRANSDUCERS

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ABSTRACT

Measurement transducers whose signal output is a pulse rate, derived by modulation of the radiation from a nuclear source, are an unconventional type now being developed in this laboratory. Analog to pulse rate conversion is performed in the sensing head essentially by mechanical means. A digital readout is obtained by means of a pulse counter.

These transducers can be designed for measurement of any physical variable that is sensed through a mechanical displacement. Two developmental models are described and test results are presented. Proposed applications include digital pressure and temperature transducers and a digital bathythermograph.

INTRODUCTION

This paper describes our development work on measurement transducers based on the inherently discrete or digital properties of radioisotope decay. It had seemed apparent that transducers of this nature would permit physical data to be digitized substantially at the source, thus preserving the initial sensing accuracy during telemetry and data processing. It had also appeared that a transducer could be built which, once calibrated during assembly, would retain its accuracy indefinitely. These impressions have been reinforced by our experience to date. It now seems likely that the special features inherent in these devices may be especially attractive in the design of measurement transducers for the marine sciences.

The basic principle of a nuclear digital transducer is so unsophisticated that it is not entirely clear why somebody did not try to build one long ago. Two of the most plausible reasons are that digital data were not in any great demand and that silicon junction nuclear particle detectors, which are particularly suitable for these transducers, were not previously available. Therefore, it is unlikely that a useful device could have been built until quite recently.

Several types of pulse count transducers, for which a time base is generated in order to

accumulate a digitized total count, are now available. Among these are: (1) tachometers and flowmeters (including anemometers and ocean current meters) of the "toothed wheel" or revolution counting type, (2) the vibrating wire type of pressure transducer and (3) DC analog transducers in combination with a voltage controlled oscillator which generates a frequency analog. Nuclear digital transducers represent a fourth type.

FUNCTIONAL DESCRIPTION

A digital transducer has been defined¹ as a coupling device which passes data along in some form of discrete code to an unlike system or subsystem. In a nuclear digital transducer, the data are transmitted by means of nuclear particles or by electrical pulses derived from nuclear particles and the coding is accomplished by counting a variable but predetermined fraction of the disintegrations occurring in a radioactive source. Most nuclear transducers, including various types of thickness and density gauges, are analog in nature owing to the fact that a DC analog signal is developed by pulse integration within the detector.

When nuclear radiation intensity or radiation flux density is measured by a Geiger counter, either a DC analog or a pulse rate analog can be used to indicate the radiation level. In the latter case, when a pulse counter including a time base is used for readout, the combined instrument is similar to a nuclear digital transducer. In other applications where the nuclear digital method might have been used, for example in some of the thickness gauges, the DC analog method seems to have been preferred.

A block diagram of a nuclear digital transducer is shown in Fig. 1. Particles from the nuclear source pass through the variable aperture controlled by the shutter and reach the detector where they generate electrical pulses. These pulses are counted by a conventional type of digital counter over a preset time base.

The mechanical sensor controls the size of the aperture through which the particles pass. In the case of a pressure transducer this may be a bourdon tube or bellows. In the case of a

¹Superior numbers refer to similarly numbered references at the end of this paper.

temperature transducer it may be a bimetallic strip. In either case a displacement is generated by the mechanical sensor which controls the shutter aperture, this displacement in turn being determined by the measurand.

The sensing head is a pulse rate transducer; strictly speaking, the instrument is not a complete digital transducer unless a counter and time base generator are included. The sensing head is also a displacement transducer in which analog to pulse rate conversion is performed essentially by mechanical means. The output signal is a representation of the physical variable to be measured in which all the information is contained in the pulse rate.

NUCLEAR SOURCES

The nuclear disintegration rate of a radioactive source is absolutely independent of temperature. Physico-mechanical effects inside the source such as thermal expansion which might alter the observed counting rate are negligible.

Fig. 1. Block diagram of nuclear digital transducer.

Therefore, the data are effectively "frequented" at the source by non-electronic means and subsequent pulse recovery is almost completely insensitive to electronic circuit stability.

Alpha particles are preferred to betas for use in this transducer. The reasons are apparent from the source energy spectra shown in Fig. 2. Alpha particles are essentially monoenergetic and their differential spectrum shows a single peak. The tailing off of this peak is due to slowing down of a few alpha particles when they escape from the source. The peak due to electrical noise in the detection equipment is extremely well separated from the alpha peak and the discriminator setting for elimination of the noise pulses is not at all critical. This means that a simple discriminator is sufficient to insure that each alpha particle reaching the detector generates one, and only one, pulse.

In the case of the beta spectrum shown in Fig. 2 the discriminator setting would be extremely critical and also would prevent a large fraction of the beta particles from being counted. This arrangement does not allow very good counting stability. Gamma rays also are not preferred because, being very penetrating, their use would require an inconveniently heavy shutter and aperture.

The variable aperture arrangement used in our experimental transducers preserves the spectrum of the source so that the alpha pulses are much larger than the noise pulses and pulse discrimination is very simple. This would not be true

ALPHA SPECTRUM

BETA SPECTRUM

Fig. 2. Source energy spectra.

if the alpha particles were to pass through some absorbing material on their way to the detector, thereby distorting the alpha spectrum.

Nuclear decay is characterized by randomly spaced pulses having approximately a Gaussian frequency distribution. The statistics associated with nuclear counting are well known.² A statistical error in each accumulated count exists such that the standard deviation of N counts is equal to $\sqrt{N}$. This means that a trade-off exists between accuracy of measurement and sampling rate. For example, if the measurand is to be sampled once per second and if the required readout accuracy is 0.1% of full scale, then at least 10^6 basic counts must correspond to full scale and the transducer must deliver at least 10^6 pulses per second to the counter or scaling circuit.

An interesting corollary of these nuclear counting statistics is that for a fixed sampling time the transducer readout error, expressed as a percentage of full scale, decreases as the scale reading decreases. In other words, more accurate readings are obtained at the low end of the scale. This contrasts with conventional readout devices whose error is practically constant at all points on the scale.

There should be no hazard problem with respect to nuclear sources for these transducers. Very weak license-free sealed alpha sources have been satisfactory for our experiments to date. If much stronger activities should be needed, the entire source chamber can be sealed. We have used Radium D sources (the actual alpha emitter is Po^{210}) which have a half-life of 20 years.

In any final design a compromise between source life and data rate, consistent with a clean alpha spectrum, would be necessary. If the source chosen for a particular application should be relatively short-lived, the decay can be compensated either by adjustment of the time base or in the course of data processing.

SILICON DETECTORS

Silicon junction nuclear particle detectors^{3,4} are particularly useful in nuclear digital transducers that employ alpha particles. They are relatively insensitive to gammas.

The detector-limited pulse rise time, which may range from 2 to 50 nanoseconds⁵ should be approachable by using very fast electronics.⁶ At least one manufacturer markets detectors having a 6 nanosecond rise time. If the 6 nanosecond figure is accepted as a reasonable limit for the rise time, the minimum practical resolving time of silicon junction detectors is about 20 nanoseconds, leading to a maximum useful random pulse rate of about 10^7 per second with

a corresponding dead time correction, $n\tau$, of approximately 20%*. At the present time a more conservative estimate of the maximum pulse rate would be 10^6 per second. The nonlinearity corresponding to the required dead time compensation² can be built either into the counter electronics or into the mechanical modulator as may be appropriate.

The transistorized preamplifier (Fig. 3) used with the silicon junction detector is a modification of a circuit described by Chase, Higinbotham and Miller of Brookhaven National Laboratory,⁷ to which we have added an extra stage of amplification and a pulse inverter. The input circuit contains a charge integrator so that the voltage height of the output pulses is proportional to the detector and therefore is proportional to the incident particle energy.

OTHER DETECTORS

Scintillation detectors or gas filled proportional detectors theoretically could be used in nuclear digital transducers. However, since either of these types would be bulkier and its resolving time longer than silicon junction detectors, no further consideration will be given to these types.

Geiger tubes are the simplest and cheapest detectors available and may be interesting for use when economy is a prime consideration. However, since Geiger tube pulses are exactly the same for all types of radiation, any required discrimination of radiation must be accomplished by variations in shielding and in detector design. Furthermore, the use of Geiger tubes, which typically have resolving times of 20 to 1,000 microseconds, would limit the maximum pulse rate to an undesirably low value for many transducer applications.

It is possible that silicon junction detectors may be capable of operating in an avalanche mode similar to a Geiger counter, thus resulting in pulse amplification in the junction. This effect should be most readily observable at cryogenic temperatures.³ If solid state avalanche detectors should ever come into use, and if they should be capable of room temperature operation with reliable performance, they might be preferable to Geiger tubes for use in low performance types of transducers.

TELEMETRY

Counters with electronic scaling decades commonly provide a binary coded decimal output suitable for telemetering. Therefore, if the counter is located ahead of the telemetry link, all the advantages of PCM telemetry are available. PCM telemetry is most suitable when several transducers are to be sampled serially and

*As used in the formula $n_0 = \frac{n}{1-n\tau}$ where n_0 is mean number of events occurring, n is mean number of events recorded and τ is counter recovery time.

Fig. 3. Preamplifier schematic diagram.

telemetered over a single channel. If the most efficient use of one channel for a large number of transducers is required, each nuclear digital transducer in such cases will require a separate counter.

When the data rate is low and bandwidth is not a limiting factor, the counter may be used in the system following the telemetry link. In this case the original transducer pulses can be telemetered, in a manner analogous to CW radio-telemetry, or by frequency shift keying. Although pulse rate telemetry is extravagant of bandwidth, it may offer considerable attraction from a cost standpoint when the transducer is to be expendable.

MECHANICAL CONFIGURATION

A cross-section of the sliding shutter transducer is shown in Fig. 4. In this transducer the aperture opening is controlled by the setting of a micrometer screw. The range of setting from a fully closed to a fully open aperture is 0.100 inch and the open aperture is square. A photograph of this transducer is shown in Fig. 5.

A corresponding transducer with rotary shutter is shown in Fig. 6. The full shutter range corresponds to less than 20 degrees rotation of the drum dial which is read by a vernier. A photograph of this apparatus, with the preamplifier circuit board visible, is shown in Fig. 7. The chamber which contains the source and detector may be evacuated through a valve when desired in order to eliminate air scattering and energy spectrum distortion.

Fig. 4. Section of sliding shutter transducer.

Fig. 5. Photograph of sliding shutter transducer.

Fig. 6. Cut-away of rotary shutter transducer.

Fig. 7. Photograph of rotary shutter transducer.

Fig. 8. Experimental transducer with counter readout.

Fig. 8 shows a photograph of the rotary shutter transducer connected to a digital counter readout. This counter is modified so as to include an infinitely variable time base generator so that direct transducer readings may be obtained in terms of any units desired. For example, the sliding shutter transducer can be made to read the micrometer screw setting directly in thousandths of an inch.

EXPERIMENTAL RESULTS

Shutter plots obtained with the sliding shutter and rotary shutter transducers are shown in Figs. 9 and 10, respectively. The straight lines obtained in these plots demonstrate the highly linear characteristics of nuclear digital transducers. It is also possible, by shaping the shutter and aperture, to produce a nonlinear characteristic. For example, it might be desirable to compensate an otherwise nonlinear system in this manner.

The slight scatter of the experimental points in Figs. 9 and 10 is a result of nuclear counting statistics.² Use of stronger sources or longer counting times would greatly reduce the scatter. If each accumulated count had been 100 times as large, for example, so that all numbers shown on the ordinate scale were multiplied by 100, then the percentage standard deviation of the transducer readout would be only 1/10 as great and the points would lie still more closely on the line. It should be mentioned that the data shown were taken with very weak Radium D-E-F sources containing only 1 to 5 microcuries of activity. Weak sources were used in these experiments inasmuch as a high data rate was not required. In transducers designed for practical use, considerably stronger sources would be desirable.

In order to test the immunity of nuclear transducers to temperature changes, the sliding shutter transducer shown in Figs. 4 and 5 was placed in the refrigerator at 40°F. After thorough cooling a plot similar to Fig. 9 was

Fig. 9. Transducer readout graph - sliding shutter.

taken with the door being opened only briefly in order to change the micrometer settings. This plot was completely indistinguishable from Fig. 9 showing that a temperature change of this magnitude had a negligible effect.

ACCURACY

In considering the accuracy of nuclear digital transducers it is necessary to distinguish the mechanical sensing accuracy from the purely statistical readout accuracy. Stated differently the readout of shutter position can be obtained to any desired statistical accuracy simply by accumulating a sufficient number of counts. This means that a nuclear digital transducer is an infinite resolution device.

The mechanical sensing accuracy of the transducer is limited entirely by the mechanical sensor. For example, although bourdon tubes of good linearity and low hysteresis are available, these sensors still have certain deficiencies which should be capable of measurement by means of a nuclear digital transducer. These transducers, due to their infinite resolution and low friction, may offer an improved means for

Fig. 10. Transducer readout graph - rotary shutter.

measuring the performance limitations associated with various types of mechanical sensors.

If the transducer is to measure a changing variable, the accumulated count will represent an average over the time interval determined by the time base generator. This automatic averaging feature may be desirable in certain applications for the purpose of eliminating the effect of rapid signal fluctuations.

APPLICATIONS

In discussing applications of nuclear digital transducers, we shall first mention the obvious one consisting of an analog-to-pulse rate or an analog-to-digital converter based on a D'Arsonval meter movement. Such a device is illustrated in Fig. 11, in which the detector, shutter and aperture are visible. The shutter is attached to the moving coil of the meter movement. This type of converter might be advantageous for use when digitizing equipment having long term stability and accuracy is required as, for example, in an untended remote data station.

Fig. 11. Analog-to-digital converter.

A pressure transducer configured for underwater use is diagrammed in Fig. 12. The pressure-tight compartment with "O" ring seals contains the helical bourdon tube which operates the shutter. With this type of bourdon tube there are no extra mechanical linkages; one end of the helix is attached to the pressure port and the other end to the rotary shutter.

A corresponding configuration for a temperature transducer, utilizing a bimetallic thermometer movement to operate the rotary shutter is shown in Fig. 13. A good bimetallic movement is capable of a 3-second time constant. A somewhat shorter time constant may be obtained by using a temperature sensor of the type employed in an ordinary mechanical bathythermograph. The latter sensor consists of a long thin tube full of toluene that expands with rising temperature and operates a bourdon tube.

The remaining figures show a proposed application of nuclear digital transducers in a digital bathythermograph. Fig. 14 shows a block diagram of the underwater unit which contains a coupling unit to permit multiplexing the signals. The single conductor performs 3 functions; it carries power down to the underwater electronics, pressure and temperature signals up from the transducers and DC control pulses down to the underwater unit for in situ calibration.

For checking the transducer calibration, a DC control pulse gates a generator which operates an electric switching device in the underwater unit, thus simulating zero and full scale transducer readings. Such simulated readings can be obtained in either of two ways: (a) by use of an auxiliary source and detector in fixed geometrical relationship or (b) by rotating the shutter so as to fully open or fully close the aperture. An underwater unit, containing these components in a housing similar to the standard electronic bathythermograph

Fig. 12. Pressure transducer.

Fig. 13. Temperature transducer.

specified by the U. S. Navy Oceanographic Office, is illustrated in Fig. 15.

A block diagram of the deck unit is illustrated in Fig. 16. The digital equipment includes two counters with variable and programmable time bases to give readouts directly in temperature and depth units, and a digital printer or other recording device. The analog equipment includes two simple integrating circuits and an X-Y recorder. The test control panel shown at the top of Fig. 16 is used to actuate the in situ calibration system described above. The deck unit would be equipped with records for making both analog and digital records.

Although the above discussion has been limited to the application of nuclear digital transducers in a bathythermograph, these devices are also being evaluated for other applications. Inasmuch as the cost of the sensing heads is expected to be moderate for pulse rate transducers of excellent long term stability and high accuracy, their suitability may depend upon system requirements as to sampling rate or data rate. It is apparent that increased readout accuracy can be obtained at the expense of sampling rate and vice versa.

Fig. 14. Block diagram of bathythermograph underwater unit.

Fig. 15. Bathythermograph underwater unit.

Fig. 16. Block diagram of bathythermograph deck unit.

The data rate capabilities of a system based on nuclear digital transducers will be dependent upon the maximum obtainable pulse rate. If a full scale rate of 10^6 randomly spaced pulses per second is obtainable, as we anticipate, this would permit one data sample per second with readout accuracy of 0.1%. Longer sampling times would, of course, produce greater readout accuracy. Ultimate mechanical accuracies will be limited by the mechanical sensors chosen. The best available bourdon tubes, for example, have an overall accuracy within a few tenths of one percent.

CONCLUSIONS

On the basis of preliminary tests, the unique characteristics of nuclear digital transducers may lead to specialized digital data systems having outstanding long term accuracy. Nuclear digital transducers appear to offer the following advantages: (1) data digitized substantially at the source, (2) long term calibration stability, (3) overall accuracy limited almost entirely by the mechanical sensor, (4) infinite resolution of readout, (5) excellent linearity of readout or alternatively, prescribed nonlinearity for system compensation, (6) automatic averaging of data over the desired sampling time, (7) unaffected by temperature and other ambient conditions and (8) suitable for rough service applications.

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AN IMPROVED SELENIUM PHOTOVOLTAIC CELL

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ABSTRACT

The selenium photovoltaic cell is frequently used in measurements of water transparency and in underwater measurements in oceanographic research. The photovoltaic cell described in the present paper is an improved type of Weston photonic cell. It consists of two semiconductors in intimate contact and the junction between the semiconductors is the source of the photo-emf.

The cell has high sensitivity particularly at low light levels. At very low illuminations the new cell has been found to generate an emf several times higher than the older types. The various cell characteristics, such as dependence of output on illumination, spectral response, time constant, fatigue and temperature dependence are described. A brief description is also given of the cell construction. It is presumed that a photosensitive heterojunction exists between the two types of semiconductors.

INTRODUCTION

Accurate measurement of light levels under water is important in certain phases of oceanographic research. Of the several types of optoelectric transducers available the most commonly used device is the selenium "barrier layer" cell. This is a photovoltaic cell which generates a potential difference between its terminals when exposed to light.¹ It is self-contained and can operate a meter without the application of an external source of power. On the other hand, photoconductive cells and phototubes can only be used when an external voltage supply is inserted in the circuit.

The selenium photovoltaic cell is rugged and compact and can easily be encased in a watertight housing. Its output is high enough to drive an ordinary meter even at low light levels. Its spectral response is closer to that of the human eye than that of any other photo-device. With the use of a simple filter the resulting response can be made to match that of the eye so that the device can measure illumination as opposed to radiant flux. Furthermore, the cell

shows excellent stability over a period of several years.

Cells of this type have been used in underwater irradiance meters for attenuation measurements of blue-green irradiance. Holmes and Snodgrass² have described an underwater irradiance meter or submarine photometer designed to operate in the upper 100 to 150 meters of water. It permits direct measurement of the downward blue-green irradiance. The detectors in the multi-detector unit are cosine flux collectors equipped with Weston photron cells. The use of the photonic cell in arctic oceanography has been reported by LaFond.³ Water transparency is measured with a hydrophotometer which consists of a standard light source in a watertight housing which transmits a focused light beam through one meter of water to another housing containing the photocell. The cell is also used in an ambient light meter for measuring the ambient light intensities at various depths under water or ice.

CELL CHARACTERISTICS

The new cell to be described is an improved type of selenium photovoltaic cell. It differs slightly in construction from the older type but is considerably more sensitive than its predecessor at low light levels (below 1 foot-candle). Hence it is particularly suited for underwater light measurements. The fabrication process is more flexible and the cell has been made up in a variety of shapes and sizes (Fig. 1). Standard configurations are given in Fig. 2.

Experimental cells have also been made up on flexible substrates. These flexible cells, as well as concave and convex cells, are useful in special applications. The process also permits the fabrication of large area cells. The output characteristics of the new type and the old type cells at moderately light levels are shown in Fig. 3. The output is shown as a family of I-V curves at various light levels ranging from 5 to 200 foot candles at a color temperature of 2870°K. At each light level the external resistance is changed from 3 to 10,000 ohms and the potential difference across the resistor measured with a

¹Superior numbers refer to similarly numbered references at the end of this paper.

Fig. 1. The new cell in various sizes and shapes.

Fig. 2. Standard circular and rectangular cell shapes (dimensions in inches).

Fig. 3. Characteristics of cells at higher illuminations (active area, 11 cm^2).

Fig. 4. Characteristics of cells at low illuminations (active area, 11 cm²).

potentiometer or a high input resistance millivoltmeter. On such a plot the external resistances are seen as diagonals. The end points of the curves on the current axis are the short circuit currents and the end points on the potential axis are the open circuit voltages. The curves give the mean values for 3 cells of each type. It is seen that the new type cells are appreciably more sensitive than the old type.

The improvement is seen to be much more pronounced at light levels below 1 foot candle. The light levels, shown in Fig. 4, range between 0.1 and 1 foot candle and the external resistances from 100 ohms to 1 megohm. While the short circuit currents of the new type cell are appreciably larger, the open circuit potentials exceed those of the old type by more than an order of magnitude. The difference is more pronounced the lower the light level. A pronounced increase in performance is present also in the maximum power capabilities of the cell. The maximum power is obtained from the limiting power diagonal at a given light level.

The output current is seen replotted as a function of the illumination of Fig. 5. With low values of external resistance the output is linear with respect to the light level. The open circuit potential, on the other hand, increases rapidly at first and gradually later and saturates at higher light levels, as seen in Fig. 6.

Fig. 5. Current output of new cell as a function of illumination (active area, 11 cm²).

Fig. 6. Open circuit voltage as a function of illumination.

The improved performance is believed to be due to the difference in the construction of the cells. The photovoltaic junction in the old type cell is between crystalline selenium and a thin, sputtered film of cadmium. A top layer of gold is applied over the cadmium to improve the conductivity of the cells. In the new type cell a thin film of cadmium oxide replaces the cadmium and gold films. Sputtered cadmium oxide is more or less transparent and electrically conducting, forming a highly photosensitive barrier with selenium.⁴ Selenium is a p-type semiconductor and cadmium oxide is n-type. A complex junction is believed to exist between the two types of semiconductors.⁵

The semiconducting properties of selenium and cadmium oxide, and the manner of application of these materials, determine very considerably the photovoltaic properties of the resulting cell. The crystalline nature and the type and amount of impurities in selenium are extremely important as well as the degree of non-stoichiometry and the impurity concentration of cadmium oxide. The optical and electrical properties of cadmium oxide which is an oxygen deficient semiconductor, have been shown to be strongly dependent on these parameters.⁶

The relative spectral response of the cell is seen in Fig. 7. The cell sensitivity is moderate in the blue, peaks in the green and falls off rapidly towards the red. By using a visual correction filter with the cell the resultant response is made to match that of the human eye.

The time constant of the cell is a function of the illumination and the load resistance. The rise and decay times are usually different from each other. For moderate illuminations and with moderate values of load resistance, the rise and decay times range between 0.1 and 5 milliseconds.

All selenium cells show a small amount of fatigue which is the gradual change in the output for a brief interval immediately following exposure to light. With the present cells such

Fig. 7. Relative spectral response.

Fig. 8. Cell fatigue.

effects are small and are generally within 5%. Fig. 8 shows this effect.

Temperature effects are also a function of the illumination and the load resistance. Fig. 9 shows the temperature dependence between 5° and 45°C at two different light levels. The variation with temperature is due to the fact that the internal resistance of the cell is strongly dependent on temperature.

A selenium photovoltaic cell can be represented electrically as a current generator, shunted by a capacitance, C , and an internal resistance, R_i in series with a small resistance, R_s . If the primary photoelectric current is i_p and the load resistance R , the current through the latter is given by

$$i = \frac{i_p R_i}{R_i + R_s + R} \quad (1)$$

This picture is a rather naive representation of the cell performance. The actual mechanism of the cell is much more involved and can only be explained in terms of semiconductor junction theory. So far the exact junction parameters have not been worked out.

Fig. 9. Temperature dependence.

Exposed cells are subject to attack by moisture and corrosive gases. For most precision measurements encased cells are used. Both hermetically sealed metal-glass cases and non-hermetic bakelite cases have been developed. Hermetically sealed cells have excellent stability over a period of several years. A model 596 cell, encased in a bakelite case, is shown in Fig. 10.

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Fig. 10. A model 596 cell.

DIGITAL PRESSURE TRANSDUCER STUDY

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ABSTRACT

The tunnel diode has a characteristic performance curve which can be utilized for underwater transducer applications. One very important application of this component would be as a pressure transducer providing a direct digital output reading. A tunnel diode and appropriate electronic circuitry has been examined and evaluated for this purpose. The design, analysis, test and evaluation results of this study are presented.

INTRODUCTION

The discovery of the tunneling effect in heavily doped P-N junctions by Esaki¹ in 1958 has made available a component which exhibits characteristics that are useful in areas ranging from computer logic to communications. A great many papers have been published since 1958 regarding tunnel diode characteristics and applications.

This paper will describe an investigation, conducted in the Research Laboratories of the Pratt and Whitney Company to evaluate a digital output tunnel diode transducer for oceanographic pressure measurement. The possibility that future oceanographic instrument systems may be computer oriented establishes the requirement for a digital output pressure transducer capable of measuring pressures to 15,000 psi with an accuracy of $\pm 0.5\%$ of full scale. The approach taken during this investigation has been to use the tunnel diode in a unique hybrid oscillator circuit rather than in the conventional amplifier or oscillator modes.

TUNNEL DIODE AS A PRESSURE TRANSDUCER

The reported works of Mason² and Sikorski and Andreatch³ demonstrated clearly that the characteristic I-E curve of the tunnel diode is pressure sensitive. Curve "A" of Fig. 1 represents the I-E characteristics of a germanium tunnel diode at atmospheric pressure. The peak current and voltage are designated by I_p and E_p respectively. The negative conductance, $-g_d$, is the slope of the I-E tunnel diode curve between I_p

Fig. 1. Tunnel diode characteristic curve.

and I_v where I_v is the valley current and E_v is the valley voltage. Germanium differs from silicon tunnel diodes in that the peak current decreases with pressure.³ The change in the I-E curve, represented by curves "B" and "C", results from the application of hydrostatic pressure. The applied pressure stresses the semiconductor, affecting the energy gap and effective mass (ratio of effective mass of the electron to its mass in free space) which are related to the tunneling probability.² The tunneling probability is related to the current through the junction resulting in the change observed in the I-E curve. Mitchell⁴ has derived the tunnel diode curve utilizing quantum mechanics and the energy level relationships.

Superior numbers refer to similarly numbered references at the end of this paper.

Depending on the circuit configuration associated with the tunnel diode, the device can operate in a switching, amplifier or oscillator mode. The amplifier mode, when used as a pressure transducer, has a gage factor which can be as high as 30,000.² Considering the bonded wire strain gage with a gage factor of less than 10, the potential of the tunnel diode as a pressure transducer can be appreciated. The 15% decrease in peak current associated with germanium tunnel diodes under 20,000 psi pressure is responsible for the great sensitivity.

TUNNEL DIODE PRESSURE TRANSDUCER OSCILLATOR MODE

Conventional Oscillator Mode

The series tunnel diode oscillator shown in Fig. 2a and the series parallel tunnel diode shown in Fig. 2b are the conventional oscillator circuits used to generate a sine wave. The series parallel oscillator shown in Fig. 2b is considerably more stable than the series oscillator because the "tank" circuit in the series parallel configuration is primarily responsible for the output frequency. Changes in frequency with pressure would be small except at very high frequencies where the tunnel diode shunt capacitance is a large part of the "tank" circuit.

The series tunnel diode oscillator shown in Fig. 2a depends on the value of the negative conductance for its frequency and stability.⁵ The negative conductance, $-g_d$, is not single valued and the value specified by the manufacturer is an average one. Obviously, the slope of the curve is voltage dependent; therefore, the stability of this configuration is not very good. With pressure changes affecting the negative slope of the I-E curve, stability is difficult to maintain over a wide range. The change in $|g_d|$ due to the variation of the I-E characteristic curve with pressure can be shown to vary with the output frequency. Thus

$$f_o = \frac{1}{2\pi} \sqrt{\frac{(1-R_T)|g_d|}{LC}} \quad (1)$$

where R_T is total equivalent circuit resistance, L is series inductance, C is shunt capacitance and $|g_d|$ is the absolute value of negative conductance. The requirement for stable oscillation is that L/C be made equal to $R_T/|g_d|$.

Hybrid Oscillator Mode

The tunnel diode switching operation can be understood by reviewing curve "A" in Fig. 1. The peak and valley currents are the key switching points. If the current reaches the peak value the diode voltage increases to correspond with the point "a" on the I-E curve. When the current is reduced to the value of the valley current the tunnel diode switches back to the low

$$R_T = \frac{r_1 \times r_2}{r_1 + r_2} + r_s + R_{DC} \text{ (coil)}$$

(a.) SERIES

$$R_T = \frac{|-g_d|}{\omega^2 C_1^2 + |g_d|^2}$$

(b.) SERIES PARALLEL

Fig. 2. Tunnel diode oscillator circuits

voltage state. A current change is all that is required to operate the tunnel diode switching mode. This switching characteristic does not depend on the value of g_d .

The hybrid configuration shown in Fig. 3 is a relaxation oscillator with a square wave output. The tunnel diode, when switching from the low voltage state to the high voltage state, turns the transistor, T-1, "on." Turning the transistor on discharges the capacitance, C_1 . When C_1 has discharged to the point where the current through the tunnel diode switches back to the low voltage state turning T-1 "off," C_1 then charges up through the circuit provided until the current through the tunnel diode reaches the value of the peak current and switches the tunnel diode back to the high voltage state. This turns the transistor, T-1, "on" and another cycle begins.

The tunnel diode characteristic curve shows that the values of the peak and valley currents of the I-E curve depend on pressure. These in turn establish the point of the charging or discharging cycle where switching occurs. This characteristic of the tunnel diode results in a

Fig. 3. Tunnel diode hybrid oscillator circuit.

change of frequency with pressure. Referring to Fig. 3, the characteristic times for the hybrid oscillator circuit can be written as

$$t_c = \frac{(r_1 + r_2)r_3 C_1}{r_1 + r_2 + r_3} \log_e \left(1 - \frac{(r_1 + r_2 + r_3)I_p}{E} \right) \quad (2)$$

$$t_d = \frac{r_2 r_3 C_1}{r_2 + r_3} \log_e \frac{I_v}{I_p} \quad (3)$$

$$t_t = t_c + t_d \quad \frac{1}{f} \quad (4)$$

where t_c is charging time in seconds, t_d is discharging time in seconds, t_t is the total time per cycle and f is the frequency of square wave output in cps.

The capacitor discharge characteristics shown in Fig. 4 result in a problem due to the non-linearity of the curve. The peak and valley

Fig. 4. Capacity discharge curve.

currents are functions of pressure; therefore, the time required for the valley current to reach the switching point during the discharge cycle varies and produces shifts in frequency which are not linear with pressure. In order to eliminate this problem the charge and discharge characteristics of the capacitor must be linearized.

The charging or discharging current must be constant in order to linearize the characteristics of the charging and discharging time. The general expression for capacitor voltage may be written as

$$e_c = \frac{1}{C_1} \int i dt \quad (5)$$

where e_c is voltage across the capacitor, C_1 is the capacitor and i is the charging or discharging current. However, if i is constant, Eqn. (5) reduces to

$$e_c = kt \quad (6)$$

where k is i/C_1 and t is the charging or discharging time.

The charging and discharging periods, therefore, can be made linear with time if i is held constant. This is accomplished by making r_1 very large and E a high voltage, producing a constant current source for charging C_1 . The transistor, T-2, has the base current set with P-1 to produce a constant discharging current. The resistor, r_5 , is provided to prevent the voltage from being applied directly to the base while the base drive is being set. The value of r_3 is selected such that the current reaches the peak current, I_p , before the capacitor is completely charged. The transistor must be saturated when the peak voltage of the tunnel diode is applied to the base. Therefore, resistor r_4 must have a value such that the product of the collector current of

transistor T-1 and r_4 is greater than the value of the voltage applied to the transistor when the base voltage is equal to the peak voltage of the tunnel diode.

If the shift in frequency due to pressure is caused to follow some predetermined schedule, the transistor T-2 can also serve another purpose. By rectifying the output and using the voltage to drive the base of the transistor, T-2, we can also perturb the frequency pressure characteristics as a function of frequency.

EXPERIMENTAL SETUP AND INSTRUMENTATION

A pressure cell was fabricated as shown in Fig. 5. A commercially available germanium tunnel diode was obtained and the top of the hat carefully removed. Silicone grease was used to fill the cap and it was the only element of the circuitry exposed to pressure. The hydrostatic pressure was applied using an air operated hydraulic pump that permitted setting the air pressure to hold a given hydrostatic pressure during readings. A pressure gage was carefully calibrated and was used to indicate the pressure in the cell. The voltages applied to the circuit were well regulated and instrumented. A Hewlett Packard (Model 524c-10) counter was used

Fig. 5. Pressure cell and electronic elements.

to measure the output frequency. Fig. 6 is a photograph of the test setup.

EXPERIMENTAL RESULTS

Using the series amplifier configuration previously described the plot of the frequency vs. pressure shown in Fig. 7 was obtained. Two sets of data are plotted on this curve for comparison. Many additional sets of data were also taken and the results were uniformly the same. A 500 cps

Fig. 6. Test setup.

Fig. 7. Series oscillator frequency vs. pressure.

frequency shift per 1,000 psi with a frequency of 90 Kcps at atmospheric pressure was observed. The deviation from the best straight line was ± 50 cps on the average. The minor shifts were due to the natural instability of the circuit under pressure.

The data from the tests of the hybrid oscillator configuration are shown in Fig. 8. The frequency variation with pressure was plotted at various atmospheric pressure frequencies, f_0 , ranging from 10 Kcps to 1 Mcps. The shift in frequency per 1,000 psi increased as the atmospheric pressure frequency was increased. An output of 20 cps/psi was obtainable when f_0 was 1.8 Mcps; however, the accuracy is better at the low frequencies. In the region from 0 to 1,000 psi a larger shift in frequency was noted, indicating the I-E curve did not vary linearly. However, compensation can be used to correct for this nonlinearity. The average shift in frequency per 1,000 psi plotted against f_0 for a 20,000 psi change in pressure is shown in Fig. 9 for the same configuration. The shift in frequency is 15% or better, depending on f_0 .

For a 200,000 cps shift in frequency from 1 Mcps when 20,000 psi is applied, the average shift is 10 Kcps per 1,000 psi representing 20%. In order to obtain the desired accuracy we must measure the frequency to at least 1 Kcps.

Fig. 8. Hybrid oscillator curves.

Fig. 9. Frequency shift vs. frequency at atmospheric pressure.

However, much better resolution can be accomplished.

Common mode rejection can be accomplished by utilizing 2 hybrid tunnel diode oscillators and beating the two frequencies as shown in Fig. 10. The difference frequency output will result because one tunnel diode is exposed to pressure but the other is not, although they are in the same environment. The output frequency is then gated into an accumulator whose output collectors indicate the stored count in binary. The difference frequency, being less than f_1 or f_2 in Fig. 10, requires less accumulator capacity. A serial or parallel readout can be accomplished with suitable circuitry. The voltage and temperature problems are now common to both circuits and effectively cancel out. Greater accuracy may be obtained using this technique.

The test circuitry did indicate that there is some apparent hysteresis. However, the overall performance characteristics indicate that this is not a serious problem because the hysteresis is well within the accuracy limits. Zero reference shift for the single oscillator configuration is due primarily to bias voltage changes and temperature. Common mode rejection would solve this problem.

Fig. 10. Block diagram of measuring system.

The test results demonstrate that a tunnel diode transducer will provide an accuracy of $\pm 0.5\%$ of full scale with high sensitivity. The applicable pressure range extends from atmospheric to 20,000 psi. It is our opinion that oceanographers can make excellent use of this device in their instrument systems.

DISCUSSION AND CONCLUSIONS

A transducer system for obtaining a direct digital output proportional to pressure has been described. The highly responsive tunnel diode as the pressure transducer provides steady state and transient pressure readings in digital form with a sensitivity of 3 cps/psi when f_0 equals 300 Kcps and 10 cps/psi when f_0 equals 1 Mcps. The demonstrated accuracy is $\pm 0.5\%$ of full scale which we believe is satisfactory for many oceanographic requirements. Improvements in accuracy can be foreseen in the near future.

The ability of the hybrid configuration to operate stably over a wide range of frequencies and provide means for selective direct compensation for nonlinearities make this configuration most attractive. Common mode rejection will reduce the effects of temperature, supply voltage changes, etc.

Reliability, life and performance tests under actual field conditions remain to be conducted but because of its favorable size and digital output the tunnel diode pressure transducer may become an important component of computer oriented oceanographic research instrumentation systems.

LIST OF SYMBOLS

- I_p peak tunnel diode current.
- I_v valley tunnel diode current.
- V_p tunnel diode voltage corresponding to the peak current.
- V_v tunnel diode voltage corresponding to the valley current.

- $|g_d|$ absolute value of the negative conductance.
- r resistor.
- C capacitor.
- L inductor.
- E_{bb} applied voltage
- V voltage applied to transistor in hybrid configuration.
- t time
- f_0 frequency at atmospheric pressure.
- f_{01} frequency shift from f_0 to f_1 .
- R_T total equivalent circuit resistance.
- e_c voltage across capacitor.
- k ratio of current to capacitance.

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