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DEVELOPMENTS IN ACOUSTIC TRANSDUCTION IN WESTERN EUROPE
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6 JUNE 1979

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I. INTRODUCTION

For the past thirty years piezoceramics has dominated the technology of underwater acoustic transduction. Older concepts such as magnetostriction, moving-coil, variable reluctance, piezoelectric single crystals, and so forth, have been used only in some limited applications. Fleet sonar has used piezoceramics almost exclusively. The general trend in sonar to low frequencies has generated various efforts to replace piezoceramics as a sound source, with variable reluctance and magnetostriction transduction and the Bouyoucos hydroacoustic oscillator as the principal challengers. None succeeded. Even with the low-frequency limitation of piezoceramics as a high mechanical and electrical impedance source, it remains the principal sonar sound source concept. As a hydrophone, piezoceramics is likewise well entrenched in spite of weakness such as brittleness and limitations on the size of homogeneous elements.

After many years of a steady decline in transduction research and development, there has been a recent rebirth of new concepts or new materials in transduction technology. These include piezopolymers, acousto-optic sensors, rare earth magnetostriction, new ceramics, SAW oscillators, ferrofluids, and fluidic oscillator sources. Some, as piezopolymers, have undergone a great deal of research. Others, as ferrofluids and SAW oscillators, have merely been demonstrated as possible concepts. In no case has any of these concepts approached the engineering stage in sonar applications. Because of this latter criterion the relatively new concept of parametric transduction that already is in fleet use was not included.

It was the purpose of this survey to ascertain the exploratory development on these transduction concepts in Western Europe. Although both research and development were surveyed, the focus was on the feasibility of using these concepts in sonar applications. Other applications, and as audio acoustics and ultrasonics, were included only in a supplemental sense. Each of the appendices of this report provides a background and an explanation of the new concept, a commentary on the research and development in the United States, and references—all as of January 1979. The appendices also comprise a synopsis of the oral presentations given at the places visited to enhance the exchange of information.

Transduction as used here includes only those concepts capable of steady-state vibration. Explosions, air-guns, and so forth are excluded.

A survey of underwater transducer calibration, test, and evaluation methods and facilities was a secondary purpose of this effort.

II. UNITED KINGDOM

a. University College of London

A group in the Electrical and Electronics Engineering Department, headed by Prof. D.E.N. Davies, was one of the first to discover and exploit the acoustic-optic effects in glass fibers. Davies has a radar background and his group (S.A. Kingsley, B. Culshaw, F. Fiddy, T.J. Hall, and D. Howard) has used the acoustic-optic effect as a means of inserting a modulation signal into the fiber. That is, the modulation is inserted by exposing the fiber to radiated sound. Currently, however, they are extending their work to the case of a fiber-optic hydrophone as described in Appendix B. They have built a hydrophone and tested it at the Plessey Company facility at Templecombe. A small tank, about 1 x 1 x 2 m, is being installed in the University building in London. They are all very knowledgeable about the various acoustic-optic effects due to dimensional changes and refractive index changes. They are probably on a par with the groups at NRL and NUSC, New London. They are all very knowledgeable about the fibers is concerned, but are relatively inexperienced in underwater acoustics. For example, they hope to get to frequencies as low as 1 kHz in their small 1 x 1 x 2 m tank. At the USRD-NRL in Orlando, the low-frequency limit in a similar size tank was 100 kHz.

Some of the research being done by the Davies' group is being sponsored by the British Navy.

b. EMI CENTRAL RESEARCH LABORATORIES
Hayes, Middlesex, England

EMI is a large British company comparable in size and function to RCA. Like RCA it has a centralized research laboratory located in Hayes, Middlesex, about a half hour on the train from central London and near Heathrow Airport. The Department of Electrochemistry and Plastics, one of 13 departments, is headed by Dr. Lyn Holt, who supervises some 14 people in research on piezopolymers, video recording disks, and acoustic imaging.

EMI is not in the sonar business, at least not yet. Its work on piezopolymers is a spin off of some research on the plastics used in video recording disks. The company has considerable resources and experience in the plastics business. Among other things, it is the largest manufacturer of credit cards in the world. Dr. John McGrath is the principal investigator on piezopolymers.

Holt and McGrath have succeeded in producing thick films of polyvinylidene fluoride (PVF₂) that could be very useful in sonar transducer technology. Most PVF₂ films produced by the Kureha Company

in Tokyo are 6 to 25 μm thick. For applications in air acoustics this thickness is satisfactory. For the reasons explained in appendix A, thicknesses of 250 μm or more are needed to fully exploit PVF_2 as a hydrophone sensor material. Thus the EMI PVF_2 , which can be made in thicknesses of 1,000 μm has significant potential for hydrophones, particularly in large aperture configurations. Thick films can be made by laminating many thin films. J.M. Powers at the NUSC, New London, has succeeded in producing a 32 layer lamination. But there is some question about the practicability of this on a large scale. In any case, one thick film is much preferred to many thin ones.

EMI can not only produce thick films, it can extrude tubes and solid cylinders. Tube diameters of 1 cm and solid cylinder diameters of 2-3 cm have been made. Larger tube diameters are feasible. However, these PVF_2 tubes are different than a PZT cylinder in that the hoop or circumferential mode of vibration is degraded by the low g_{32} constant. Unlike PZT the g_{31} and g_{32} constants are not the same. The extrusion process puts the g_{31} mode and the polymer chain lengths in the axial direction, and the g_{32} in the circumferential direction.

EMI still treats its processing techniques as proprietary information. However, the piezoelectric and dielectric constants of the thick film are similar to the thin Kureha PVF_2 . The speed of sound can be controlled in the range 800 to 2000 m/s. The 400 to 500% stretching and poling techniques are the same as for the thin film. The material is linear to peak signals of at least 240 psi (about 2×10^{11} μPa).

The EMI effort in PVF_2 to date has been relatively small, with McGrath and two others as the total manpower. It is strictly a research laboratory effort. What samples they can and do furnish cost about \$100 per square inch. They seem poised to expand into a large scale production effort if they can find a market. In such case the cost should drop by an order of magnitude. Holt and McGrath were planning a visit to NUSC New London, NOSC San Diego, ONR Code 472, and the National Bureau of Standards (Broadhurst and Edelman) in April 1979. Dr. A. Hajimichael, Chief Chemist of the EMI Electronics Division, is working with Holt's group in case large-scale production is funded.

The British Navy is of course also interested (see section on AUWE).

Mr. Brown in Holt's department has developed an acoustic imaging system or acoustic camera that works quite well, at least at a 1-m range. A person's hand is clearly definable on the CRO readout. A 50-kHz noise band centered at 2 MHz is used to expose the target to radiated sound. A plastic lens focuses the sound reflected from the target onto a quartz sensor built into a scanning CRO tube. The image plane is 3 x 3 cm with 100 x 100 image points. It's unclear whether this system resolves the conflicting requirements of good resolution and long range.

c. Admiralty Underwater Weapons Establishment
Portland, Dorset

The Admiralty Underwater Weapons Establishment (AUWE) is the British counterpart of the U. S. Navy Underwater Systems Center (NUSC) and to a lesser extent the Navy Ocean Systems Center (NOSC). It is located in Portland harbor on a naval base used for British Navy training as well as for the AUWE.

Sam Mason is head of the Sonar Department in which the transducer work is done largely in the Submarine Sonar Systems Division under Dr. Liddell. Mr. Richard Gale is the principal investigator in transducers. The RDT&E spectrum of the work varies from the equivalent of our 6.1 thru 6.4. However, they are manpower limited, and it's the 6.1 end that suffers. They accordingly contract some of the 6.1 work to the University College of London for research on fiber optic acoustic sensors and, somewhat indirectly, to EMI Central Research Laboratories for research on piezopolymers. In this way they have kept up-to-date on these two new developments.

At AUWE there is some duplication of transducer research effort because of the singular importance of towed line arrays. There is a Towed Line Array Division separate from the Submarine Sonar Systems Division. Dr. Allan Parsons was recently transferred to AUWE and the TLA Division, in a reorganization that abolished the former Admiralty Research Laboratory at Teddington. He has experimented with piezopolymer hydrophone elements in a towed line array with inconclusive results. He wrapped some 30 μm thick Kureha polymer around solid cylinders of syntactic foam. In this way the g_{31} mode and the conventional mechanical transformer in cylinders produced a theoretical level of about -180 dB re: 1 V/ μPa , and a measured level somewhat lower. The results were variable and there were impulse noises of unknown origin.

Mr. Martin Earwicker has worked on the near-field calibration technique developed by Dudley Baker at ARL Texas. This technique for monitoring large submarine sonar transducer performance has been built into a submarine system so that a calibration measurement can be made at sea at any time!

The sonar transducer calibration facilities at AUWE are impressive. "Crystal," the test barge that floats in Portland Harbour, is 413 ft long, 56 ft wide, displaces 3000 tons, and at one point is 93 ft high although the draft is only 6 ft! It has 19 stations for inserting transducers into the water, two of which are very large, and one of these appears like rocket launching gantries at Cape Canaveral. The drawbacks of the Crystal facility are a noisy environment and only 60 ft of water depth. The low frequency limit is set by

the noise at about 500 Hz. On shore a tank similar in size to the NRL/USRD Anechoic Tank is used without an anechoic lining. The reverberation keeps the pulse repetition rate down to about 8 pps and the low-frequency limit at 10 kHz. An air pistonphone is available for low-frequency measurements in small hydrophones. An open tank about 8 x 8 x 8 feet is lined with old fafnir. Mr. F. T. P. Carter is in charge of the calibration facilities.

d. Admiralty Marine Technology Establishment
Holton Heath, Dorset

The Admiralty Marine Technology Establishment (AMTE) is a new R&D organization composed of the former Admiralty Research Laboratory (ARL) in Teddington, the former Admiralty Materials Laboratory (AML) in Holton Heath, and other miscellaneous activities. The reorganization has not affected the program of the Holton Heath activity. It is still a materials research center, without counterpart in the U. S. Navy.

There are three groups at AMTE doing research in transduction or related materials. Dr. Michael Lindley is working in rare-earth iron alloy magnetostriction. His current objective is developing sintering techniques for producing grain-oriented pieces of the alloys. Later, if the techniques are successful, he envisions a cooperative effort with AUWE in applying his alloys to transducers.

Mr. Douglass Luff is a ceramist. His work is aimed at identifying chemical techniques that will insure less variability in the electro-acoustic parameters as the d , g , k , and e constants. He has found that the amounts of zirconium and titanium in PZT must be controlled to 0.3% to insure optimum results. Luff is also following up on the work of the Russians and Japanese in mixing various amounts of lead magnesium niobate into PZT. They are able to get a d_{33} constant as high as $800 \text{ CN}^{-1} 10^{-12}$ with certain mixtures. Luff routinely makes a wide variety of piezoceramics, each tailored to specific application requirements--not necessarily in sonar. In producing ceramics, metals, rubbers, etc, AMTE has extensive in-house capability for fabrication on a research scale.

Mr. Bernard Nicholls does research in anechoic coatings and decoupling materials. His techniques for evaluating these materials are largely copies of similar techniques developed at the USRD/NRL as pulsed impedance tubes, active transducer absorbers, and an anechoic tank not yet in operation.

The British concept of an R&D center that deals with materials from basic research through fleet support is one that the U. S. Navy would be well to copy. As an example of the fleet support function, AMTE trains the technicians who cement anechoic coating tiles to submarine hulls.

e. Plessey Marine Research Unit
Templecomb, Somerset

The Plessey Marine Research Unit provides research and development for the Plessey Marine Company, which in turn is the division of the Plessey Corporation that manufactures sonar and other marine systems and equipment. Mr. W. Craster supervises a group of about 10 people in transducer research and development. They design experimental transducers for a wide variety of potential applications--wide band hydrophones, arrays, high resolution sonar, and so forth. Calibration facilities include a 60-ft deep quarry and an indoor tank about 12 x 12 x 10 ft lined with a material like insulcrete, but in building-block shape.

Craster is following developments on piezopolymers and fiber optic sensors. He had a separate Plessey research establishment at Carswell furnish some "drumhead" type hydrophones with enough internal excess pressure to provide an outward diaphragm displacement bias. Craster said that it was very sensitive but quoted no figures.

The fiber optics researchers described the hydrophone developed with the cooperation of the University College of London. Apparently T.J. Hall, a graduate student at the University, developed the hydrophone while holding a "summer student" job at Plessey. Plessey, the University, and AUWE all seem to be taking at least partial credit for the same hydrophone. The Plessey people emphasized that the hydrophone worked exceptionally well. Unlike the Naval Research Lab (NRL) version, a heterodyning technique is used, and no reference fiber is needed. The optical signal is inserted into the sensor fiber as a 72-MHz carrier. The acoustic signal modulates the carrier. Then conventional demodulation techniques are used to measure the acoustic signal.

Craster said that they still use a great deal of barium titanate. Luff at AMTE made a similar statement. I expressed some surprise at this. Craster attributed the situation to a reluctance by AUWE to change but also felt that PZT would completely replace barium titanate in the next few years.

While Craster is interested in continuing both piezopolymers and fiber optic sensors, he is limited by manpower and funds, and is unlikely to get much in-house support for pursuing any further research and development.

f. The University of Birmingham
Birmingham

The Department of Electronic and Electrical Engineering of the University of Birmingham is located in the Edgbaston section of the city. One of four divisions in the Department is Acoustics under the supervision of Dr. V. G. Welsby. This Department appears to be

the principal source of engineers for the various academic, industrial, and government groups involved with sonar and underwater acoustics in the United Kingdom. The main area of research and development is sonar systems--particularly high-frequency high-resolution systems. They do no transducer research and development for its own sake. However, they design and build all their own transducers. They also are keenly aware of the transducer as the link in their systems that is most vulnerable to problems, errors, and limitations. Consequently transducer theory and practice is emphasized in their teaching and research. Conventional transducer technology is used, and the Department has a 27 x 15 x 10 ft tank for test and calibration. When deeper water is required, they go to sea--usually on a vessel furnished by the government department of fisheries.

g. Loughborough University of Technology
Leicestershire

The group in Loughborough is near Birmingham and is similar to Welsby's Acoustics Division in many respects. This group is in the Department of Electronic and Electrical Engineering and concentrate on high resolution scanning sonar. They have both a test tank and a calibration tank and also use fisheries vessels for at-sea measurements.

One difference is the work of Dr. B. Woodward in piezopolymers. He is one of few who have done research and published reports on the underwater applications of PVF₂. (See reference 6 of Appendix A.) Although he hasn't done much research in the past year, he plans to do so, largely in the direction of applying PVF₂ to medical ultrasonic uses.

h. Bath University
Bath, Somerset

Dr. H. O. Berkday is a well-known researcher in nonlinear acoustics and parametric transduction. He recently moved from the University of Birmingham to Bath. The author received many suggestions that he visit Bath because of Dr. Berkday's presence there and a research program closely associated with the British Navy. Unfortunately such a visit could not be arranged within the time available. However, any future similar survey should certainly include Bath University.

III. ITALY

a. Istituto di Acustica "Corbino" (Corbino Institute of Acoustics)
Consiglio Nazionale Delle Ricerche (National Council for Research)
Rome Via Cassia 1216

The Corbino Institute of Acoustics is one laboratory among many of the Italian National Council for Research. It has 15 professional scientists working in environmental acoustics, solid state physical

acoustics, signal processing with acousto-optic and surface acoustic wave devices, and ultrasonic technology as used in non destructive testing and medicine. Prof. A. Barone is the director.

There is no acoustic transduction research. However the acousto-optics and SAW research of Dr. G. Socino is somewhat in line with the SAW hydrophone concept described in appendix G. He also is investigating how transparent piezoelectric crystals such as quartz and lithium niobate can be used as signal processing devices by having surface acoustics waves modulate optical signals--somewhat the same objective as the group at the University College of London.

Dr. M. Pappalardo is working in ultrasonic imaging in the depth direction, for medical applications. He uses a dynamic shading technique that changes the focal point of a focused transducer at the same speed as the speed of sound and reads out reflected signals in real time. His transducer array is conventional piezoceramic, but after our discussions he showed interest in piezopolymers, which were unfamiliar to him. Pappalardo learned about transducer technology during a sabbatical period at the University of Birmingham under Dr. Welsby.

During a casual luncheon conversation Barone described an experiment that he conducted many years ago but was never able to follow up. A glass vertical cylinder is filled with water and surrounded by a heavy wire coil. A large electrical charge is dumped into the coil. An acoustic shock wave was produced in the water by an unknown transduction mechanism. The water after the shock wave was described as full of bubbles--probably cavitation! Barone has no theory on the transduction mechanism, but the anecdote was motivated by my description of the USRD Overby experiment with ferrofluids.

b. USEA,
Via G. Matteoti 63, 19030 Pugliola
Di Lerici (SP)

USEA is a small company in Lerici that specializes in producing sonar transducers for the Italian Navy. Prof. Ing. G. Pazienza is the general manager. Their designs are conventional PZT in tonpilz configurations for active sonar and cylindrical elements for passive sonar. They are doing some research on materials with a copy of the USRD/NRL impedance tube. They have somewhat ambitious plans for an anechoic tank like that of the USRD. Meanwhile, they use an Italian Navy open-water site at Sarzana where the water is 15 to 20 m deep. A modified tug-like boat serves as the instrumentation platform. Their work spaces were most impressive indicating their appreciation that assembly of transducer elements requires a clean orderly environment.

c. Italian Naval Base and NATO SACLANT ASW Center in La Spezia

The Italian Naval Base at La Spezia is largely a test and evaluation center. SACLANT is a tenant organization. Neither has much capability for transducer work, although both seem to badly need such capability. Mr. George Connolly at SACLANT, but from NUSC New London, is a submarine sonar specialist but has inherited transducer development by default. He felt that the absence of a transducer program is a significant weakness in SACLANT's program. Their facilities for making towed line arrays, for example, are part of the same mechanical shop that provides rigging and so forth. USEA would be a convenient and excellent contractor for SACLANT transducers. However, key individuals on the SACLANT staff knew nothing of this company only 15 minutes away.

Connolly was interested in piezopolymers, fiber optic sensors, and rare earth magnetostriction. He has visited Plessey Marine in Templecomb and volunteered some opinions. Plessey has an electronics group in Havant, UK, that is knowledgeable about fiber optics. If Plessey gets further into the acoustic fiber optic work, Connolly feels that the Havant group will do it, not Plessey Marine.

d. Institute for Research in Electromagnetics
via Panciatichi, 50100 Florence

The Institute for Research on Electromagnetics (IROE) is associated with the University of Florence. Prof. L. Masotti at IROE has been doing work with optical fibers. Like others, his initial interest was in data transmission, and now it is expanding into acoustic sensors. The author did not visit Florence. The information was provided by Prof. G. Tacconi of the Istituto di Elettrotecnica at the University of Genoa and Dr. Fossi of USEA who is a graduate of the University of Florence.

IV. FRANCE

a. Groupe d'Etudes et Recherches de Detection Sous-Marine,
(The Study and Research Group for Underwater Detection)
Le Brusac, 83140 Six Fours Les Plages

The Study and Research Group for Underwater Detection is the French Naval counterpart of NUSC, located at Le Brusac, and composed of two organizations. The Laboratoire de Detection Sous-Marine (Laboratory for Underwater Detection) works at the research and exploratory development (or 6.1 and 6.2) levels. The Group D'Etudes de Detection Sous-Marine (The Study Group for Underwater Detection) works at the prototype and engineering (or 6.3 and 6.4) levels. Mr. M. Quivy (Kwee-vee) is in charge of transducer research and development and the transducer calibration, test, and evaluation facilities.

It is the policy of the French Navy to use contractors as much as possible for research and development, and this is evident in Quivy's program. Transduction research on electret sensors and piezopolymers is being sponsored at the Ecole Supérieure de Physique et de Chimie Industrielles in Paris and at one division of the large Thomsen-CSF company near Nice. Sponsored research on fiber optic acoustic sensors is planned at CIT-ALCATEL in Marcoussis near Paris and on ceramic-elastomer composites at some as yet unidentified contractor. (See Miscellaneous topics for more on Marcoussis.)

In piezopolymer research Quivy's experience has been similar to Parson's at the AUWE. Attempts to use the g_{31} mode by stretching the polymer over a foam or elastomer results in instability as a function of depth. Laminations of 50 sheets of 90 μm thick Kureha polymer have been successfully prepared--but only with a great deal of care and trouble. The most successful hydrophones have been those designed with a symmetric drive using the g_{33} mode.

The electret research sponsored at the Ecole Supérieure in Paris has produced a new twist to electret sensors as described by a paper by Lewiner and Hennion in the *Journal of the Acoustical Society of America* of April 1, 1978 (p 1229) entitled "A new principle for the design of condenser electret transducers." In this concept there is no air gap, and theoretically the sensitivity can be independent of hydrostatic pressure. A bilaminar device of teflon and polyether produces a charge at the interface when the interface is distorted by vibration. According to Quivy the independence of hydrostatic pressure has not been achieved in practice, and more research is needed. Temperature effects also have not yet been studied.

The same authors also published an earlier paper "Condenser electret hydrophone" *JASA* 63, 279 (Jan. 1978) that described a more conventional electret condenser hydrophone. Typically, it was sensitive to hydrostatic pressures.

A Madame Richard has been performing some in-house research on small wide-band sensors with cardioid patterns using the basic concepts of Bauer and of Marciniak, where a phase shifting acoustic network is inserted into the signal on one side of a bimorph sensor. She has successfully obtained one decade bandwidths (2-20 kHz) with a sensor about 2 centimeters in diameter.

The Le Brusac laboratory is exceptionally well equipped for calibration, test, and evaluation measurements. They have a deep water facility (similar to the NUSC Lake Seneca and the NOSC Lake Pend Oreille) at Castillon in the French Alps. There are several open tanks at Le Brusac. The largest of these is 12 x 8 x 6 m and appears similar to the former reactor pool at NRL now used by the Physical Acoustics Branch there. A new anechoic tank facility is essentially

a copy of the USRD facility including Insulcrete and a Groves/Trott near-field array. Like the tank at the Naval facility in Crane Indiana the high pressure limit is equivalent to a kilometer depth. A glass filament pressure vessel (as developed by Green at NOSC) and a USRD pulsed impedance tube are also available. A pistonphone calibrator can be used for low-frequency calibration, but has a high-frequency limit of only a few hundred Hz, and no pressure or temperature control.

Much of the electronic equipment is familiar B&K, Hewlett Packard, Tectronics and so forth.

V. NORWAY

- a. SIMRAD Company, Strandpromenodan 45,
P.O. Box 111, N-3191 Horten,
The Technical University, Trondheim

The SIMRAD Company (originally Simenson Radio Co.) is a major manufacturer of sonar systems for the Norwegian fishing industry, the Norwegian Navy, and the off-shore oil industry. It employs about 500 people between its locations in Horten and Oslo. About half of its sales consist of fish-finding sonar. This equipment does not fit the American concept of a fish-finder as a crude and low priced depth-finder. Fishing is a major industry in Norway, and some of its largest ships in the fishing fleet have investments as high as \$500,000 in sonar equipment. The Irish, Australian, and British navies have bought some of the largest fish-finding sonar systems for military applications!

Mr. Per Pettersen is Product Manager of their Naval Systems Division, and their principal transducer engineer. Although their transducer designs are conventional piezoceramic and magnetostriction, some of their technology is different from American practice. For example, their magnetostrictive stacks are completely exposed to the salt water--even the interstices between stacks! Their design philosophy is to use only corrosion resistant metals such as brass, stainless steel, and nickel. This is initially expensive, but the equipment lasts as long as 20 years! They also use a polyurethane foam with small piezoceramic "tonpiliz" elements. The foam serves both as the only mechanical support of the elements and as an effective pressure release baffle to radiation to the rear.

SIMRAD does no in-house research and development, but does sponsor four research associates at the Technical University in Trondheim. This university appears to serve as the principal academic and research institution in Norway in underwater acoustics. The sponsored group is headed by Dr. Jens Hoven who has been at SACLANT in La Spezia,

Italy and who at this writing is spending a year at the Applied Research Laboratory at the University of Texas. During Hoven's absence Dr. Tor Knudsen is in charge. The details of the sponsored research is proprietary information. Suffice to say that it involves mostly high resolution sonar techniques. A small start on piezopolymers has been made. The University has interest and capability in fiber optics for data transmission, but nothing has been done as yet on acoustic sensors.

SIMRAD is located on the shore of a fjord about 50 miles south of Oslo. They have a small and shallow pier calibration facility, and a boat for taking equipment to deeper water.

- b. Norwegian Defence Research Establishment
Division for Underwater Warfare
P. O. Box 115
N 3191 Horten

The Norwegian Defence Research Establishment (NDRE) group at Horten is a neighbor of SIMRAD. Mr. I. Englesen and Mr. Kjellsby are their key people for transducer work. Their research and development problems are familiar--low-frequency sound sources, pressure gradient hydrophones for arrays, and hydrophones insensitive to vibrations in 3 dimensions.

Mr. Kjellsby has done some work on laminating 16 layers of PVF₂. Like others, he was successful, but only after much difficulty.

Unlike the Americans, British, and French, the NDRE does not sponsor research at universities.

The NDRE at Horten has a floating calibration barge in the fjord and both an air and water-air pistonphone in the laboratory.

VI. DENMARK

- a. Danish Defence Research Establishment (DDRE)
Copenhagen

The naval part of the DDRE is a small organization of only 100 employees. Of these only five or six are involved directly in underwater acoustics. Their main effort has been in studies of reflections from the bottom of the Baltic Sea. Although very shallow, with an average depth of 30 m the Baltic Sea nevertheless has a sound channel at 20 to 50 m! This channel is caused by salinity gradients rather than the static pressure and temperature effects common in deep ocean sound channels. The Baltic Sea receives a great deal of fresh water drained from a large land mass almost completely surrounding the Sea. The fresh and salt water apparently do not mix, but remain in separate layers--thus, the gradients in sound speed, and sound channel!

The DDRE does not do any transducer research and development, except when a specific transducer tool is not available. One such case is worth describing. They needed a broad band sound source for the 500 to 2500 Hz range. Without any prior experience they designed and built a moving coil transducer that is very similar to the USPD type J9. They had no calibration curves, but claimed that it worked satisfactorily in the 500-2500 Hz range. The many pitfalls in the design of this type of transducer were apparently avoided by careful analysis and design.

b. Technical University of Denmark
Lyngby

The Technical University of Denmark is located in Lyngby, a suburb of Copenhagen. It is not to be confused with the University of Copenhagen that also has a strong acoustics faculty, with special orientations toward environmental acoustics. At the Technical University the key faculty member is Prof. Leif Bjørnø whose interests are many--fluid mechanics, electroacoustics, underwater acoustics, ultrasonics, shock and vibration, and nonlinear acoustics. The Bjørnø group does a great deal of research and development in transducers at ultrasonic frequencies. This has been mostly with very small and thin piezoceramic elements. Recently they have moved into piezopolymers. They have laminated as many as 200 layers of Kurehas piezopolymer! However, instead of using 200 separate pieces, they fold one long piece zigzag fashion. Like others they are interested in thicker films. One PhD dissertation is on some theoretical aspects of rare-earth magnetostriction.

Bjørnø's group is well equipped with facilities for making their own transducers, and for calibrating the transducers in water and air.

One notable development with PZT was a tiny probe hydrophone with a first resonance at 8 MHz!

Bjørnø is very knowledgeable about fluid mechanics. In this connection he expressed some doubts about the "tow-powered fluidic oscillator" conceived by Hanish and Trott at NRL described in Appendix F, and to be reported in an oral paper by Trott at the Cambridge Mass. meeting of the Acoustical Society in June 1979. The doubt centered on the "tow-power" aspects of the concept, not on the oscillator itself. Bjørnø felt that the unstable conditions in scooping up a jet stream by towing, along with boundary layer losses, would prevent a high velocity jet from ever materializing.

c. Bruel and Kjaer Company
Naerum

The Bruel and Kjaer Company is located in Naerum, a suburb of Copenhagen. They are probably the largest producers of sound and vibration instrumentation in the world. Their home facility

in Naerum alone employees 1600 people. They are an international company in that 98% of their products are sold outside of Denmark. They have offices in 55 nations. Their short catalog is written in 18 languages and their complete catalog and instruction books in 5 languages. They have a line of hydrophones, some of which are reversible and can be used as sound sources above 5 kHz. A self-contained hand-held calibrator for the hydrophones is also produced. They have a tank facility for measurements above 5 kHz. The Company uses a well-developed and well-proven technology for their hydrophones. Although they are interested in new concepts as piezopolymers and fiber-optic sensors, they would be slow to adopt these new ideas as substitutes for their existing piezoceramic designs. However, the Company keeps moving into such new areas as medical ultrasonics and acoustic emission measurements. Here piezopolymers might find a place.

Mr. Ole Olesen is Bruel and Kjaer's engineer for underwater acoustics. Olesen spent six years at the SACLANT Center in La Spezia. He moved from naval research and development to the Bruel and Kjaer position largely because he could not find a government position in Denmark.

VII. WEST GERMANY

a. Max-Planck-Institut für Festkörperforschung Stuttgart

The Max-Planck-Institute for Solid State Research is located in the outskirts of Stuttgart. The surroundings are beautiful. The building is new, of modern architecture, and magnificently furnished and equipped--including guest rooms for visiting scientists.

Prof. K. Dransfield and Dr. H. Sussner have been performing research on the fundamental nature of the piezoelectric effect in polyvinylidene fluoride (PVF₂) and their experiments can have some important consequences on the use of PVF₂ in hydrophones. These experiments are reported in reference (8), Appendix A, which is recommended and easy reading for anyone working with piezopolymers. Their work of the last year only confirms their conclusion of one year ago that the piezoelectric effect is heterogeneous in the film thickness direction, being strongest near the positive electrode, and requiring direct metal-to-polymer contact at the positive electrode. Their experiments support the theory of insertion and trapping of charges. (Both Dransfield and Sussner were unavoidably absent during the author's visit. Dr. S. Hunklinger provided the author with the information about the results of recent research.)

If the trapped positive charge theory is correct, it would have an important impact on the use of PVF₂ films 1,000 μm thick. Sussner found that films of 6 μm thickness require about 1,000 seconds to reach about 80% of full polarization, and about 1 hour to reach almost

the maximum. If the piezoelectric effect is caused by charge insertion, it would seem that the poling time would be proportional to the thickness. A 1,000- μm thick film would then require very long poling periods.

Another consequence of the Sussner and Dransfield theory is that a heterogeneous film would act somewhat like a "bimorph," and flexure resonances would be easily excited. They did, in fact, measure low flexure resonances that are forbidden in a freely supported homogeneous film, and this was one piece of evidence to support their theory. Low-frequency spurious resonances reported by others who have built experimental hydrophones may be caused in part by the heterogeneous piezoelectric effect in the thickness dimension.

b. Institut für Elektroakustik
Technische Hochschule
Darmstadt

Prof. Gerhard M. Sessler of the Electroacoustics Institute at the Technical University in Darmstadt was, along with James West, the original developer of the electret microphone. He was at the Bell Telephone Laboratories at the time. This microphone has since been a huge commercial success. It is used in a wide variety of applications. According to Sessler, the Japanese alone manufacture 50 million electret microphones per year! These are mostly the very low cost versions used in tape cassette recording and other commonly used consumer products. Nevertheless, it probably makes it the most widely used electroacoustic transducer in the world--surpassing even the ubiquitous carbon microphone in telephones.

Since returning to Germany and the Technical University in Darmstadt, Sessler has continued work with electrets. The term "electrets" in German usage includes piezopolymers. His work with PVF_2 leads him to agree with Sussner and Dransfield that the piezoelectric effect in PVF_2 films is heterogeneous in the thickness dimensions, being strongest near the positive electrode.

Much of Sessler's research is in the electret materials per se. Teflon is the favorite and has been found to exhibit an interesting characteristic. Electrons inserted into Teflon are trapped there and immobile. Movement time constants, at room temperatures, are measured in centuries. However, positive charges (or holes) move freely! Sessler has found this characteristic only in Teflon. However, the author sees a similarity here with the Sussner and Dransfield contention that the large piezoelectric effect near the positive electrode PVF_2 is due to charge insertion and that there seems to be no electron charge insertions at the negative electrode.

Sessler's program could conceivably develop something useful for underwater acoustic transduction--perhaps along the line of work in Paris by Lewiner et al reported in the section on France.

One important development was confirmed in Darmstadt. There have been rumors that the Kureha company would no longer sell PVF₂ film. Mr. R. Lerch of Sessler's group definitely reported that the Dusseldorf office of Kureha told Lerch in December 1978 that Kureha would no longer sell him PVF₂ film. No explanation or comment was provided. Although PVF₂ is available from other sources, including the Penwalt Company in Pennsylvania, the quality of these other sources does not match that of Kureha. Since Kureha has been the source of the PVF₂ used everywhere, the author has surveyed, the withdrawal of Kureha from the market casts a cloud over future research and development. Since the Pioneer Electronic Company of Japan is already using PVF₂ in commercial audio equipment, one wonders if Pioneer too cannot buy the Kureha film?

c. Physikalisch-Technische Bundesanstalt (PTB)
Braunschweig

The initials PTB are as well known in West Germany as NBS is in the United States. PTB is indeed the German counterpart of our National Bureau of Standards. It has responsibilities for calibration, test, and evaluation in all the physical sciences and engineering disciplines including atomic energy. Like NBS it is located in mostly modern buildings, in a park-like setting, the outskirts of Braunschweig. It also has a small department in Berlin. The departments are organized along the classical divisions in physics, i. e., mechanics, optics, electricity, etc. The Acoustics Division has 70 employees working in physical, architectural, audio, and musical acoustics, shock and vibration, and ultrasonics. Prof. H. J. Diestel is the Head of the Acoustics Division.

No transducer research itself is done, but the Ultrasonics Group under Dr. K. Brendel does research very similar to that of the Underwater Sound Reference Division (USRD) of NRL. His mission is to develop the methodology for making acoustic and electroacoustic measurements at ultrasonic frequencies--particularly above 1 MHz where medical applications still have serious unresolved problems of methodology and standards. The methodology used for sonar loses feasibility at megahertz frequencies because of attenuation in the water medium, the extremely short wavelengths, and the fact that most applications use the near field instead of the far field of the radiated sound.

The research of the Brendel group uses radiation pressure and acousto-optic methods, and combinations of the two. The theory of both methods is old, but the practice has never been thoroughly developed. Lasers and holography have also added a new dimension to the old acousto-optic methods as the schlieren technique. In one method that combines holography and the radiation pressure, which produces the well-known "dimples" on a water air surface, a high resolution picture of the sound field in a near-field plane normal to the transducer acoustic axis can be obtained and used to calibrate the radiator.

One objective of Brendel's research is to develop techniques that describe the near field in 3-dimensions in a point-by-point basis--not the usual spatial intergration and averaging in planes normal to the axis.

It is noteworthy that the Acoustics Division of PTB is flourishing while the corresponding organization at NBS has been disestablished.

- d. Forschungsanstalt der Bundeswehr für
Wasserschall und Geophysik (FWG)
Kiel

The Federal Defense Institute for Underwater Sound and Geophysics sees itself as the German counterpart of NUSC, with which it has close relations. Actually its mission is much more limited. Basically it does the research in the medium and its boundaries necessary to develop models that will predict sonar performance in the shallow waters of the North and Baltic Seas. It's a small organization of 130 employees of which only 26 are professionals and 38 constitute the crew of the research ship PLANET. Aside from the ship, the building, facilities, and staff are similar in scope to the Underwater Sound Reference Division of NRL.

FWG does no in-house transducer work. They depend on contractors often American. One local contractor ELAC (for electroacoustic) has recently become ELAC-Honeywell. FWG has a new North Sea platform somewhat like NRL's old Argus Island, but larger. A set of 3 large sound sources to cover the range 0.4 to 10 kHz is currently being built by Rockwell International with the assistance of NUSC for installation on the platform. The sources have Toulis squashed tube parabolic reflectors. The active element is conventional PZT built by International Transducer. The transducers will be tested at the NUSC Lake Seneca Facility.

Dr. Ziehm is the laboratory director. Dr. Wille is the head of the Scientific Department.

PLANET has facilities similar to the USNS GIBBS, HAYES, and others.

VIII. THE NETHERLANDS

- a. Physics Laboratory, TNO
The Hague

The Physics Laboratory of TNO is a civilian research organization, and technically not a part of The Netherlands Defence Establishment. However, almost all of its work is sponsored by The Netherland's

Navy, so in practice it functions like a navy laboratory. Of some 300 people in 9 divisions, 17 are in the Acoustics Division. Mr. B. C. Reith is the Head of the division; Mr. H.A.J. Rijnja is his deputy and principal investigator in transducers. The group spends most its effort in troubleshooting acoustic problems for the Navy, and serving in an advisory capacity for sonar procurements. They are knowledgeable about conventional transducer technology, but have limited opportunity for research or exploratory development.

Rijnja has, however, done considerable experimental research on acoustic absorbers, using an impedance tube similar to that at the USRD. His most notable finding has been in cork-rubber composites. The B. F. Goodrich "Corprene" in the USA is considered a poor material for transducers because of its instability with time, hydrostatic pressure, and temperature. Rijnja has tested 20 different kinds of cork and rubber supplied by James Walker and Co., Ltd., Lion Works, Woking, Surrey GU22 8AP, UK and found some to be stable up to pressures of 30 atm. Rijnja's interest has been in the absorption of cork-rubber cones, not the pressure-release application. Their laboratory has a 10 x 8 x 8 m indoor test tank lined with cork-rubber wedges as an anechoic boundary. A fresh look at these British versions of Corprene may be useful.

IX. MISCELLANEOUS TOPICS

a. European Fibre-Optics Survey--June 1978

ONR London Report R-6-78, "European Fibre Optics Survey--June 1978" by CDR David A. Hart, 22 August 1978 is a 72-page report on a visit to 23 European organizations by a team of 6 U.S. Navy individuals. NAVAIR, NOSC, NUSC and the Naval Avionics Center in Indianapolis were represented. An NRL representative was scheduled but had to back out. The report is an extensive source of information (much of it proprietary) on current efforts in optical fibre science and technology in Europe. It concludes that ". . . there is a massive effort in fibre optics technology in Europe. The manpower and investment . . . are almost overwhelming." However, a quick reading of the report by this author revealed that of the 23 organizations only one is doing anything in the area of hydrophone applications, and this was described as a "future activity" and only "some preliminary work is being started. . . ." This was the Central Research Laboratory of the Compagnie Générale d' Electricité (CGE) at Marcoussis, France, and referred to as "Lab de Marcoussis." This appears to be the same organization that Quivy of Le Brusac referred to as a potential contractor. He however, also mentioned CIT-ALCATEL, which is the telecommunications and electronics company within the CGE corporation. Perhaps the Central laboratory would do the research and CIT-ALCATEL the production.

b. International Electrotechnical Commission Meeting in Stockholm

For 12 years a "Hydrophone" working group of the Electroacoustics Technical Committee of the International Electrotechnical Commission has labored over 2 international standards--one on a standard hydrophone and a second on standard calibration methods. W. James Trott of the USA was the Chairman up to his recent retirement. At a meeting in Stockholm on 9 May 1979, the group completed its work with the addition of "water-air pistonphone" and "vibrating column of water" techniques to the methods standard. Mr. H. A. J. Rijnja of The Netherlands was the Acting Chairman. Other attendees were Messrs. Rimsky-Karsokov and Golenkov of the USSR, Quivy of France, Kjellsby of Norway, Miro of Japan, and Woollet and Bobber of the USA. Bobber and Quivy will put the final editorial touches to the additions in the English and French versions respectively. No further meetings are planned.

X. CONCLUSIONS AND COMMENTARY

If more time had been available, the author would have visited the universities in Florence, Paris, Trondheim, Bath, Delft, Munich, Heidelberg, and Aachen. So this survey is necessarily incomplete and the conclusions drawn must be accepted with this in mind.

It is noteworthy that the list of omitted institutions are all universities, and this illustrates the first conclusion. Government defense or naval laboratories in Western Europe do relatively little in-house applied research (or exploratory development) in sonar transduction. Their limited resources are devoted mostly to engineering, troubleshooting, and procurement advisory functions. In a few cases they do sponsor applied research in universities. AMTE in Holton Heath was an exception.

From a management point of view the author saw no evidence of any systematic or coordinated program management comparable to the (6.2) transducer block program sponsored by the U.S. Naval Material Command.

In reviewing new transduction concepts, there is widespread interest in piezopolymers, but only in the United Kingdom and France has this interest reach the stage of building experimental hydrophones. The production of thick PVF₂ films by the EMI Laboratory in England, and the implications of the Sussner and Dransfield work in Stuttgart, are both considered significant to further piezopolymer hydrophone development.

Research in fiber optic acoustic sensors is being done, or about to be done, in the United Kingdom, France, and maybe Italy and Norway. However, the total effort is almost negligible compared to the U. S. Navy Project FOSS.

The only significant amount of applied research on rare-earth magnetostrictive or piezoceramic materials for transduction applications is being done at the laboratory in Holton Heath, UK. At the more basic research level there is probably more being done in various universities and research institutes but the author cannot estimate the extent.

No underwater acoustic transduction concepts beyond those described in the appendices were found except that of Lewiner cited in the trip report for France.

And finally, the author received the impression that in sonar transduction, our NATO allies look to the U. S. Navy laboratories for new development in sonar transduction technology.

APPENDIX A

Piezopolymers

Among all of the new transduction concepts discussed here piezopolymers, or polyvinylidene flouride (PVF₂) in particular, is the most highly developed and has attracted the most attention, particularly, in Japan¹⁻⁵. It has, in fact, already been used in loudspeakers and some other audio engineering applications by the Pioneer Electronics Company in Tokoyo. However, research continues because the fundamental nature of the piezoelectric phenomena in PVF₂ remains a controversial subject. The Kureha Chemical Industry Company in Tokoyo is still the only commerical source of the prepared material. As yet, underwater applications are very much in the early experimental stages⁶⁻⁷. Seventeen papers on piezopolymers were presented at a joint meeting in December 1978 of the American and Japanese Acoustical Societies in Honolulu.

PVF₂ has many advantages over a piezoceramic. It is more acoustically transparent and is flexible, inexpensive, and shock resistant. It can be made in very wide and long sheets, and the material itself will have a very high first resonance. It can be formed to cover odd shapes, as, for example, a ship's hull.

Typically PVF₂ is manufactured in a thickness of 6 to 25 μm . It has a density of 1,780 kg/m³ and a sound speed of 1,960 m/s. It is both piezoelectric and pyroelectric. The monomer in the polymer chain is CH₂CF₂. In the α form of the polymer, the adjacent monomer units are rotated 120 degrees with respect to one another. In the β form there is no rotation. The α form is only slightly piezoelectric while the β form is strongly piezoelectric. A third or γ form is mentioned in the literature but is not significant. The material is stretched uniaxially and sometimes biaxially 400 to 500%. This produces a more uniform orientation of the dipoles inherent in the crystalline units and also seems to change some α forms into the β forms.

The poling fields are very high--normally 200 to 400 kV/cm, but reaching as high as 2 to 3 MV/cm. Because this material is thin, the actual voltage is, of course, only a few hundred volts. The poling temperature is in the 50 to 110°C range. The material is electroded by either vapor deposition or photolithographic techniques.

Comparing PVF₂ and PZT-4 in Fig. A1, the d constants (charge/stress or strain/field) and the electromechanical coupling coefficient k are low. This indicates the PVF₂ has little potential for a sound source in underwater acoustics. The g constants (field/stress) and the compliances are high, indicating that the potential as a sensor is high. The dielectric constant is low, but this is less important to a sensor than to a source.

If one visualizes a disk of PVF₂ 25- μ m thick and 1 cm in radius as a hydrophone element functioning in the 33 mode with a rigid back plate, the free field voltage sensitivity below the first resonance calculates out to -222 dB reference 1 V/ μ Pa with a capacitance of 1330 pF. The resonance frequency would be 19.6 MHz.

This is a low sensitivity but a high resonance and a high capacitance. Piling ten such disks into a laminated element with the disks electrically connected in series would add 20 dB to the sensitivity and reduce the capacitance by a factor of ten. The resulting sensitivity of -202 dB reference 1 V/ μ P and capacitance of 133 pF are quite acceptable. The resonance frequency would also be reduced by a factor of ten to 1.96 MHz, still leaving a very wide bandwidth for sonar applications.

The lamination technique has been used by Powers at the U. S. Naval Underwater Systems Center. He has laminated as many as 32 sheets of PVF₂ with results that conform to theoretical computations. However, the practicability of such a technique outside of laboratory experiment is doubtful. Preferred is a straightforward 10- to 100-fold increase in the thickness of the PVF₂ provided by the manufacturer. Such thick sheets are as yet not available.

The characteristics of PVF₂ have been exploited in audio acoustics by using the drumhead design shown in Fig. A2. That is, the PVF₂ is stretched across a cup or bowl-like housing. The sound impinging on the PVF₂ membrane stretches the PVF₂ further. A displacement bias is needed to prevent frequency doubling since the membrane would be extended in both the positive and negative halves of the sound pressure signal without a constant displacement. The 31 mode is used here. Although the g_{31} is smaller than the g_{33} constant, the design has an inherent mechanical transformer feature that amplifies the PVF₂ internal stress-to-sound pressure ratio, which more than compensates for the lower g constant. This design is not very useful for underwater acoustics because of its sensitivity to the difference between the hydrostatic pressure outside of the drum and the air pressure on the inside.

For underwater acoustics the "blocked" or "symmetric" designs shown in Fig. A3 are more suitable. They use the 33 mode, require no bias, have no problem with high hydrostatic pressures, and are basically a design for a medium of high acoustic impedance and low displacement.

Future research is needed to resolve the controversy over the fundamental theory. The competing theories involve dipoles, trapped charges, and surface phenomena. Sussner and Dransfield⁸ and Broadhurst et al at the U. S. National Bureau of Standards have published the most recent contribution on this subject⁹. They describe a combination of the dipole and trapped charges theories.

Current materials research includes studies on the effects of manufacturing variables, stretching, poling voltages and temperatures, long-term stability, and linearity. The feasibility of thicker sheets and the characteristics of copolymers are also being investigated.

Design configurations are strongly dependent on the application. In addition to the air-versus-water designs already pointed out, there are applications in ultrasonics--usually for medical purposes and at megahertz frequencies. Edelman at the U. S. National Bureau of Standards has also studied industrial applications in which PVF₂ replaces strain gauges and accelerometers.

The location where research and development related to naval problems are being done in the United States are summarized in Fig. A4.

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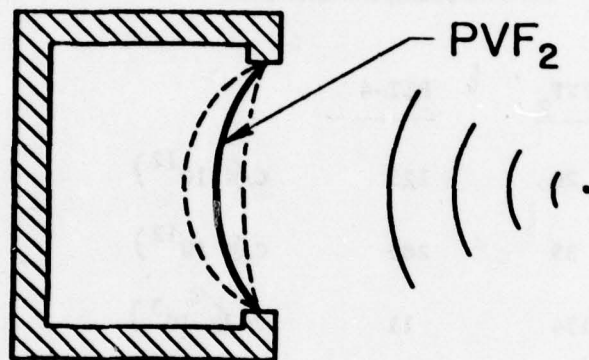
TRANSDUCTION CONSTANTS

	<u>PVF₂</u>	<u>PZT-4</u>	
d_{31}	20	123	$C(N 10^{12})$
d_{33}	35	289	$C(N 10^{12})$
g_{31}	174	11	$V_m(N 10^3)$
g_{33}	330	26	$V_m(N 10^3)$
s_{31}		5.3	$m^2(N 10^{12})$
s_{33}	320	15	$m^2(N 10^{12})$
k_{33}	0.19	0.70	
k_{31}	0.10	0.33	
ϵ	12	1300	

* PVF₂ CONSTANTS ARE A FUNCTION OF POLING
VOLTAGE AND TEMPERATURE

Figure A1

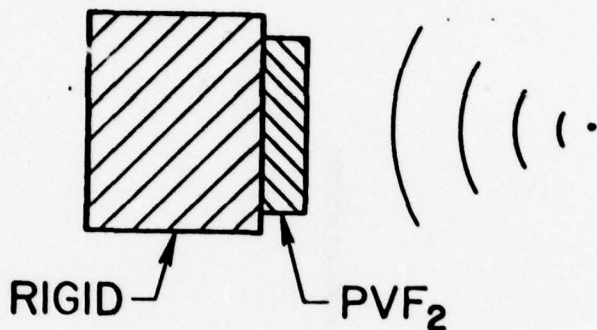
DRUMHEAD DESIGN



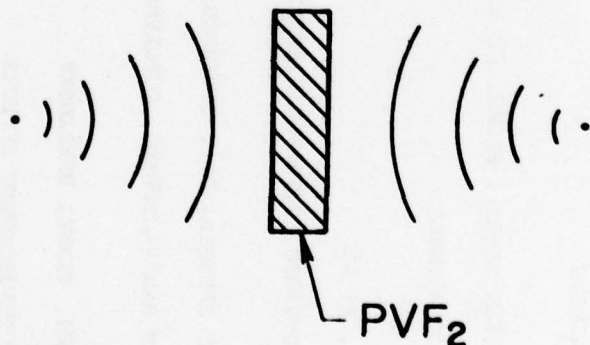
- g_{31} MODE PLUS TRANSFORMER
- DISPLACEMENT BIAS REQUIRED
- LOW FLEXURAL RESONANCE
- SENSITIVE TO STATIC PRESSURE
- LOW MECHANICAL IMPEDANCE
OR HIGH DISPLACEMENT

Figure A2

BLOCKED BACK PLATE



SYMMETRIC



- g_{33} MODE
- NO BIAS
- HIGH THICKNESS RESONANCE
- RESISTANCE TO STATIC PRESSURE
- HIGH MECHANICAL IMPEDANCE
OR LOW DISPLACEMENT

Figure A3

CURRENT R&D IN USA

- NATIONAL BUREAU OF STANDARDS (GAITHERSBURG), BROADHURST, EDELMAN, ET AL
- BASIC THEORY AND APPLICATIONS
- NAVAL UNDERWATER SYSTEMS CENTER (NEW LONDON), POWERS, SULLIVAN, LE BLANC, ET AL
- SOMAF APPLICATIONS, AGEING
- NAVAL OCEAN SYSTEMS CENTER (SAN DIEGO), HICKS, ET AL
- MATERIALS RESEARCH (COPOLYMERS)
- STANFORD UNIVERSITY, LINVIL, ET AL
- MATERIALS RESEARCH, DEVICES, ULTRASONIC APPLICATIONS, INTEGRATED CIRCUITS
- PENWALT CORPORATION (KING OF PRUSSIA, PA), STEFANOU, FERRIN, ET AL
- MATERIAL RESEARCH AND MANUFACTURING, COPOLYMERS
- NAVAL RESEARCH LAB. (ORLANDO), TIMME, BERLINSKY
- DYNAMIC RANGE, OCEAN ENVIRONMENT EFFECTS

Figure A4

APPENDIX B

Acousto-optic Sensors

Acousto-optic transduction is one of the newer, interesting, and completely different concepts. It is primarily transduction in a unilateral sense--that is, only as a sensor. In 1977, researchers at the U. S. Naval Research Laboratory¹, TRW Corporation², and the University College of London³ each reported on the sensitivity of optical fibers to acoustic pressures. About the same time, the U. S. Naval Underwater Systems Center⁴ developed an acousto-optic sensor using the Doppler effect in an interferometer device. Other acousto-optic sensors have been suggested that depend on variations in a laser light beam external to an optical fiber that result from vibrations. This latter class of sensors is termed hybrid sensors because of the use of optical fibers for signal transmission but other optical devices for the sensor. This distinguishes hybrid sensors from pure fiber optic sensors that use the fibers for both functions.

The principle of each type is illustrated in Fig. B1 in its most common form. In both cases a carrier signal from a laser is coupled into two optical fibers--one a sensor fiber and the other a reference fiber. The optical signal in the sensor fiber is changed by the acoustic signal. The two signals then emerge from the fibers and are recombined and converted into an electrical signal by a photo detector.

In the fiber-optic sensor the output signal is changed in phase caused by the acoustic pressure producing both a change in density and refraction index of the glass and a change in dimensions of the fiber⁵. The sensitivity is given by the expression,

$$\frac{\Delta\phi}{p} = k \left(\frac{n}{l} \frac{dl}{dp} + \frac{dn}{dp} \right) l$$

where $\Delta\phi$ = phase change,
 p = acoustic pressure,
 k = optical wave number,
 n = refraction index, and
 l = fiber length in the sound field.

The first part of the expression in parentheses is the effect of the dimensional change. The second part is the effect of change in the refractive index.

It is important to note that the sensitivity is proportional to l, the fiber length exposed to the sound pressure. Fiber lengths of 100 m and longer are envisioned.

Hybrid sensors using a variety of principles are possible. Nematic liquid crystals between crossed polaroid plates is one version. Sound pressures in the liquid crystals change their optical transmissivity in proportion to the sound pressure. Experiments have been conducted in the basic phenomena⁶⁻¹⁰, but there have been no attempts to make a hydrophone on this principle. The hybrid sensor shown in Fig. B1 consists of a parallel mirror device where one or both mirrors vibrate when exposed to a sound field. The Doppler effect shifts the signal frequency. It is presumed that the change in frequency can be made proportional to the sound pressure.

There appears to be little advantage to adding a hybrid sensor to a system that can consist more simply of only optical fibers. For this reason, future research and development are expected to concentrate on the fiber-optic sensor version.

Much remains to be investigated about fiber-optic sensors. Experiments to date have been confined to the laboratory bench. Only one real hydrophone has been built.⁴ Although fiber optics for communication purposes has undergone much development, the acoustic sensor application poses new questions and problems--such as protecting the fibers from the water or ocean environment, optimizing the fiber characteristics for maximum acousto-optic effect, minimizing bending and transmission losses, distinguishing between acoustic and temperature effects, exploiting the configuration flexibility, and so forth.

The potential advantages of fiber-optic sensors are elimination of copper wires, fewer electromagnetic interference problems, configuration flexibility, sensors that are continuous in one dimension, small dimensions, low self noise, and low cost.

All current research and development sponsored by the U. S. Navy are being managed in a single project called Project FOSS, an acronym for Fiber-Optic Sonar Systems. Mr. J. E. Donovan, Code 8105 of the Naval Research Laboratory, is the project manager.

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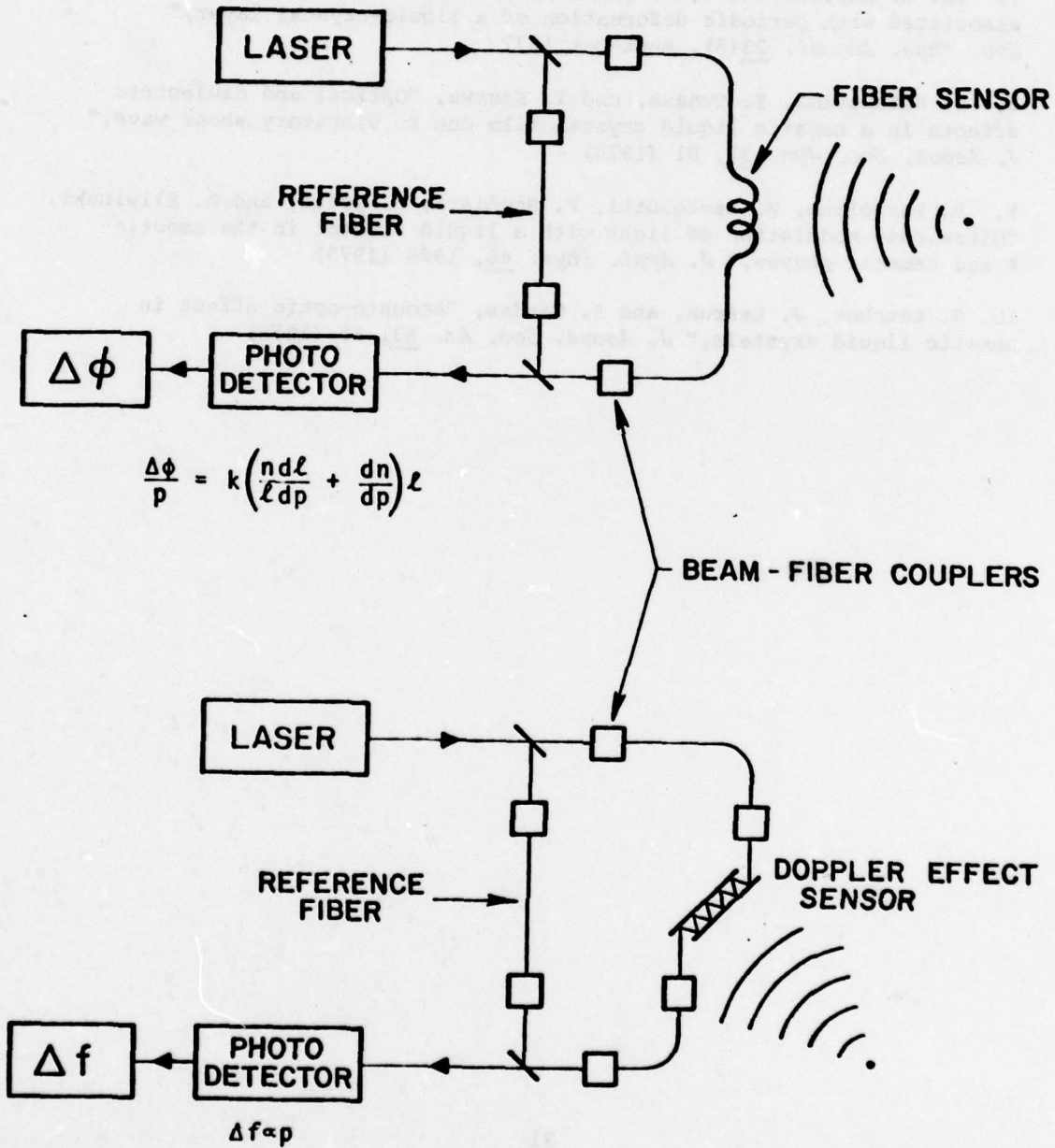


Figure B1

APPENDIX C

Rare Earth Magnetostriction

The magnetostriction effect was used in sonar during World War II and for a short time thereafter. Then, starting about 1950, it was rapidly replaced by piezoelectric ceramics. The early magnetostriction transducer was usually made of nickel alloy. It was replaced because it had a low electromechanical coupling coefficient, was inherently nonlinear, had substantial eddy current losses, and required a magnetic bias field. In all these factors, piezoceramics were superior. However, in some characteristics, magnetostriction remained superior to piezoceramics. It was strong and rugged, whereas the ceramic was brittle. At low frequencies it had the lower electrical impedance or an induction as compared to the high electrical impedance of the ceramic capacitor. And finally, the magnetostriction metals offered more flexibility in configuration and ease in manufacture than did the ceramics. Thus, interest in magnetostriction never completely disappeared.

In 1963 large magnetostriction effects were discovered in rare earths at cryogenic temperatures^{1,2}. Then in 1971 and 1972 Koon, Schindler, and Carter at the U. S. Naval Research Laboratory³ and, almost simultaneously, Clark and Belson at what was then the U. S. Naval Ordnance Laboratory⁴ (now White Oak Laboratory of the U. S. Naval Surface Weapons Center) discovered giant magnetostriction effects in rare earth iron alloys at room temperatures. These discoveries renewed the interest in magnetostriction.

Binary, tertiary, and quaternary alloys of terbium, dysprosium, and holmium with iron were studied and a few transducers were built^{5,6}. Figure C1 shows the large magnetostriction strains obtained with various rare earth alloys as compared with nickel. Figure C2 shows similar increases in the electromechanical coupling coefficient k_{33} .

Most of the past research and development has been on polycrystalline metals with random-grain orientations. Recent and current research is on alloys that are grain oriented. Single crystal samples have yet to be successfully made.

In Figs. C1 and C2, the symbol R refers to random orientation and the symbols 112 and 111 to crystallographic axes of the grain-oriented samples. The symbol o refers to a grain-oriented sample but of unknown crystallographic axis. The electromechanical coupling coefficient k_{33} for the random grain orientation is of the same order as piezoceramics (.4 to .6). The coefficient for the grain-oriented samples (.75 to .82) exceeds that of piezoceramics.

The rare earth magnetostriction is clearly superior to the old nickel alloy in electroacoustic performance, but two drawbacks cloud its future use. The rare earth iron alloys are as brittle as ceramics,

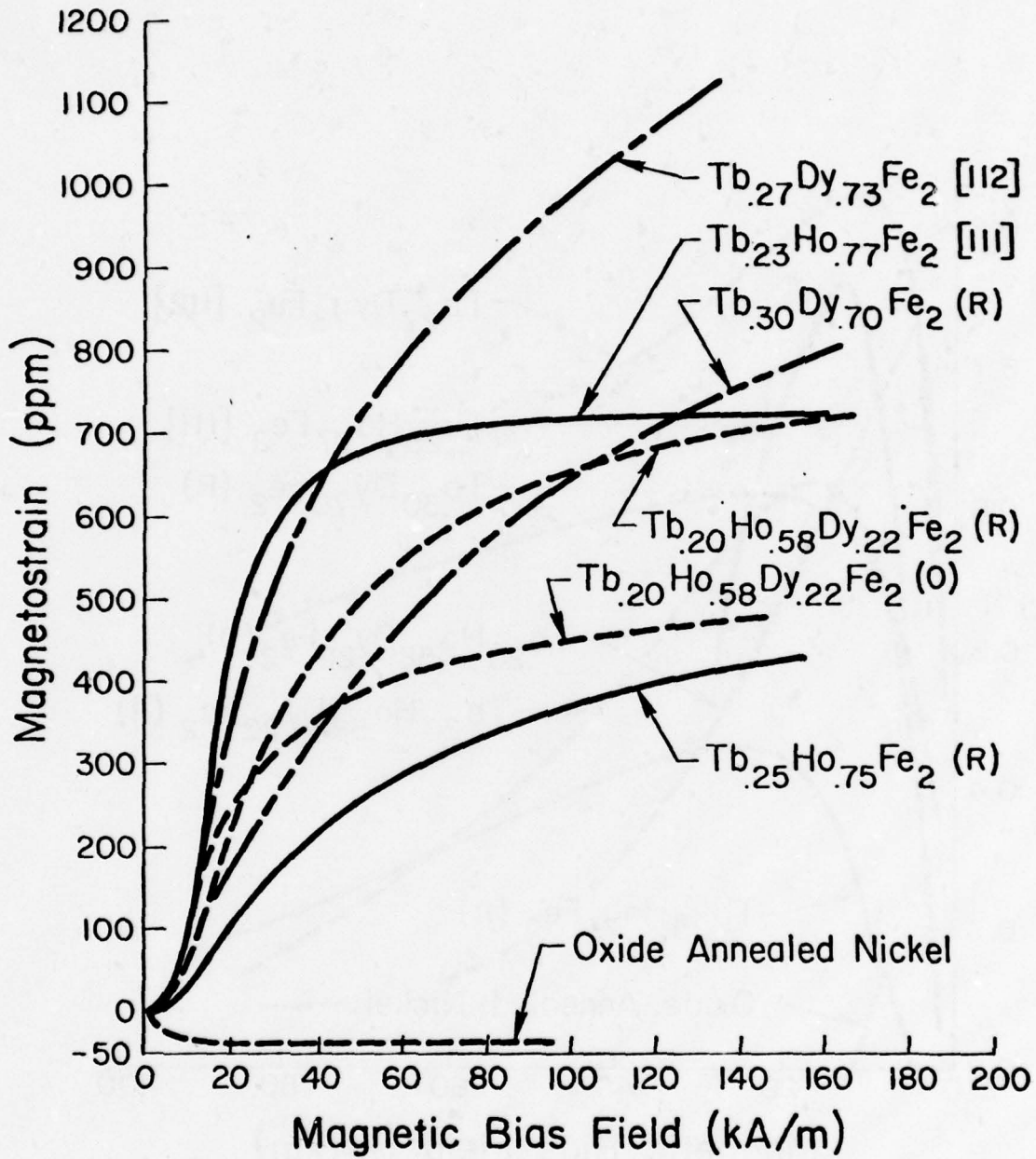
and a large magnetic flux density (0.6 T or 6,000) is needed to exploit the large strain capability.

Summarizing, the electromechanical efficiency is potentially about the same as that of piezoceramics. The advantage of low electrical impedance at low frequencies is retained. The linearity is comparable to that of piezoceramics. The configuration flexibility has been degraded (as compared to nickel alloys) but is similar to that of ceramics for random-oriented grain samples, but less so for grain-oriented samples that are comparable to piezoelectric crystals in growing technique complexity. The need for a large magnetic bias adds a considerable penalty in weight. The cost is uncertain, but the term rare earths can be misleading because they are more abundant than mercury, and about equally as abundant as tin or lead.

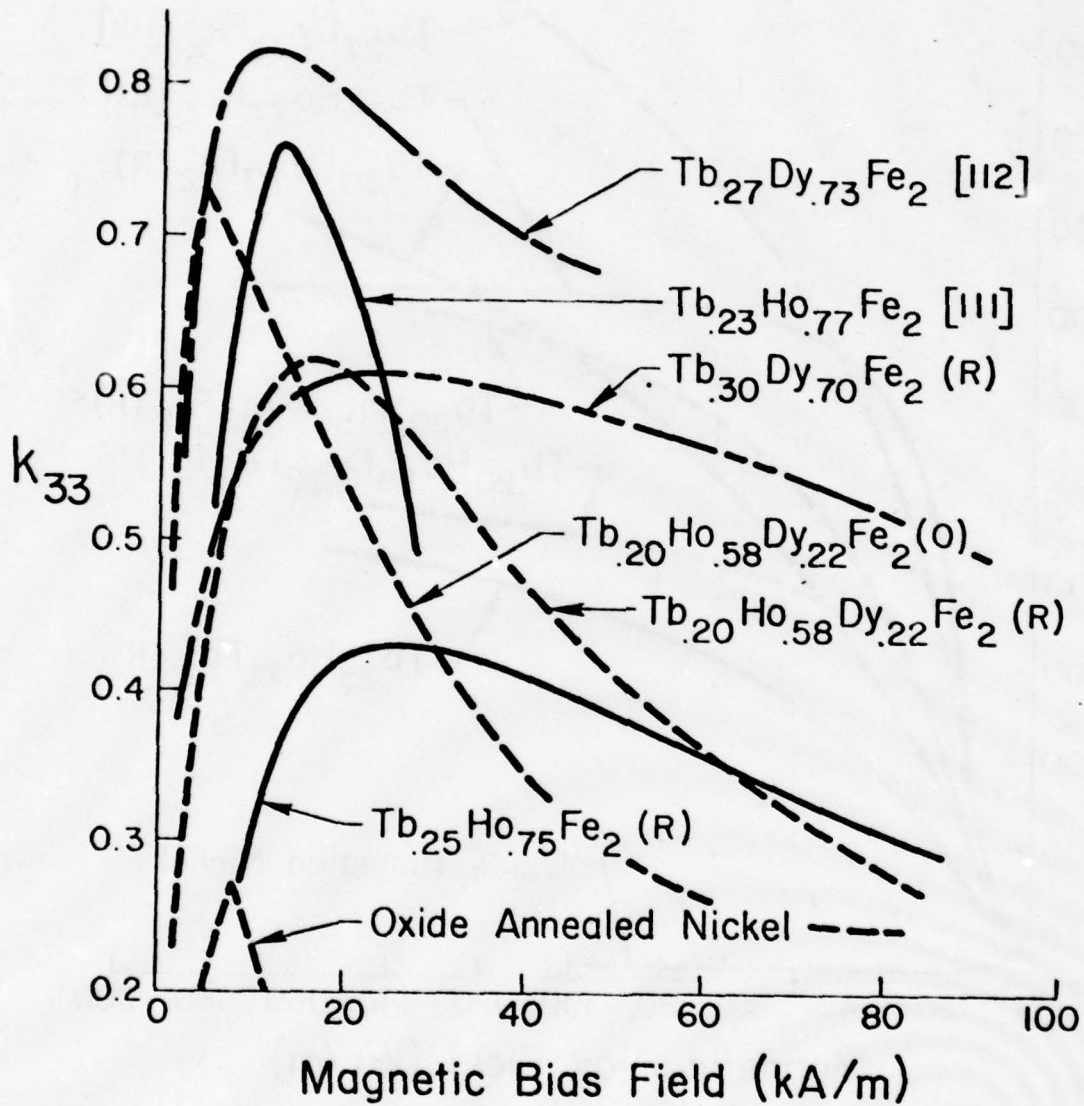
The current status of research and development is that 1) rare earth magnetostriction is not competitive with piezoceramics as a general-purpose sonar transduction material; 2) it has some advantage as low-frequency a sound source by virtue of its low electrical impedance and high strain limits development in this application and research is continuing at the Submarine Signal Division of the Raytheon Corporation in Portsmouth, Rhode Island, USA; and 3) research is continuing on grain-oriented samples and the growth of single crystals under Dr. A. E. Clark, Code WR 34 at the U. S. Naval Surface Weapons Center in White Oak, Maryland.

Rare Earth Magnetostriction References

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Comparison of the magnetostrain as a function of magnetic bias field.



Comparison of the electromechanical coupling constant as a function of magnetic bias field.

Figure C2

APPENDIX D

New Ceramics

Research and development in new transduction ceramics fall into three categories. The largest effort is in ceramic-elastomer composites using conventional PZT. A smaller effort is in going beyond the usual concept of a piezoceramic as a macroscopic, homogeneous, polycrystalline material with the crystal domains initially random oriented to a deliberately tailored heterogeneous material with preferred grain orientation. To some extent, the ceramic-elastomer composite may be considered a special case of a tailored heterogeneous ceramic. The third effort is a revival of the old concept of electrostriction. There is little to report on the second category except that L. E. Cross^{1,2} and his associates at the Materials Research Laboratory at Pennsylvania State University in the USA are conducting research on heterogeneous ceramics under the sponsorship of the U. S. Office of Naval Research. More can be said about ceramic-elastomer composites and electrostriction (that Cross et al are also investigating).

Ceramic Elastomer Composites

A ceramic elastomer composite consists of small particles or pieces of conventional piezoceramic (as PZT) imbedded in an elastomer matrix (such as a silicone rubber or polyurethane). As in the case of piezopolymers, a ceramic elastomer can be made larger than individual pieces of piezoceramic, has great flexibility as to shape, and is much less vulnerable to fracture than is ceramic alone. Thus, the objective of ceramic elastomer composites is primarily to obtain these improved physical characteristics, with or without improvements in the electro-mechanical parameters.

The original approach to ceramic elastomer composites was to use ceramic powder or small grains in the elastomer. This approach failed because the material could not be adequately poled. To some degree, the ceramic particles and the elastomer matrix could be modeled as electrical capacitances in series. The electrical impedance of the ceramic capacitances was much lower than that of the elastomer capacitances because of the large difference in the permittivity. Thus, little of the poling voltage appeared across the ceramic. It follows then that the electrical model must consist of parallel capacitance rather than series, or in the ideal physical model each particle should extend from electrode to electrode.

The stress produced in the ceramic particles in a composite (of the parallel type) by a sound pressure is about the same as that in an ordinary piezoceramic element. As a result the d constant

(charge/stress) of a composite is about the same as that of a conventional piezoceramic. The g constant (electric field/stress), however, is large because the average permittivity of the ceramic and elastomer is lower than for the ceramic alone. The three constants are related by $d = g/\epsilon$. Inasmuch as the receiving sensitivity of a hydrophone is proportional to gt where t is the thickness or electrode separation, the composites are superior to conventional ceramics as a sensor material in both physical and electro-acoustical characteristics.

Current research follows three different approaches. Harrison et al⁴, at the Honeywell Ceramics Center in Minneapolis, Minnesota, is using large particles on the order of 1 mm to insure the parallel model. L. E. Cross, at the Materials Research Laboratory at Pennsylvania State University, has developed a technique for molding piezoceramics into a foam-like or coral material, imbedding it into an elastomer and then crushing the composite to obtain a flexible material while retaining electrical continuity of the ceramic between the electrodes. Pohanka and Rice, at the U. S. Naval Research Laboratory (NRL), take a different approach⁵. They use very small disks of ceramic--about 3-mm wide and 0.05-mm thick. Such disks are manufactured for electrical filter applications and are already electroded and poled. The disks are imbedded in the elastomer in a tightly packed, well-ordered array. Each of the three techniques still has problems with consistency of material and effects of hydrostatic pressure. The NRL and Penn State versions also have a high probable cost.

Future research directions include use of PVF_2 as the elastomer in the composite and employing the small NRL disks as the substrate of integrated circuits similar to the Stanford research with piezopolymers.

Electrostriction

Revival of electrostriction as a practical transduction concept is because of new technologies that enable an electrostrictive ceramic such as the solid solution of barium titanate and sodium niobate ($BaTiO_3:NaNbO_2$) to be manufactured in pieces as thin as 1 mil. The quadratic nature of electrostriction requires a bias electric field on the order of 30 kV/cm. For a conventional thickness of several millimeters or larger, the voltage is then an impractical 5 kV or more. For 1 mil or 0.0025 cm, the voltage is a more feasible 75 V. The effective d_{31} constant of $BaTiO_3:NaNbO_2$ has been measured at $120/10^{1-2}$ V/m, or about the same as that of PZT-4.

New Ceramics Reference

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APPENDIX E

Ferrofluid Transduction

A ferrofluid is a colloidal suspension of small magnetic dipoles in water or a hydrocarbon. The dipoles are small ferrous particles with a typical dimension of 100 Å. The particle density in the liquid is about $10^{17}/\text{cm}^3$. When a ferrofluid is placed in a magnetic field, the dipoles are oriented in the direction of the field. If, further, there is a magnetic field gradient, the dipoles will move. The viscous coupling between the dipoles and the liquid causes the whole body of the ferrofluid to assume the configuration of the magnetic field to the extent that the fluid is free to move ^{1,2,3}.

Ferrofluids were developed about ten years ago but have been used only in static or quasi-static applications. In switches, for example, the fluid is conducting and is the only moving part. As a bearing lubricant, the fluid is held in place by a magnetic field instead of confining boundaries. The only known use in transducers has been as a heat dispersal medium around the voice coils of loudspeakers. Magnets can be levitated and the fluid made to emerge upward out of a dish in other interesting experiments.

Cary and Fenlon⁴ first discussed the potential of ferrofluids for acoustic transduction in 1969, but nothing further happened until 1978 when an acoustic and electroacoustic transduction experiment was performed by J. W. Overby at the U. S. Naval Research Laboratory in Orlando, Florida, as shown in Figure E1. The fluid was confined in a cylindrical non-magnetic housing with thin polymer diaphragms at each end. One diaphragm was free to radiate into a water medium. The other interfaced with an air-filled cavity. The cylinder was surrounded by a solenoid coil (with many more windings than shown in the figure) and a 400-Hz signal fed to the coil. Sound was radiated into the water, verifying the transduction concept.

Work at NRL in Orlando is continuing with the objective of developing mathematical models and transduction constants, and also investigating the feasibility of a hydrophone or sensing mode of operation.

The major advantage of a ferrofluid transducer would be the absence of mechanical constraints and fewer resonances. Unlike conventional transducers that are usually electro-mechano-acoustic systems, the ferrofluid transducer would be almost a pure electro-acoustic system.

Ferrofluids are available from the inventor and sole supplier the Ferrofluidics Corporation, 144 Middlesex Turnpike, Burlington, Massachusetts 01803, USA.

Ferrofluids References

1. Thermomechanics of Magnetic Fluids, Ed. by B. Berkovsky, McGraw-Hill International Book Company
2. A Catalog of Magnetic Fluids, Ferrofluidics Corporation, 144 Middlesex Turnpike, Burlington, Mass. 01803
3. R. E. Rosenweig, Magnetic Fluids, Ferrofluidics Corporation, 144 Middlesex Turnpike, Burlington, Mass. 01803
4. B. B. Cary, Jr. and F. H. Fenlon, "On the Utilization of Ferrofluids for Transducer Applications," *J. Acous. Soc. Am.* 45, 1210-1216 (1969)
5. J. W. Overby III, A Study of the Feasibility of Development of a Ferrofluid Transducer, Masters Thesis at the Florida Institute of Technology, Melbourne, Florida, and the Naval Research Laboratory, Orlando, Florida

FERROFLUID TRANSDUCTION

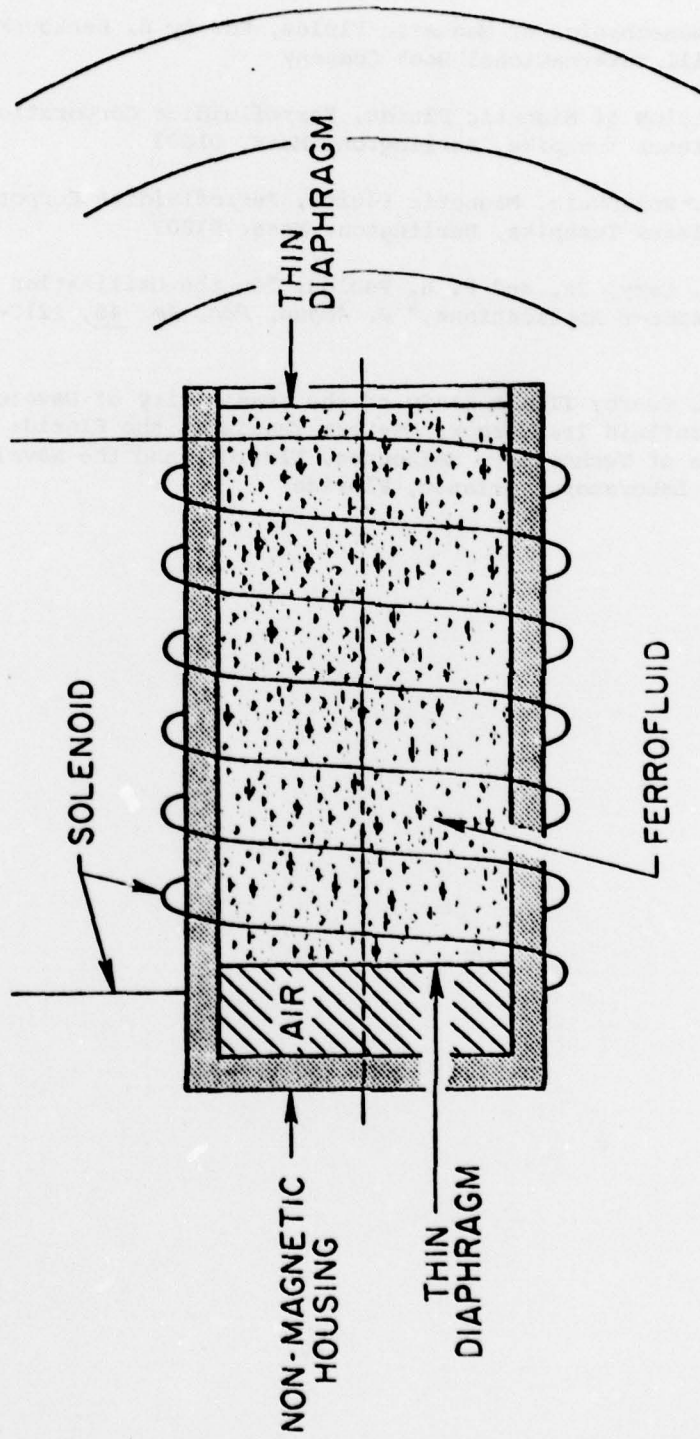


Figure E1-

APPENDIX F

Fluidic Transducers

In the context of sonar or underwater acoustics, fluidic transduction is intended to include any sound source that uses fluids as a dynamic medium in lieu of electromagnetic fields and vibrations in solids. In this sense the term is broader than when used only in the sense of a device that is a fluid analogy of a triode vacuum tube.

Fluidic transducers are not new. The conventional siren is one very old version. Bouyoucos and Hunt invented the hydroacoustic oscillator about twenty years ago. Because of their high cost, however, hydroacoustic oscillators have never been a viable threat to conventional sonar transducers.

Figure F1 illustrates the general principle of a fluidic oscillator. A fluid under high pressure flows from an energy source through some type of valve that modulates the flow, thereby producing an alternating flow. The valve or modulating frequency can be controlled by an independent electromechanical transducer, or a self-excited oscillator can be had by acoustic feedback from the acoustic load. The alternating flow drives a mechano-acoustic system of diaphragms, cavities, and so forth, all of which are tuned to the modulating frequency. One or more of the diaphragms radiates sound into the surrounding water medium. The fluid discharged from the mechano-acoustic system is either wasted into the surrounding medium or pumped back into the energy source.

The newest variation of this general concept uses the power available from the motion of a ship through the water. That is, it is "tow" powered. The whole transducer is towed through the water, with the water flow energy into the transducer produced by the towing pressures.

The valving mechanism is also different from the Bouyoucos type. The same Coanda Effect and controlling technique is used as in fluidic digital switches and other devices^{1,2}. Figure F2 shows the concept as developed by W. J. Trott at the U. S. Naval Research Laboratory³.

When a high-velocity jet flow emerges from a nozzle, the fluid will attach itself to the nozzle wall. This happens because molecules in the surrounding fluid are entrained in the high-velocity jet flow, thereby lowering the pressure on all sides of the flow. On the side toward the wall the molecules cannot be replenished as fast as they are entrained and swept away, so the pressure remains low. On the other side the molecules are replaced to some degree

and the static pressure is higher than on the wall side. The pressure difference pushes the jet to the wall. The jet will remain attached to the wall until fluid supplied by the control orifice in the wall raises the pressure on that side. The jet then flips over to the opposite wall, where the process of attachment and orifice flow is repeated. The jet is thus bistable in a manner analogous to an on-and-off switch.

The frequency with which these changes take place is proportional to the flow velocity and inversely proportional to the flow volume. For small switches it is typically 1 kHz. For the low-frequency sound source envisioned by Trott it is approximately 10 Hz.

Now, as shown in Figure F2, in one stable position the flow is waste into the surrounding medium. In the other it drives an acoustic cavity that has one or more diaphragms that radiate sound into the medium. The switching frequency is designed to be the same as that of the cavity resonance.

The two orifice signals must, of course, be 180° out-of-phase. These signals are controlled by independent transducers. Here, too, a self-excited oscillator can be made by having a half-wavelength connection between the two orifices.

This transducer is still in the development stage. W. J. Trott is scheduled to present a paper on his work at the next meeting of the Acoustical Society of America (in Cambridge, Massachusetts, USA, 10-15 June 1979).

One foreseeable problem is the effect of "downstream" pressure. That is, when the jet flow impinges on the acoustic cavity, there will be pressures produced by the impact. These pressures will propagate backwards toward the interaction area where the orifices are located and can interfere with the bistable switching action.

The feasibility of this tow-powered fluidic oscillator still remains to be proved.

Fluidic Transducers References

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FLUIDIC TRANSDUCER CONCEPT

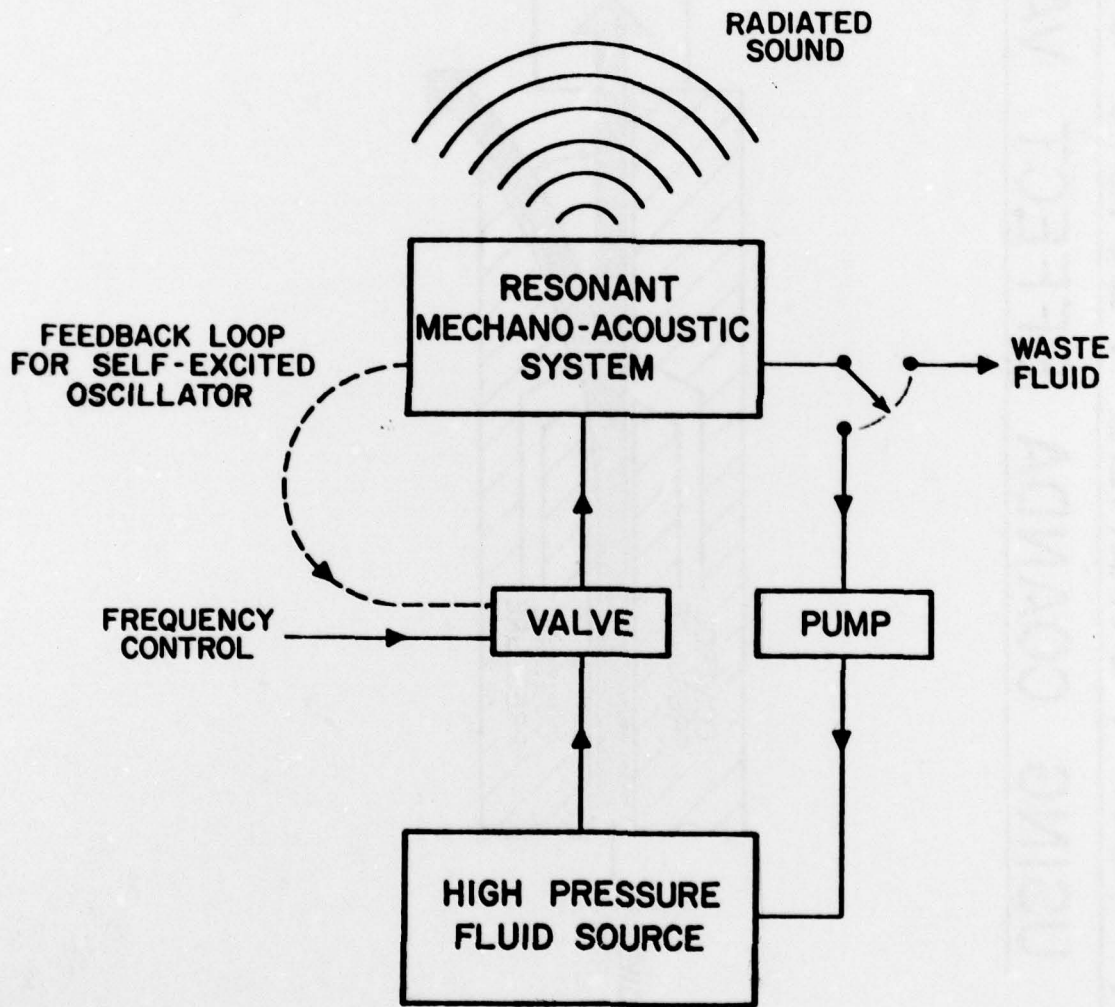


Figure F1

TROTT TOW-POWERED FLUIDIC OSCILLATOR USING COANDA EFFECT VALVE

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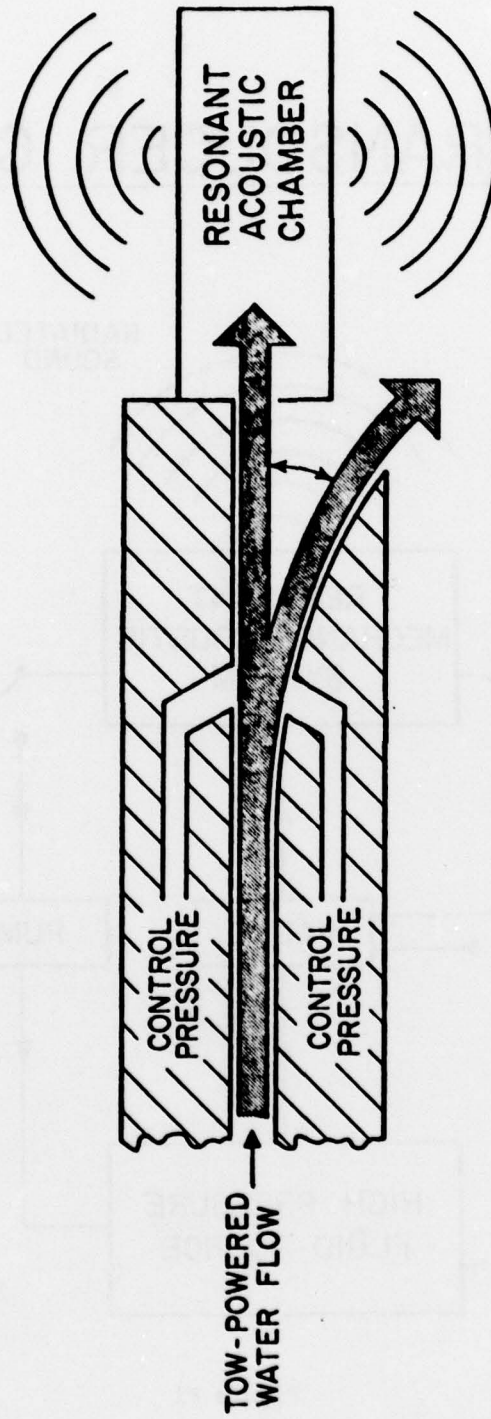


Figure F2

APPENDIX G

SAW Oscillator SensorsSAW

The surface acoustic wave (SAW) transducer as an electronic circuit component is a well-developed technology. Only recently, however, has the concept of using SAW oscillators as acoustic sensors been tested.

The concept illustrated in Figure G1 depends on the fact that the frequency of oscillation of a SAW oscillator depends on the physical spacing between two interleaved electrodes on the surface of a piezoelectric substrate and the speed of surface or Rayleigh waves in the substrate. Surface acoustic waves travel from one electrode to the other--the travel time determining the oscillation frequency. The principle appears similar to the ring-around circuit familiar to acousticians, but the function is really more analogous to a crystal-controlled oscillator. Now, if the piezoelectric substrate is caused to vibrate by an impinging sound wave, then the electrode spacing and the density and stress in the material change with the same frequency as does the vibration. This modulates the at-rest oscillator frequency. Since the dynamic changes are proportional to the vibration and sound amplitude (assuming small and linear displacements), the frequency modulation is proportional to the sound pressure.

The SAW oscillator sensor is unique in using the frequency rather than the amplitude of the output signal as the measured parameter. In this lies a potential advantage if one agrees that frequency is a more stable and more easily measured parameter than is amplitude. A second advantage is potentially small size.

The disadvantages or drawbacks are not yet clear because development to date has produced little qualitative data and little effort in joining the design technologies of acoustic sensors and SAW components. It has been demonstrated, however, that SAW oscillator sensors do work.

Research and development in the United States have been confined to a modest program at Rensselaer Polytechnic Institute in Troy, New York, by P. Das and his colleagues^{1,2}. Proposals have also been made by International Science Center of the Rockwell Corp.

SAW Oscillator Sensor References

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SAW OSCILLATOR ACOUSTIC SENSOR

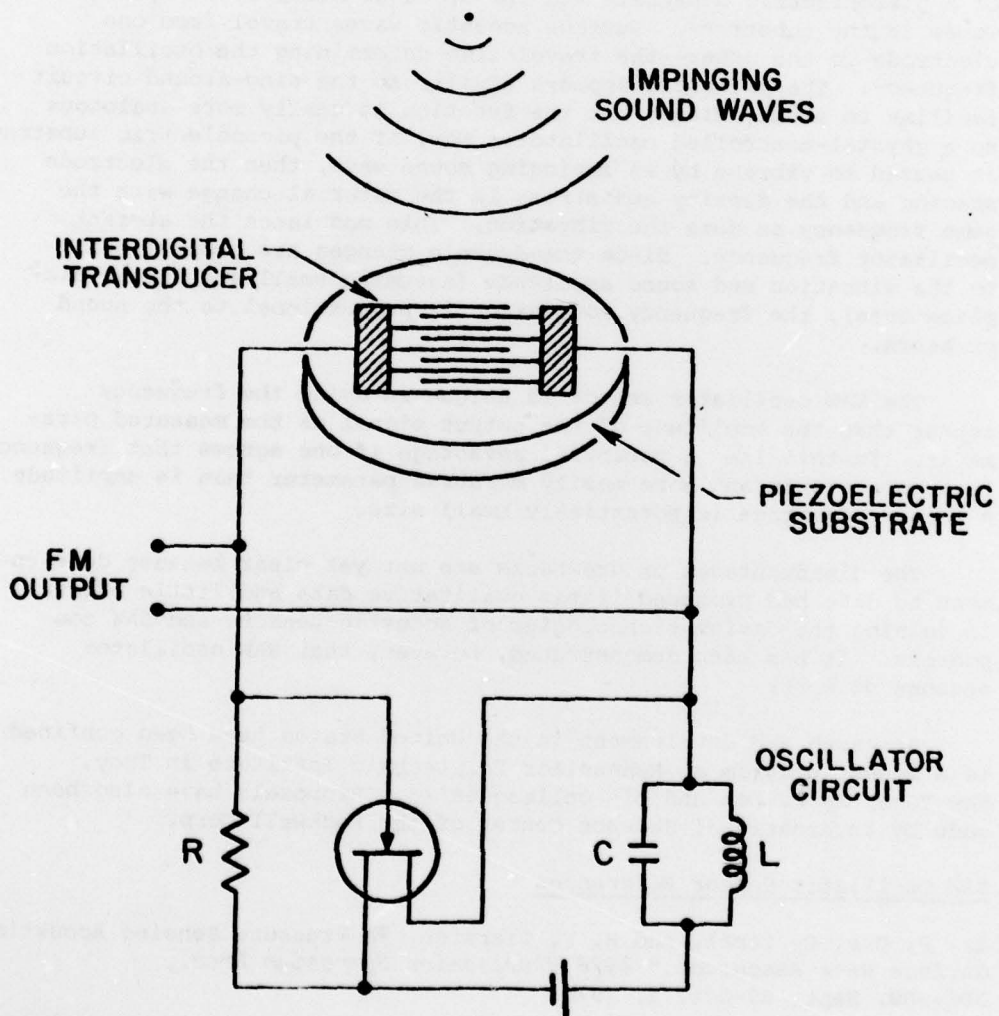


Figure G1

APPENDIX H

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