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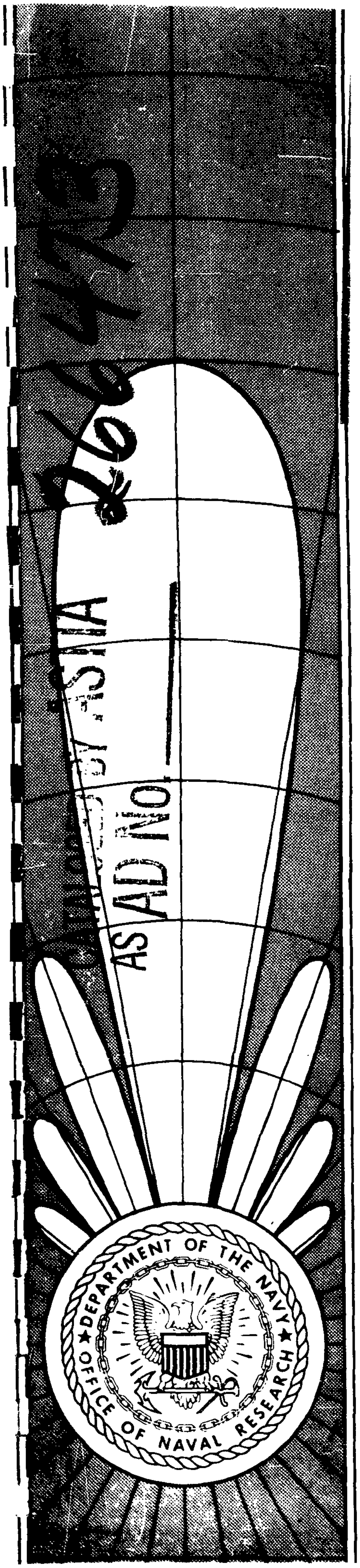

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TWENTY YEARS OF SONAR CALIBRATION METHODS

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ABSTRACT

In 1941, there existed a negligible capability for anyone to calibrate an underwater sound transducer. With the invention of the reciprocity method of calibration and the impetus provided by World War II, the art and science of sonar calibration methods developed rapidly. During the years after World War II, the theory and practice of calibration methods have become ever broader in scope.

A chronology of this development from 1941 to 1961, and the role of the Navy Underwater Sound Reference Laboratory in it, is presented.

TWENTY YEARS OF SONAR CALIBRATION METHODS

INTRODUCTION

The history of the science and art of calibrating underwater sound or sonar transducers begins about 1941. Before that time, interest and activity in this field was almost nonexistent. A few scientists [1-5], mostly in foreign countries, had experimented with methods of measuring sound pressure in fluids, but their methods were very complicated and of little practical use outside of an academic research laboratory. Calibration methods for air microphones had been developed, but these methods were not feasible for underwater measurements and were limited to audio frequencies. In 1941 on the eve of our participation in WW II, the U. S. had negligible capability for calibrating sonar transducers.

The Office of Scientific Research and Development, recognizing the paucity of research in this area, entered into a contract with the Bell Telephone Laboratories (BTL) in July 1941 and with the Columbia University Division of War Research (CUDWR) in March of 1942 for the establishment of the Underwater Sound Reference Laboratories. BTL was to supply measurement instrumentation and systems; CUDWR was to operate the laboratories, do research on methods, and perform calibrations.

1940-45

In 1940 and 1941, MacLean [6] and Cook [7] devised a method for calibrating electroacoustic transducers by using the reciprocity principle. Only electrical measurements and a few easily determined constants were required. The reciprocity calibration method proved to be a break-through that gave impetus to the growth of the science and art of calibrating sonar transducers. In the summer of 1942, only a few months after its establishment, the USRL studied and tested reciprocity calibration concepts, and found the method to be an accurate and reliable technique for calibrating sonar transducers [8]. This finding was contrary to expert opinion prevailing at the time.

In the period 1942-45, the science and art of sonar transducer calibration advanced very rapidly at the USRL [9,10]. The reciprocity calibration method was put on a sound theoretical and experimental basis. Practical procedures were worked out for making measurements in shallow lakes and tanks. The use of baffles and reflectors was studied. Bands of acoustic noise instead of pure-tone signal were experimentally used to eliminate reflection problems. Corrections for data obtained under less-than-ideal conditions were analyzed and computed. The pulsed-sound technique invented by O. M. Owsley, [11], who was later to become Director of the USRL, was further developed and exploited.

Two pier calibration systems were established at Mountain Lakes, New Jersey, and one pier and one barge system at Orlando, Florida. A 300-psi high-pressure tank 8 ft in diameter and 14 ft long was built to simulate ocean depths of more than 600 ft. A new method for calibrating hydrophones to frequencies as low as 2 cps was developed and the required facilities were built. A system for transducer calibrations at frequencies up to several megacycles per second was built. Transducer production testing methods were devised for use by transducer manufacturers. Auxiliary acoustic material such as absorbers, baffles, and domes were evaluated. Hundreds of transducers were calibrated.

Standard hydrophones were developed by BTL using Rochelle salt and ADP (ammonium dihydrogen phosphate) piezoelectric crystals. Hydrophones in which the interaction of electric currents and magnetic fields was utilized were also devised and built. BTL developed wide-frequency-band sound sources or projectors using piezoelectric crystals for the ultrasonic-frequency range, and modified moving-coil loudspeaker principles for the audio-frequency range.

Other activities also contributed to transducer development. The Massachusetts Institute of Technology's Underwater Sound Laboratory developed Rochelle salt hydrophones and a condenser hydrophone system in which an impedance bridge modulation carrier principle was used. The Brush Development Company built several types of piezoelectric wide-range transducers. The Harvard Underwater Sound Laboratory exploited the principle of magnetostriction for wide-range hydrophones. The Naval Research Laboratory used tourmaline in piezoelectric transducers.

Automatic measuring systems were developed by BTL for the USRL. The hetrodyne principle was used, which allowed continuous-sweep frequency measurements in which noise and other interference were eliminated by filtering through a 10-cps frequency band. Frequency response data were recorded continuously on linear recorders, and directivity patterns on polar recorders. Wide-band impedance bridges were borrowed from the telephone industry. Wide-band power amplifiers capable of delivering up to 1½ kw to a transducer were available.

At the end of WW II in 1945, it was possible to calibrate a small hydrophone from 2 cps to 2.2 mc. Projectors or sound sources weighing up to a few hundred pounds could be calibrated from about 50 cps to 150 kc, with driving powers of 1½ kw available in the audio-frequency range. When pressure and temperature were variables, the capabilities were limited to 2-100 cps and 100 psi for small hydrophones only, temperature range 34 - 100°F; and to 10-150 kc and 300 psi for fairly small hydrophones and projectors (less than 100 lbs). Standard hydrophones and projectors were adequate, but far from ideal. Stability with time, static pressure, and temperature was in many cases poor for "standard" purposes. Sound sources were generally cumbersome, and response curves were not the smooth flat curves desirable in calibration work. The automatic measuring systems did not have capability for pulsed-sound measurements. Thus, in spite of great strides forward during WW II, the sonar calibration art in 1945 was still in a relatively crude state.

1945-50

After WW II, the sharp drop in all phases of military-connected research and development affected underwater sound and sonar calibration work. Columbia University, Bell Telephone Laboratories, and almost all other private organizations who had been active in underwater sound work during the war withdrew wholly or partially from this activity. The Navy assumed responsibility for operating the USRL at Orlando. Scientific and engineering personnel who had been active during the war turned to other pursuits. By 1948 not a single one of the 29 professional scientists and engineers employed by CUDWR remained at the USRL. The USRL professional staff had dwindled to about 15 people who were not only to continue the work of the 29 CUDWR professional staff, but also the work of the unknown number of BTL engineers who had provided electroacoustic and electronic instrumentation and systems.

Although little research and development work was actually done during the years immediately following the war, books, reports, and papers were published in the open literature covering unclassified material worked on during the war. The work of the USRL in particular was published as a NDRC Summary Technical Report [9]. Under the auspices of ONR, Beranek published the first book [12] devoted entirely to acoustic measurements. The work of the Germans on absorbers was translated and published [13]. The first commercial general-purpose measurement hydrophones were produced by Massa Laboratories and the Brush Development Company. Mason and Hibbard published their WW II work on small tank sound absorbers [14].

There were a few instances of calibration methods research: Carstensen at the USRL extended the reciprocity calibration concept with a self-reciprocity technique [15] wherein the calibration of an unknown transducer required no auxiliary measurement transducer. McMillan explained how a passive and linear system could be nonreciprocal if it contained transducers with both electrostatic and electromagnetic coupling [16]. Bobber and Darner at the USRL built a transducer demonstrating McMillan's point [17]. Simmons (a former USRL employee) and Urick devised a plane-wave reciprocity parameter [18].

In 1948 the USRL began a research and development program that had two major purposes: 1) To improve the quality of standard hydrophones and calibration of transducers in general, and 2) to find methods of calibrating transducers in tanks over wide ranges of pressure and frequency.

By 1950 open-water calibration facilities consisting of one barge or one pier were in operation at the Underwater Sound Laboratory, New London, Conn., the Naval Research Laboratory in Washington, D.C., the Naval Ordnance Laboratory in Silver Spring, Maryland, the Navy Electronics Laboratory in San Diego, California, and the Ordnance Research Laboratory at Pennsylvania State University. Some other research and development organizations and transducer manufacturers had small tank facilities. Other than the USRL, however, none of these organizations had facilities for calibrating at infrasonic frequencies, at megacycle frequencies, or with pressure and temperature as variables. All of the government activities and many industrial manufacturers used standard hydrophones and sound sources furnished or calibrated by the USRL. These other facilities were largely calibration service groups catering to the immediate needs of a parent organization.

1951-61

During the decade 1951-61 old methods of calibration were refined and new methods were invented for special cases in which the conventional spherical-wave reciprocity method could not be used.

The WW II BTL/USRL system for calibrating small hydrophones in the frequency range 2-100 cps was improved by Bobber [19] and Beatty [20]. Beatty also developed a quasi-static method called a "Dunking machine" [21] for the calibration of hydrophones below 5 cps. BTL, in connection with a classified project, adapted the air pistonphone technique to water [22]. All these methods were subsequently superseded at the USRL by Trott's two-projector null method [23] which was more convenient and reliable and was applicable to frequencies up to 500 cps.

At the USRL, Sabin [24] modified and simplified Carstensen's self-reciprocity concept so that the only electrical parameter measured was impedance. He also devised a method for measuring the blocked impedance of a resonant transducer [25] — a parameter that could only be estimated or computed before. Sims invented the pressurephone [26] for calibrating primary standard hydrophones under high static pressures in the frequency range 500 cps to 5 kc. Bobber and Sabin provided still another reciprocity method [27] —this one involving cylindrical waves and applicable to very long line transducers.

There was also a growing awareness that the reciprocity method could, in principle, be used for any set of boundary conditions if a reciprocity parameter peculiar to the conditions could be calculated. This even included such cases as diffuse sound fields [28]. Sims and Paine developed economical calibration methods for special cases such as production testing of sonobuoys [29] and qualitative evaluation of a hydrophone's stability with temperature [30]. Sabin studied and calculated the effects of very long cables on the sensitivity [31] and impedance [32] of transducers.

In universities, older methods of measurement, such as the measurement of sound pressure by optical diffraction and refraction [33] and calibration by radiation pressure [34], were pursued and demonstrated.

Perhaps the most significant evidence of maturity in the state of the art of sonar calibration methods came with a formal standardization of procedures. In 1952, a group under the joint sponsorship of the American Standards Association and the Acoustical Society of America was appointed to write a standard for the calibration of underwater sound transducers. With W. J. Trott of the USRL as chairman, and a membership consisting almost entirely of personnel from naval activities, this group worked on the task for several years. The standard was published in 1957 [35].

Great advances in facilities occurred during the 1951-61 decade, starting with the replacement of the USRL 300-psi tank by the installation of a larger 1000-psi tank [36] in the new USRL laboratory. The usefulness of this tank was extended by making it "anechoic" or free from echoes by the discovery of "insulkrete" [36, 37]. Insulkrete is still the only sound absorber that will retain its absorbing characteristics under high static pressure. Other tank facilities at the Navy Electronics Laboratory and Naval Ordnance Laboratory were being used at only ambient pressure; they contained a new sound absorbing rubber, SOAB, [38, 39] manufactured by the B. F. Goodrich Co.

At the USRL, a new 1000-psi low-frequency calibrating system [40] was developed and built to supplement the old BTL 100-psi system.

The BTL/USRL high-frequency tank system built in WW II was replaced by a larger tank with improved mechanical instrumentation [41].

By 1961, the USRL had four pier systems, two low-frequency tank systems, a 1000-psi anechoic tank for the high audio and ultrasonic frequency range, and a high-frequency tank system for the megacycle range. Elsewhere, many government activities and companies had installed calibration facilities in open tanks or bodies of water. Only a few, however, had any facilities for calibration measurements at extremes of frequency, pressure, or temperature, and the USRL remained the primary source for this type of calibration.

About 1949, the USRL began a program to gradually improve or replace all of the old BTL standard hydrophones and transducers that had been designed and built early in WW II. The USRL pioneered in the use of lithium sulfate piezoelectric crystals grown by the Brush Development Company, [42] and lead metaniobate piezoceramic [43] from the General Electric Company, in underwater sound transducers.

The USRL type E8 [44] replaced the BTL type MH as a high-frequency standard. The USRL used the tourmaline motors from the NRL type OLA to develop the H9, a high static pressure standard for the ultrasonic frequency range. The H9 was later superseded by the H29 [45]. The old BTL dynamic type 4B transducer, used as a sound source for low audio frequencies, was modified [46] to make it easier and more convenient to operate. A new standard hydrophone [47] for the frequency range 0.3 cps to 2 kc was developed. The Edo Corporation built a replacement for the BTL type 6B according to USRL specifications. The USRL developed the type J9 [48], the only high-fidelity underwater sound transducer in existence, which replaced all of the BTL/USRL dynamic type transducers. The USRL type H17 was developed as a stable wide-range hydrophone to supersede the old BTL type 3A and several other commercial models.

Having the only high pressure calibration facility in the free world, the USRL was in a good position to learn much about the effects of high static pressure on transducers and to apply these observations to the design of standards. The experience of the USRL was disseminated to the Navy and naval contractors [49,50].

Unusual types of transduction were investigated. The USRL developed an electronic hydrophone [51], a "bubble" transducer [52], and the theory for a distributed coupling transducer [53]. The Beta Corporation developed an electrokinetic hydrophone [54].

Although almost all standard hydrophones can be used to measure sound pressure, there is an occasional need to measure sound particle velocity. Velocity hydrophones were developed at the Naval Ordnance Laboratory [55] and David Taylor Model Basin [56].

1961

The period 1950-60 was a decade of steady growth in the state of the art of sonar calibration methods. New methods were developed and old methods refined to cover ever increasing ranges of transducer size, frequency, pressure, temperature, and electrical power. Calibration methods were formally standardized. The art of building stable standard transducers matured. By 1961, however, two developments in sonar kept pushing the requirements beyond the state of the art—the trend to low frequencies and giant high-powered transducers, and the increasing depth at which sonar transducers were to be used.

The capability to meet the first of these requirements is being approached in two ways. Large facilities for the calibration of giant sonar transducers from stable platforms under ambient pressure have been studied and planned, but have not been built for economic reasons. In the second approach, the theory and practice of making measurements in the near field of a transducer where the maximum discrimination against boundary interference can be obtained, is being investigated. The possibility of making such measurements and computing far-field performance from near-field data appears very promising [57,58,59].

The second requirement of greater depth or higher pressures is the subject of intensive research. Three approaches are being used. The possibility of a 5-10,000 psi tank designed so that current anechoic tank measuring techniques can be used is being investigated. The feasibility of this approach is probably low because large size and high pressure are largely incompatible. The second approach is to combine limited tank size with near-field techniques. The feasibility here is unknown as yet, but the USRL is optimistic. The third approach is to devise new methods that can be used in small tanks. One new method called the active impedance tube is now in the research stage [60,61].

The ever-increasing requirements affect instrumentation research and development as well as methods and facilities. For example, transducers for 10,000 psi have to be developed, and electronic measuring equipment that is accurate, reliable, and stable when measuring signals of electrical power in the kilowatt and even megawatt range must be built.

After 20 years of development, the science and art of calibrating underwater sound transducers has matured in most respects; however, as in other areas of science and engineering, the magnitude of the problems has grown in size and complexity, so that we currently find that the state of the art is lagging behind requirements of the Navy.

REFERENCES

[1] Langevin, International Hydrographic Bureau, Monaco, Special papers, No. 3, 1924, No. 4, 1926

[2] R. W. Boyle, Proc. Roy. Soc. Canada, III 167 (1925)

[3] Gerlach, *Wissenshaftliche Veröffentlichungen aus dem Siemens-Konzern*, *3*, 1939 (1923)

[4] F. D. Smith, "The absolute measurement of sound intensity," *Proc. Phys. Soc.* (London) ***41***, 487 (1929)

[5] E. Klein, "Absolute sound intensity in liquids by spherical torsion pendula," *J. Acoust. Soc. Am. 9*, 812 (1938)

[6] W. R. MacLean, "Absolute measurement of sound without a primary standard," *J. Acoust. Soc. Am.* ***12***, 140 (July 1940)

[7] R. K. Cook, "Absolute pressure calibration of microphones," *J. Acoust. Soc. Am.* ***12***, 415, (June 1941)

[8] L. L. Foldy, "Free field reciprocity calibration of underwater sound reference laboratories standards," CUDWR/USRL/OSRD report C4-sr20-206 (1942)

[9] *Sonar Calibration Methods*, Summary Technical Report of NDRC, Div. 6, Vol. 10 (1946)

[10] *Sonar Calibration Measurements*, Summary Technical Report of NDRC, Div. 6, Vol. 11 (1946)

[11] O. M. Owsley, "Testing devices for sound projectors," U. S. Patent No. 2,451,509 (filed 5 July 1944)

[12] L. L. Beranek, *Acoustic Measurements* (John Wiley & Sons, Inc., New York, 1949)

[13] Erwin Meyer et al., "Sound absorption and sound absorbers in water" (Department of the Navy, Washington, D. C., 1950), NAVSHIPS 900,164.

[14] W. P. Mason and F. H. Hibbard, "Absorbing media for underwater sound measuring tanks and baffles," *J. Acoust. Soc. Am. 20*, 476 (1948)

[15] E. L. Carstensen, "Self-reciprocity calibration of electroacoustic transducer," *J. Acoust. Soc. Am. 19*, 961, (1947)

[16] E. M. McMillan, "Violation of the reciprocity theorem in linear passive electromechanical systems," *J. Acoust. Soc. Am. 18*, 344 (1946)

[17] R. J. Bobber and C. L. Darner, "A linear passive nonreciprocal transducer," *J. Acoust. Soc. Am. 26*, 98 (1954); "The design of a linear, passive, non-reciprocal, electroacoustic transducer," USRL Research Report No. 11 (1949)

[18] B. D. Simmons and R. J. Urick, "Plane wave reciprocity parameter and its application to calibration of electroacoustic transducers at close distances," *J. Acoust. Soc. Am. 21*, 633 (1949)

[19] R. J. Bobber, "The calibration of a low-frequency calibrating system," USRL Research Report No. 23 (1952)

[20] L. G. Beatty, "Acoustical properties of a small, closed, rigid-wall water-filled calibration chamber," USRL unpublished internal memorandum (1958)

[21] L. G. Beatty, "The dunking machine method of hydrophone calibration at infrasonic frequencies," USRL Research Report No. 35 (1955)

[22] D. E. Willig, "Low-frequency high-pressure hydrophone calibration," Bell Telephone Laboratories Memorandum for File, Oct. 10, 1952 (Confidential)

[23] W. J. Trott and E. N. Lide, "Two-projector null method for calibration of hydrophones at low audio and infrasonic frequencies," *J. Acoust. Soc. Am. 27*, 951 (1955)

[24] G. A. Sabin, "Transducer calibration by impedance measurements," *J. Acoust. Soc. Am. 28*, 705 (1956)

[25] G. A. Sabin, "New technique for measuring transducer blocked impedance," *J. Acoust. Soc. Am. 30*, 146 (1958)

[26] C. C. Sims and R. J. Bobber, "Pressure phone for hydrophone calibrations," *J. Acoust. Soc. Am. 31*, 1315 (1959)

[27] R. J. Bobber and G. A. Sabin, "Cylindrical wave reciprocity parameter," *J. Acoust. Soc. Am. 32*, 923(A) (1960); *33*, 446 (1961)

[28] H. G. Diestel, "Reciprocity calibration of microphones in a diffuse sound field," *J. Acoust. Soc. Am. 33*, 514 (1961)

[29] C. C. Sims, "Hydrophone calibrator," *J. Acoust. Soc. Am. 33*, 838(A) (1961)

[30] W. L. Paine, "Acoustic measurements under transient temperature conditions," *J. Acoust. Soc. Am. 33*, 816 (1961)

[31] G. A. Sabin, "Effect of cable on transducer frequency response measurements," USRL unpublished internal memorandum (1954)

[32] G. A. Sabin, "Effect of cable on transducer impedance measurements," USRL unpublished internal memorandum (1954)

[33] M. A. Breazeale and E. A. Hiedemann, "Optical methods for the measurement of sound pressure in liquids," *J. Acoust. Soc. Am. 31*, 24 (1959)

[34] A. R. Laufer and G. L. Thomas, "New method for the calibration of a plane hydrophone," *J. Acoust. Soc. Am. 28*, 951 (1956)

[35] American standard procedures for calibration of electroacoustic transducers particularly those for use in water, Z24.24-1957, American Standards Association, Inc., New York

[36] C. L. Darner, "Anechoic tank for underwater sound measurements under high hydrostatic pressure," *J. Acoust. Soc. Am. 26*, 221 (1954)

[37] C. L. Darner, "An underwater sound absorber for an anechoic tank," USRL Research Report No. 31 (1953)

[38] W. J. Toulis, "Simple anechoic tank for underwater sound," *J. Acoust. Soc. Am. 27*, 1221 (1955)

[39] W. S. Cramer and T. F. Johnston, "Underwater sound absorbing structures," *J. Acoust. Soc. Am.* **28**, 501 (1956)

[40] L. G. Beatty, "A Hydrophone calibration system for low frequencies and high static pressures," USRL Research Report No. 41 (1958)

[41] P. F. Hurt, "Mechanical rigging system for the calibration of high frequency underwater sound transducers," USRL Research Report No. 38 (1956)

[42] H. Jaffe, "Piezoelectric crystal," U. S. Patent No. 2,490,216 (filed June 17, 1947)

[43] C. C. Sims, "Lead metaniobate in high-pressure transducers," *J. Acoust. Soc. Am.* **32**, 923(A) (1959)

[44] R. J. Bobber, "The USRL type E8 transducer - an underwater sound calibration standard for the 100-1000 kilocycle range," USRL Research Report No. 22 (1952)

[45] C. C. Sims, "Standard calibration hydrophone," *J. Acoust. Soc. Am.* **31**, 1676 (1959)

[46] R. J. Bobber and I. D. Groves, "The USRL low frequency transducer type J2," USRL Research Report No. 28 (1953)

[47] I. D. Groves, "The USRL infrasonic hydrophone type H11," USRL Research Report No. 37 (1956)

[48] C. C. Sims, "High-fidelity underwater sound transducers," *Proc. Inst. Rad. Engr.* **47**, 866 (1959)

[49] R. J. Bobber, "Effects of high static pressure on transducer performance," *J. Underwater Acoust. (USN)* **7**, 101 (1957)

[50] R. J. Bobber, C. C. Sims, and I. D. Groves, "Transducers for high pressure and low temperature," *J. Underwater Acoust. (USN)* **11**, 427 (1961)

[51] R. J. Bobber, "Electronic hydrophone for calibrations at very low frequencies," *J. Acoust. Soc. Am.* **26**, 1080 (1954)

[52] C. C. Sims, "Bubble transducer for radiating high-power low-frequency sound in water," *J. Acoust. Soc. Am.* **32**, 1305 (1960)

[53] W. J. Trott, "A passive reversible distributed coupling transducer," paper presented at 3rd International Congress on Acoustics (1959)

[54] E. V. Hardway, Jr., "Electrokinetic hydrophones," Beta Corporation Technical Report No. 4, ONR contract NOnr-617(00) (Feb 1954)

[55] C. B. Leslie, J. M. Kendall and J. L. Jones, "Hydrophone for measuring particle velocity," *J. Acoust. Soc. Am.* **28**, 711 (1956)

[56] G. L. Boyer, "Instrumentation for measuring underwater acoustic intensity," *J. Acoust. Soc. Am.* **32**, 1519(A) (1960)

[57] W. J. Trott, "Transducer calibration from near-field data," USRL Research Report No. 55 (1961)

[58] J. Pachner, "On the dependence of directivity patterns on the distance from the emitter," *J. Acoust. Soc. Am.* **28**, 86 (1956)

[59] C. W. Horton and G. S. Innis, Jr., "The computation of far-field radiation patterns from measurements made near the source," *J. Acoust. Soc. Am.* **33**, 877 (1961)

[60] R. J. Bobber and L. G. Beatty, "Impedance tube for underwater sound transducer evaluation," *J. Acoust. Soc. Am.* **31**, 832(A) (1959)

[61] R. J. Bobber, "An active load impedance," *J. Acoust. Soc. Am.*, in press.