Transducers and Arrays for Underwater Sound (2nd edition)
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This book is addressed to students, engineers and scientists who use or design transducers and arrays of transducers for underwater sound. The text covers important topics for underwater acoustics, theory and applications, within its 12 chapters. An ample appendix is organized as the 13th chapter and provides additional background information. The book conveys the expertise of the authors, known for their research at US Navy and their academic work in several US Universities. Sample exercise calculations for the discussed topics are inserted in the text. Problems and questions are included at the end of each chapter to be answered by the readers. The solutions to the odd-numbered exercises are provided.

Chapter 1 briefly presents a historical review of underwater sound transducers and arrays of transducers along with a survey of their applications. The authors discuss in a unified way the main aspects on the electroacoustic conversion for six types of transduction mechanisms which will be analyzed in the text:

1 – piezoelectric,
2 – electrostrictive,
3 – magnetostrictive,
4 – electrostatic,
5 – variable reluctance and,
6 – moving coil.

The transducer characteristics briefly discussed here are the electromechanical coupling coefficient, the transducer response, the directivity index and the source level.

Chapter 2 discusses in detail the six types of transducers. The electromechanical equation of motion is deduced for each type of transducer. In the case of the piezoelectric transducers, the equations for the 31-mode and 33-mode longitudinal vibrators are provided. A comparison of the fundamental features of the transduction mechanisms is provided, which helps selecting the suitable transducers for different applications. The text presents equivalent circuits for the analysis of the electroacoustic transducers and discusses, based on equivalent lumped circuits, the main parameters of transducers: the resonance, circuit quality factor, bandwidth, tuning, powering factor, power limits, and efficiency. Topics on the circuit and noise analysis of a hydrophone are also discussed. The text also presents fundamentals on the thermal analysis: a lumped model for the thermal process and means for calculating the power and heating of a transducer at resonance.

Chapter 3 deals with models and methods used in the analysis of transducers: the lumped-parameter models and equivalent circuits, the distributed models, matrix models and finite element models. The lumped-parameter models consist in equivalent circuits for transducers seen as single degree or two-degree of freedom mechanical resonators. The text presents distinctly the equivalent lumped circuits for piezoelectric ceramic and magnetostrictive transducers. The effects of Eddy currents in the analysis of the magnetostrictive transducers are also briefly discussed. Distributed mechanical models are explained based on the infinitesimal analysis of the mechanical bar. The reader can learn to deduce the equations which describe the vibration of a mechanical bar and how this model is extended to a series of bars connected together. The equivalent circuit for the piezoelectric distributed parameters is separately discussed, with further details for different vibration modes of the mechanical bar, for thickness mode plate and for the magnetostrictive rod. The matrix models reveal the benefits of the matrix representation of the mechanical distributed circuits seen as two-port or three-port structures. The discussions on the finite element models introduce the reader into the advanced methods for the analysis and design of electroacoustic transducers. Modern high-speed computers and special software perform finite element analysis (FEA) for finite element models which allow determining, for instance, the behavior of the variable cross-sectional bars. The text discusses the FEA matrix representation, the inclusion of a piezoelectric finite element in modeling, FEA for magnetostrictive elements, FEA in air and in water loading conditions, and means of shaping equivalent circuits for the FEA models.

Chapter 4 discusses the most important characteristics of any transducer: the resonance frequency, the mechanical quality factor, the characteristic mechanical impedance, the electromechanical coupling coefficient, and the figure of merit with specific aspects for projectors. The mathematical modeling of any transducer involves material characteristics and the equivalent circuits developed before. Along with the definitions found in the literature for the mechanical quality factor, the text quantifies through rigorous math the effect of the mass and the influence of the mechanical resistance on the quality factor of the mechanical bar. Similarly, when discussing the electromechanical coupling coefficient, the text provides the energy definitions found in the literature along with a rigorous analysis of the elements which can influence the coupling coefficient.

Chapter 5 is wholly dedicated to projectors, the transducers which produce sound for the underwater applications.

After presenting the principles of operation for projectors, the text defines figures of merit and evaluates ways of improving the design of these transducers for various applications. The authors discuss the following projector types: ring, cylindrical, spherical, piston (Tonpilz), transmission line, flextensional, flexural, modal and low-profile piston transducers. The text develops equations of motion, provides equivalent circuits and calculates coupling coefficients, mechanical quality factors, resonance frequencies and other main parameters. The authors discuss constraints and practical solutions for each type of projector, making clear how to adopt the best transducer for a real-life application. The reader can find under the main categories listed above the thorough analysis of over 25 projector models, from classical makes to recently designed ones. The authors recommend bibliography to the readers who want to learn about projector types not found in the text, such as historic models or designs which do not fit the six transduction mechanisms considered in this book.

Chapter 6 discusses the hydrophones, transducers which are intended to convert the underwater sound into electrical signals. In principle, any projector can transform acoustical signals into electrical ones. Moreover, there are applications where the transducers are used in dual projector/hydrophone mode. However, specific demands such as the wide frequency band needed for the acoustic receivers and the passive sonar applications require specially designed transducers to be used as hydrophones. The text describes the principles of operation and deduces equations for the sensitivity and figure of merit for hydrophones. For the transducers, which are used both as projectors and hydrophones, the text deduces the equation which links the transmitting voltage response in projector mode and the receiving voltage sensitivity in the hydrophone mode. The discussion continues with the analysis of four main transducer types: cylindrical, spherical, planar, and bender hydrophones. The text also presents the category of vector hydrophones, which are sensitive to both the magnitude and the direction of the acoustic wave. In this group discussed are the dipole vector, pressure gradient vector, velocity vector, piezoelectric multimode vector, summed scalar and vector sensors, and the intensity sensors. For investigating the hydrophones in their environment, the text defines a plane wave diffraction constant and graphically presents values for this parameter in the case of four hydrophone models. A formula given in the text relates the diffraction constant, the directivity factor and the radiation resistance of the hydrophones. The discussion is completed with a thermal noise analysis. The text provides a comprehensive noise model for hydrophones, including details on the vector sensors susceptibility to local noise.

Chapter 7 deals with the arrays of projectors. The authors discuss the composite structures of projectors for naval applications and refer practical aspects, constraints and problems which arise when multiple projectors are operating close to each other. The product theorem given in the text allows calculating the far field created by planar or line arrays formed of identical transducers with the same orientation. Then, the text develops equations for determining far field directivity functions for the line, rectangular and circular arrays. The grating lobes of several arrays are analyzed, along with solutions for reducing the side lobes and optimizing the shape for the directivity functions of the arrays. The mutual radiation impedance between transducers is defined for resolving the array equations and for determining the performance of a given array. The text deduces the mutual radiation impedance for planar arrays of piston transducers and discusses basics for the radiation impedance in the case of nonplanar arrays. For the arrays of non-fixed velocity distribution transducers, the authors present a modal analysis of the radiation impedance. The discussion is extended to the volume arrays, which radiate from two or more sides. As an example, the radiation impedance is calculated for a system of two pulsating spheres. The near field aspects for the projector arrays are also discussed. The text shows that the complexity of the array structures impedes the accurate modeling of the near field. However, the finite element analysis can provide approximate guidance in design for the near field problems. The chapter is completed with the analysis of the nonlinear parametric arrays and doubly steered arrays.

Chapter 8 presents the hydrophone arrays. After a general presentation of these arrays, the authors investigate the main topics regarding the directional response, gain, noise and methods of reducing the noise in arrays of hydrophones. Specifically, the directional response of a hydrophone array involves the analysis of directivity functions, beam steering and shading techniques. For determining the gain of the array, the text defines and uses in calculations cross correlation functions. The discussions on noise include the characterization of the main sources (ambient sea noise, structural noise, and flow noise) along with techniques of reducing the noise of the array from each of the sources mentioned above. For the arrays of vector sensors, evaluated are the main directivity properties and the behavior of the arrays against the ambient noise. Another topic refers the noise in the case of the hull-mounted arrays. The text argues the modeling, deduces signal to noise ratio formulas, and shows experimental results from such mountings. The chapter ends with the analysis of a steered planar circular array of hydrophones.

Chapter 9 discusses calibration aspects, procedures and means for evaluating and measuring the main parameters of the transducers, both projectors and hydrophones. The measurements are made in air or water loading, near field or far field conditions for the transducer under test. The text shows equivalent circuits and equations for determining the impedance and admittance parameters for the electric field and magnetic field transducers and describes measurements for resonance frequencies, effective dynamic coupling coefficient and electromechanical turns ratio. The measurements in water reveal the influence of the water loading on the resonance frequencies, mechanical quality factor, the efficiency coefficients and the acoustic response of the transducers.

The text presents the reciprocity calibration by using the transducer transfer matrix and develops equations for the reciprocal parameters. A way of optimizing the performance of the transducers during the calibration tests consists in electrically tuning their responses. The text gives details on this technique for electric field and magnetic field transducers. Another discussed topic regards the near field measurements on transducers, which are convenient to be made. After establishing the far field for a projector or hydrophone at the so-called Rayleigh distance, the text describes measurements in tanks and discusses the near field to far field extrapolations for small and large sources. The effect of transducer housings on measurements is also discussed. At the end of this chapter, the authors present a list of transducers developed and calibrated at US Navy for serving as standards in calibrating other transducers.

Chapter 10 is dedicated to the acoustic radiation from transducers. After presenting the core problem for the acoustic radiation of a vibrating sphere with detailed modeling in rectangular, cylindrical and spherical coordinates, the authors develop the theory of the far-field radiation from a line source and from flat sources in a plane (point sources, flat circular piston and rectangular piston). The theory includes deducing the Rayleigh integral equation and calculating the far field patterns for the line sources and a circular piston. The spherical and cylindrical sources are also discussed, with details on their far field beam patterns. The analysis continues with the evaluation of the near-field radiation on the axis of a circular piston, the near field of circular sources, and the effect of the near field on cavitation. Special attention is given to the radiation impedance which is a main characteristic for the acoustic field of a transducer. The text deduces formulas for the radiation impedance of spherical sources and circular sources in a plane. This chapter concludes with the analysis of the acoustic radiation from a small dipole transducer in the presence of a small passive monopole radiator.

Chapter 11 presents the main equations and formulae developed for physical sciences and adapted for use in acoustics. This chapter is of real help for those who want to thoroughly understand the content of this book, aiming to further research on electroacoustic transducers. A main subject regards modeling of the mutual radiation impedance for piston transducers on a sphere and piston transducers on a cylinder. The analysis uses spherical and cylindrical coordinates and involves Legendre polynomials, Hankel and Helmholtz equations, Fourier and Hilbert transforms, along with other special math functions. The Green's theorem is used to demonstrate the acoustic reciprocity theorem. Then, the Green's function solutions are used for acoustic problems with boundary conditions such as calculating the radiation from the line or plane sources. A special problem regards the scattering of waves from rigid objects. The text develops solutions for the scattering of the plane wave from a sphere and from an infinitely long cylinder and calculates diffraction constant formulas. The mathematics includes Helmholtz integral equation, Legendre polynomials, and Bessel and Hankel functions. The authors discuss numerical methods developed for applying the special math functions in the engineering analysis and cite the new field in acoustics research named "boundary element methods."

Chapter 12 deals with the nonlinear mechanisms and their effects in the analysis of the transducers. In a simplified approach, the discussions in previous chapters considered that the vibrating elements behave linearly at least in a small range for the mechanical and electrical signals. However, there are deviations from the linear rules and the nonlinear mechanisms are discussed in this chapter for lumped parameter and distributed parameter transducers. The equations of motion are re-written by considering additional relations between the electric or magnetic field quantities and the movement of the vibrating elements. This way, the linear differential equations of motion turn into nonlinear equations and the solutions reveal new details for analysis. The text discusses nonlinear mechanisms and develops nonlinear equations of motion for the piezoelectric, electrostrictive, magnetostrictive, electrostatic and variable reluctance, and moving coil transducers. The main effect of the nonlinearities consists in harmonic distortions which are thoroughly analyzed. The text shows that the nonlinearities may create even instabilities in the case of electrostatic and variable reluctance transducers. The chapter ends with the nonlinear analysis of a distributed parameter transducer. In this case, the modeling of phenomena leads to nonlinear partial differential equations rather than ordinary differential equations.

Chapter 13 is an appendix which provides handy information for the reader, such as unit conversions, physical constants, materials used for manufacturing of transducers, various coefficients and small signal properties for piezoelectric and magnetostrictive materials, etc. The addendum includes basic math for time averages, power factor and intensity, complex algebra, integral transforms (Fourier, Hankel, and Hilbert), basics for electric and magnetic circuits, Thevenin and Norton circuits, modeling of cables and transformers. The appendix also includes a brief discussion on stiffness, mass and resistance for the piezoelectric transducers, and characteristic parameters for piezoelectric ceramics, and presents the development of a hydrophone noise model.

Through the whole content, with detailed analysis and rigorous math, accurate modeling and numerous references in each chapter, the Transducers and Arrays for Underwater Sound authored by John L. Butler and Charles H. Sherman is a very valuable text. This book is recommended to all those who are connected to the theory and practice of the underwater acoustics.

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