



PIEZOELECTRIC ELECTROMECHANICAL TRANSDUCERS FOR UNDERWATER SOUND

Boris S. Aronov

Part I

Introduction to Energy Method
of Treating the Transducers

BOSTON
2022



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ISBN 9781644698211 (hardback)

ISBN 9781644698259 (Open Access)

Published by Academic Studies Press

1577 Beacon Street

Brookline, MA 02446, USA

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www.academicstudiespress.com

*In memory of
my mentor, Lev Yakovlevich Gutin,
and my friends and colleagues, prominent Russian electroacousticians, '
Lev Davidovich Lubavin and Vladimir Igorevich Pozern*

FOREWORD

The book is the most comprehensive coverage of piezoelectric acoustic transducers and all the related aspects of practical transducer designing for underwater applications in the field. It uses a physics-based energy method for analyzing transducer problems. This gives great physical insight into the understanding of the electromechanical devices. The great benefit of the energy method is that the multidisciplinary subject of electro-mechano-acoustics can be presented in parts and the solutions to the problems (electrical, electro-piezo, mechanical, and radiation) are combined using equivalent electrical circuit network theory. The energy and equivalent electromechanical circuit method at first is illustrated with transducer examples that can be modeled as a single degree of freedom system (such as spheres, short cylinders and flexural beams and plates). Then transducers are modeled as multiple degrees of freedom devices and the results are presented using multi contour electromechanical circuits. Special focus is made on the effects of coupled vibrations on the transducer performance. The Book gives also extensive coverage of acoustic radiation including acoustic interaction between the transducers. It provides practical results that are directly useful for the transducers modeling. While there have been many studies of acoustic radiation of various shapes, non-previous presented the results in terms of such practical utility.

The book is inherently multidisciplinary. It provides essential background into vibration of elastic passive and piezoelectric bodies, piezoelectricity, acoustic radiation, and transducer characterization. Scientists and engineers working in the field of acoustics will find such a comprehensive treatment extremely useful not only for underwater acoustics, but also for electro-mechanics, energy conversion and medical ultrasonics.

David A. Brown, Dartmouth, Massachusetts, 2022

PREFACE

This book is initiated by the engineering experience of the author. Throughout his career the author has encountered many of the problems known to others involved in the design of electroacoustic transducers. The fact of the matter is that the complexity of designing electroacoustic transducers is inherent in the multidisciplinary nature of the subject. Therefore, the developers and designers of the transducers must possess the knowledge of several different theoretical disciplines (such as the vibration of mechanical systems, electromechanical conversion by deformed piezoelectric bodies, and acoustic radiation) and be able to actively use this knowledge to derive equations that describe the performance of the transducers. Furthermore, creating practical transducer designs that meet certain requirements and can operate under realistic environmental conditions requires the knowledge of properties of materials used and a certain level of engineering intuition that cannot be developed without a clear understanding of the underlying physics. Hardly anyone may possess all these capabilities without having received a specially targeted education, which, to the best of the author's knowledge, is not commonly available in the academic world. Usually, the necessary skills may be acquired through self-education, which was the case for the author. The main difficulties that arise in this endeavor are not in the lack of available information. On the contrary, the theoretical disciplines listed above are very well developed and are well-represented in the literature. Nevertheless, all these disciplines employ different methods for solving their problems and the results obtained are usually presented in forms not suitable for direct use in concert for synthesizing equations that govern transducer performance. Thus, the results must be tailored accordingly.

Experiencing the above difficulties over several decades, the author gradually developed a special approach to treating transducers problems that allows one to overcome many of the obstacles. The essence of this approach is in the consistent application of the physics-based energy method for solving all the problems that arise in the course of treating electromechanical and electroacoustic transducers. The first attempt to describe this concept was undertaken in *Electromechanical transducers from piezoelectric ceramic* published in 1990 in Russia. This version has now been updated and expanded to the extent that it can be considered a completely

different book. Only the underlying energy approach to solving the problems has remained unaltered. This book is written for students, applied scientists and engineers in a way that should prove fruitful both for those who have only begun to chart their careers in electroacoustics as well as for those at a more advanced level. The content of the book is split into four parts.

In Part I, titled “Introduction of energy method of treating the transducers,” the main concepts of the method are considered (Chapter 1); applications of the method to calculating properties of transducers with single degree of freedom are illustrated (Chapter 2); and the study of problems for designing the transducers as a part of the transmit/receive channel is made (Chapter 3). The main concept is that of energy and following its transformation. Different types of energies involved in the electro-mechano-acoustic conversion in the course of transducer operation are presented in the generalized coordinates. All the governing equations are derived from the energy principles, that is, from the Law of Conservation of Energy for transducers with a single mechanical degree of freedom, and from the Principle of Least Action for transducers with multiple degrees of freedom. Equations describing the electromechanical part of the problem are reinterpreted as Kirchhoff’s equations for the corresponding equivalent electromechanical circuits. In Chapter 2, the general approach is applied towards calculating the properties of transducers of widely used types (spheres, cylinders, bars undergoing extensional vibration and for circular plates and rectangular beams vibrating in flexure) that may be considered as systems with single mechanical degree of freedom. In Chapter 3, the operating properties of transducers as a part of a transmit/receive channel are considered and some recommendations regarding a rational transducer designing are presented. Given that the single degree of freedom approximation covers many practical transducer designs, Part I can be regarded as a self-sufficient study of underwater electroacoustic transduction on a basic level and can be read independently from the rest of the book.

The general treatment of electroacoustic transduction requires an advanced knowledge of the vibration of mechanical systems, electromechanical conversion in the deformed piezoceramic bodies and acoustic radiation. Information about these topics, which is necessary for the consideration of virtually all practical transducer types is presented in Chapters 4-6 of Part II under the title: “Subsystems of the Electroacoustic Transducers.” All the constitutive equations are derived in these chapters from the Principle of Least Action as Euler’s Equations in

generalized coordinates. The obtained results are presented in the form of impedances, (including the radiation impedances), electromechanical transformation coefficients and acting forces (including those of acoustic origin) that can be directly substituted into the equivalent electro-mechanical circuits (multi contour in general) of the transducers. The diffraction coefficients and directional factors for differently configured transducer surfaces are also presented.

In Chapter 4, special attention is paid to the consideration of coupled vibrations in the generally two-dimensional mechanical systems. The results allow determining the range of aspect ratio, at which the system can be approximately considered as one-dimensional, where the problem can be simplified.

In Chapter 5, especial importance is ascribed to the theorem that sets the conditions, at which the electromechanical conversion under the longitudinal and transverse piezoelectric effects can be treated qualitatively in the same way. This allows for the unifying calculation technique for the transducers that employ these types of ceramics polarization. Another important subject is the general analysis of optimizing the effective coupling coefficients in nonuniformly deformed piezoceramic bodies.

Chapter 6 touches upon several noteworthy issues. Besides solving the general radiation problems, it provides a detailed consideration of the effects of baffling parts of the surfaces of cylindrical and spherical transducers, which ensures their unidirectionality. The technique for the experimental investigation of the acoustic interaction between transducers (or between the mechanically isolated parts of the same transducer) is also analyzed. Since the baffles have an effect on the acoustic near field, the interactions can rarely be treated analytically for practical transducer configurations, hence more reliable characterization of the interaction can be obtained through an experimental investigation.

The results obtained in the Part II are used in Part III of the book titled “Calculating transducers of different types” for synthesizing equations that describe the detailed operation of transducers of various configurations: cylindrical (Chapter 7), spherical (Chapter 8), plates and beams vibrating in flexure (Chapter 9) and bar transducers (Chapter 10).

Chapter 7 presents a study of cylindrical transducers that employ multimode extensional and flexural vibration of complete and incomplete cylinders (slotted cylinder projectors are also considered) for various practical applications. Different modes of the cylinder polarization are

considered, including the tangential polarization (with striped electrodes). An extensive study is provided of the effects of coupled vibrations on the electromechanical and acoustic performance of transducers that employ cylindrical piezoelements having finite thickness to diameter aspect ratios. Chapter 8 covers transducers which employ general multimode extensional vibrations of complete and incomplete piezoceramic spherical shells, (hemispherical in particular). The baffling of the parts of the surface that allows using multiple modes of vibration for unidirectional transducer operations is also considered.

In Chapter 9, a general analysis is provided of transducers which feature flexural vibrations of circular and rectangular piezoceramic plates (beams), including non-uniform over thickness and radius (length) transducer designs. Optimizing the effective coupling coefficients of the transducers is considered making use of the nonuniformity of the distribution of deformations in the volume of the plates. Corrections for transducer parameters due to a finite thickness to radius (length) ratio of the plates are taken into account. It is then concluded that the accuracy with which the wave numbers can be predicted substantially depends on the aspect ratio (especially for the higher modes of vibration) and presenting their values without the notion of the aspect ratios is not appropriate.

In Chapter 10, the length expander bar transducers are considered. Transitions of configurations of bars to thickness vibrating plates at different polarizations and related dependencies of their effective coupling coefficients on the aspect ratios are considered using the technique of coupled vibrations. Relatively small attention is paid to the widely used Tonpilz transducer designs because they have already been described in detail in the available literature.

Part IV (Chapters 11 through 15) is titled: “Some aspects of the transducers designing.”

In Chapter 11, a review of the existing data and some new results is presented regarding effects of operating environmental conditions, such as the hydrostatic pressure, temperature, and drive level on the parameters of piezoceramics. It is emphasized that, under these conditions, the parameters of ceramics may deviate significantly from those that are given in specifications for normal conditions. Moreover, they may differ for samples of ceramics supplied by different (and even by the same) manufacturers. This must be kept in mind when calculating the operating parameters of transducers under real conditions and in estimating a reasonable accuracy of calculation of the parameters. The variations in the parameters of transducers

intended for operating at great depths can be avoided by using designs, which incorporate hydrostatic pressure compensation. Issues related to the practical implementation of the pressure compensation are examined in Chapter 12 (more general information), in Chapter 13 (regarding the liquid filled cylindrical projectors) and in Chapter 14 (regarding the hydrophones).

Chapter 13 presents some considerations regarding the practical challenges of the projectors design. Using the concept of the Reserves-of-Strength for improving parameters of the transducers of different types by optimizing their matching with the acoustic field is considered. The possibilities of increasing the dynamic and static mechanical strength of the projectors by prestressing and combining piezoceramic with passive materials in their mechanical systems are analyzed.

Chapter 14 is dedicated to the design of hydrophones and related issues. The hydrophones employing different transducer types are classified by the pressure and pressure-gradient hydrophones of the diffraction and motion types. Their properties as a source of energy of signal and internal noise for a receive channel are considered. Special attention is paid to the response of the hydrophones and accelerometers to unwanted actions and to measures aimed at increasing their noise immunity.

Chapter 15 is crucial for the structure of the book because it introduces the practice of combining Finite Element Analysis (FEA) with analytical energy methods. This is illustrated with examples of flextensional and oval transducers. Combining powerful computer-based FEA techniques that are used to obtain results for vibration mode shapes with the energy method that yields great physical insight opens up a new area of research collaboration for many transducer problems. FEA allows the determination of the vibration mode shapes for mechanical systems that cannot be approximated analytically due to the complexities of the mechanical system and its boundary conditions.

The book also contains appendices with information on the properties of the piezoelectric ceramics and passive materials that may be used in transducer designs, and on the properties of the special functions that are referred to throughout the book.

In summary, the book presents methods for calculating the properties of most common electroacoustic transducer problems with particular focus on underwater applications. Moreover, by combining the FEA technique to determine the prerequisite vibration mode shapes with

the energy method, virtually any transducer type may be analyzed. Still however, when it comes to choosing and designing a particular transducer for a particular application under demanding operating and environmental specifications – this remains somewhat of an art. Thus, recommendations of transduction choices for representative problems remain a guide and not a prescription for success.

It is inevitable that the book may contain typographical or content errors and thus the author would welcome the readers' comments and notifications of such.

Boris S. Aronov

ACKNOWLEDGEMENT

I am indebted to many people I have worked with throughout my career without whom this book could not have been written. Firstly, I am grateful to my mentor, the outstanding acoustician Lev Yakovlevich Gutin, who was my PhD advisor. He taught me that even complicated problems can be solved in a simple and physically clear way and demonstrated this throughout all his work. He was a strong proponent of using the energy physics-based approach to solving problems of electroacoustics, my first mentor in this regard.

It was my good fortune during the early part of my career to have worked for many years in the acoustic laboratory of Morphizpribor (Russian Marine Research Institution) in Saint Petersburg (then Leningrad) that was headed by R. E. Pasyukov and O.A. Kudasheva. A creative and friendly atmosphere existed in the laboratory, which resulted in many fruitful scientific research accomplishments. Discussions with my friends and colleagues L. D. Lubavin, V.I. Pozern, M. D. Smaryshev, E. L. Shenderov, V. E. Glazanov and advising my colleagues and Doctoral PhD students G. K. Serebnev, N.M. Gribakina, L. B. Nikitin were priceless experiences that profoundly impacted this book. The style and content of this book have been influenced by my Doctor of Science Dissertation (1974) and my previous text *Electromechanical Transducers from Piezoelectric Ceramic* (1990) that were to a great extent based on the results of that period of my career.

The next stage of my professional career is in United States of America, where I started working with Dr. David A. Brown of BTech Acoustics LLC and the University of Massachusetts Dartmouth. David and I became and remain close friends for more than 20 years, and collaborated on many research projects, journal papers, and on co-advising graduate PhD and MS students in Electroacoustics. Hence, I am grateful to David Brown for providing me an unprecedented opportunity to teach and advise students at the University and work at the same time on the practical realization of my research and development transducer projects with BTech Acoustics. The results of this collaboration have been rewarding and have greatly contributed to the content of the book.

Furthermore, I would like to acknowledge many of our graduate students, who were eager to learn and assist in putting theory into practice often devoting long hours to experiments and computations. Specifically, Dr. Corey Bachand for transducer subsystem modeling and countless laboratory projects, coauthor of many journal publications; Sundar Regmi for participating in the research of coupled vibrations, Dr. Sairagan Saragapani for stripe-electrode tangential polarization research, Dr. Tetusuro Oishi for baffled multimode cylindrical transducers and their mutual impedances; Dr. Yan Xiang, who performed calculations regarding radiation of the baffled cylindrical and spherical transducers and FEA modeling, and many more students and engineering technicians too numerous to count including Gregory Bridge, Austin Souza, Zach Souza, Glenn Volkema, and others.

Further, our work would not have been successful had it not been the generous support from the Office of Naval Research (ONR) and especially Jan Lindberg, Michael Traweck, Michael Wardlaw, Fletcher Blackmon, as well as the entrepreneurial activity of BTech Acoustics LLC, the SBIR innovative research program, the unique facilities funded by the Commonwealth of Massachusetts – Advanced Technology and Manufacturing Center (ATMC-UMass), Center for Innovation and Entrepreneurship (CIE) and the Underwater Acoustics Tank Test Facility at the Center for Marine Science and Technology (CMAST).

I am immensely grateful to Dr. Corey Bachand and to my Russian colleague, Aleksey Leznikov, with his team for their truly gigantic work in preparing the manuscript of the Book for the publication that included all the formatting and numerous graphical works.

My special thanks go to my sons, Igor and Vitaly, for their moral and financial support throughout this years-long effort.

Part I

Introduction to Energy Method of Treating the Transducers

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