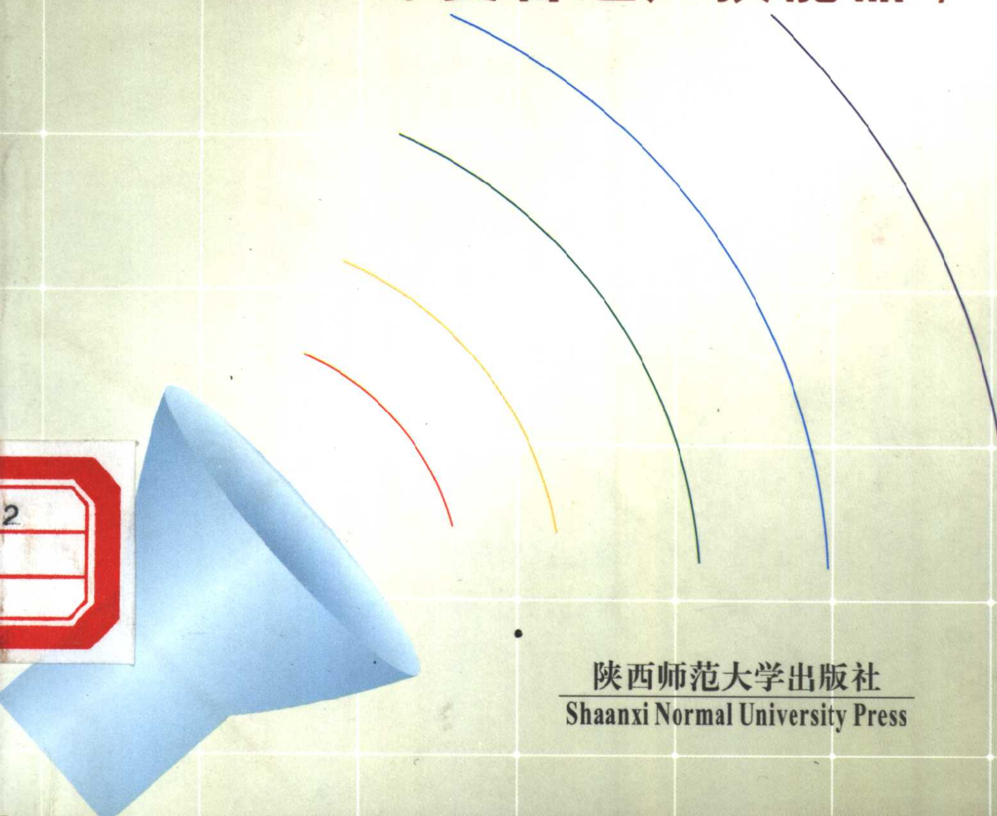
Lin Shuyu（林书玉）

Composite Ultrasonic Transducers

（复合超声换能器）



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PREFACE

The development of ultrasonic technology over the past decades has been remarkably rapid and intensive. The number of physicists and engineers working in this field is growing steadily and the subject is now taught in most technical colleges and universities. The range of original contributions in this field has become so great that a number of books in which the fundamentals and applications of ultrasonic technology have been presented coherently.

It was obvious that this book could not consider all the details of the ultrasonic technology-the range would have been impossibly wide. Some choice had to be made. The decision was reached to include the generation of ultrasonic vibration, especially the torsional and the longitudinal-torsional compound vibration in the fields of high power ultrasonics and ultrasonic motor, which at present are basic to ultrasonic transducer and seem likely to continue to be so in the future. In particular the author felt that it was important to give, both qualitatively and quantitatively, the design theory governing the operation of those torsional and longitudinal-torsional compound transducers now used in ultrasonic welding, ultrasonic machining and ultrasonic motor The material is presented in such a form as to be suitable for a reader with the physical and mathematical background of a post-graduate student The author hopes that the physicists or engineers working in ultrasonic transducer laboratory will also find the book a valuable tool which can be used to provide a rapid survey of the problems likely to be met from day to day

The purpose of this book is to consider some of the means available for the generation of torsional and longitudinal-torsional compound vibration This is undertaken however with particular reference to high power ultrasonics and ultrasonic motor and this implies limits on the frequency range of interest and also on the levels of power output which will be considered.

The majority of high power ultrasonics applications are carried out within the frequency range 20 kHz to 200 kHz and this will be the range of frequencies to which the observations in this book are particularly directed. It would be impossible to delineate quantitative limits of this kind with which every reader will agree. It is thus realized that some high power ultrasonic applications, for example, ultrasonic sonochemistry, are carried out at much lower frequencies, while at the same time, higher frequencies are interesting as in ultrasonic cleaning.

Throughout the book, an attempt has been made to avoid the extremes of being too theoretical or too practical. I feel that either extreme would make the book too large and too laborious to read. An approach somewhat on the theoretical side was adopted, though, so that the material would be of a more general nature and of a more lasting value. Excursions into theoretical fine points were avoided, and I tried to "keep my feet on the ground" at all times.

The physical and mathematical presentation of the main topics has been planned in such a way that it is necessary to consult the references attached to each chapter. These references have been chosen, first for their historical interest; that is to say the papers quoted either were first publications in the field or are particularly clear presentations of their subject. Second, references have been included which will help the interested reader pursue the problems considered beyond the scope of this book.

The author wishes to repeat here his thanks to all who helped him in his work on the paper, among whom he mentions especially Professor Sadayuki Ueha, Professor Sumio Watanabe, Associate Professors Minoru Kurosawa, Nobuyuki Iwatsuki, and Kentaro

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CHAPTER 1
INTRODUCTION

1.1 History and research status

Ultrasonic vibrating systems are important parts in all ultrasonic applications. In traditional ultrasonic technologies, especially in the fields of high power ultrasonics and macrosonics, such as ultrasonic cleaning, ultrasonic drilling and ultrasonic welding, the ultrasonic vibrating systems that consist of ultrasonic transducer, ultrasonic horns and tools resonate at longitudinal vibrational modes. The high power sandwiched piezoelectric ultrasonic length extension transducer is widely used and its design theory was well developed [1-9].

In recent years, with the development of ultrasonic technologies, some new ultrasonic applications, such as ultrasonic motors, ultrasonic plastic welding, ultrasonic machining and ultrasonic fatigue testing [10-15], have been further developed and more and more attentions have been paid to such applications. In these cases, apart from the longitudinal vibrational mode, the torsional vibrational mode and the longitudinal-torsional composite vibrational mode have also been used and sometimes they are more preferred to the traditional longitudinal mode.

In the early work [16], the methods of producing the torsional and flexural vibrations are the conversion of longitudinal vibration into torsional or flexural vibration. However, as the transducer construction is complex and the energy conversion efficiency is low, they have not been widely used in high power ultrasonic applications.

In Reference [17], a method to directly excite flexural oscillations using two separate piezoelectric ceramics was described and a new type of piezoelectric ultrasonic longitudinal-flexural motor was developed. By superposing a longitudinal and a flexural oscillation of a rod-shaped resonator and selecting the relative phase of the electrical stimulations of both modes, the speed of the motor can be continuously varied in both directions.

With the development of ultrasonic motors, ultrasonic plastic welding, ultrasonic fatigue testing and other high power ultrasonic technologies, a torsional transducer which has simple construction and high energy conversion efficiency is needed. Therefore, sandwiched piezoelectric ultrasonic torsional transducers are developed in which the active elements are tangentially polarized piezoelectric ceramic rings instead of axially polarized piezoelectric ceramic elements [18]. At the same time, the sandwiched piezoelectric ultrasonic transducer of longitudinal-torsional compound vibrational mode has also been studied, especially in the field of ultrasonic motors [19]-[20]. As the sound speeds of longitudinal and torsional vibrations in the same material are different, the longitudinal and torsional vibrations in the traditional sandwiched transducers, whose back and front parts are cylinders, are difficult to resonate at the same frequency. This gives rise to a difficulty in exciting the sandwiched transducer of longitudinal-torsional compound mode. Two sets of electric generators with different ultrasonic frequencies are therefore needed to excite the transducer.

In traditional high power ultrasonic transducers and underwater sound transducers, the active piezoelectric ceramics elements very often incorporate the longitudinally polarized drive since the electromechanical coupling coefficient is higher than other practical types of polarization. The longitudinal vibrations of the single and segmented longitudinally polarized piezoelectric ceramic cylinder have been studied and the theory has been well established [21-22]. As the development of ultrasonic technology, some new applications such as ultrasonic motor and torsional machining have been developed. In these cases, the torsional transducers are needed. For producing torsional vibration, apart from the vibrational mode conversion, the piezoelectric ceramic slender cylindrical tube and thin ring polarized in tangential direction are needed. Therefore, the electrical and the mechanical vibrational characteristics of the piezoelectric ceramic elements polarized in tangential direction should be developed.

For the creation of torsional and longitudinal-torsional compound vibration, two methods can be used. One is by means of the conversion of longitudinal into torsional vibration, and the other is by using the tangentially polarized piezoelectric ceramics. In the first method, the conversion of longitudinal into torsional vibration is by means of two sandwich longitudinal transducers that are attached on the sides of a transmission cylinder. The torsional vibration in the cylinder can be produced by means of choosing the phase of the input voltage of the transducer. In this case, the total input electric power can be large and the system can be used in high power ultrasonic applications. However, since the volume of the vibrating system is large and the efficiency of conversion of longitudinal into torsional vibration is low, the system has not been widely used. Another method to create the torsional and longitudinal-torsional vibration by means of conversion of longitudinal into torsional vibration is by using a drilling tool with spiral slots that is attached to the output end of a longitudinal sandwich transducer. In this case, the vibration system can create longitudinal-torsional compound vibration. Since the geometrical shape of the transmission cylinder is complex, the computation and design of this kind of transducer is difficult. The vibrational characteristics cannot be studied analytically. Even if the numerical methods such as the finite element method are used, the analysis is still complex and cumbersome.

For the creation of torsional and longitudinal-torsional compound vibration by means of the tangentially polarized piezoelectric ceramics, its design theory has been established [23-25]. In this case, the torsional sandwich transducer is composed of the tangentially polarized piezoelectric ceramic tubes and the front and back metal cylinders, while the longitudinal-torsional compound transducer is composed of the longitudinally and tangentially polarized piezoelectric ceramic tubes and the front and back metal cylinders. Although this kind of transducer is similar to the sandwich longitudinal transducer in appearance, the concrete manufacture of the transducer is complex, especially for the processing of the tangentially polarized piezoelectric ceramic ring. Since the polarization is along the circumferential direction, large sectors are difficult to polarize and electrical break down may happen. In this case, an entire polarization is difficult to achieve. To overcome these difficulties, the piezoelectric ceramic sectors must be small and the lateral dimension (Such as the diameter of the segmented ceramic ring and the wall thickness of ring) is limited. This gives rise to a problem that the power capacity and the efficiency of the transducer are also limited. Therefore, these kinds of transducer are mostly used in ultrasonic motor and other low power applications rather than high power ultrasonic applications. On the other hand, for the longitudinal-torsional compound transducers, since the sound speeds of longitudinal and torsional vibrations are different, the longitudinal and torsional vibrations are difficult to resonate at the same frequency. This makes the effective electrical excitation of the longitudinal-torsional compound system complex. Although the simultaneous resonance of longitudinal and torsional vibrations can be achieved by properly choosing the shape and dimension of the transducer, the computation is complex.

To avoid these problems in computing and processing the torsional and longitudinal-torsional transducer, a new type of longitudinal-torsional compound transducer with slanting slots is developed and used in ultrasonic motor [26-28]. However, the theoretical analysis for the vibrating system with slanting slots has not been done. In this paper, the longitudinal-torsional compound vibration of a half wavelength cylinder with slanting slots is studied theoretically and experimentally. An equivalent circuit model used for the analysis and design of the cylinder with slanting slots is given, and the effect of the slanting slots on the resonance frequency and the velocity ratio is analyzed.

In modern ultrasonics, many kinds of ultrasonic transducers are used. However, piezoelectric ceramic transducers are the most popular. Piezoelectric ceramic transducers have been used for many years as sensors and transmitters of acoustic signals. In underwater acoustics and high power ultrasonics, low-frequency Langevin transducers that consist of two or more identical piezoelectric elements sandwiched between a back and front cylinder are widely used for finding fish, deep-sea seismology, sounding, ultrasonic cleaning, ultrasonic soldering, ultrasonic atomization and other applications. The other principal applications of piezoelectric ceramic transducers are in medical ultrasound, nondestructive testing and ultrasonic imaging, where they are used for ultrasonic diagnosis, ultrasonic therapy, and material evaluation and flaw detection.

Piezoelectric ceramic transducers or resonators have many vibrational modes. The widely used vibrational modes of transducers are the thickness extensional mode of a thin piezoelectric ceramic plate, the radial vibration of a thin ceramic circular disk or ring, the thickness shear vibration of a thin ceramic rectangular plate and the longitudinal vibration of a slender piezoelectric ceramic cylinder. For these traditional vibrational modes, their analytical and design theory has been well established, and widely used in the design of piezoelectric ceramic resonators that are employed in piezoelectric transformer, piezoelectric filter, ultrasonic emitter and receiver.

Unfortunately, very little work has been carried out on the thickness shearing vibrational mode of piezoelectric ceramic elements. In recent years, ultrasonic motor and other ultrasonic applications such as ultrasonic soldering and material fatigue testing have been paid more and more attentions. In these applications, thickness shearing and longitudinal-thickness shearing compound vibrations are needed. Accordingly, the requirement for the insight into the thickness shearing vibration of piezoelectric ceramic elements becomes more and more pronounced.

1.2 Main research contents and objectives

In this book, the torsional and the longitudinal-torsional compound vibrational transducers and horns are studied, the main contents are listed as follows.

(a) The torsional vibration of the segmented piezoelectric ceramic cylinder of which the sandwiched piezoelectric ceramic torsional transducer is composed is analyzed. The segmented piezoelectric ceramic cylinder consists of a number of tangentially polarized coaxial piezoelectric ceramic cylindrical tubes. The torsional vibration of the single piezoelectric ceramic slender cylindrical tube polarized in the tangential direction is first studied, and the electromechanical equivalent circuit for an individual piece is derived. Then, based on the equivalent circuit and the network theory, the behavior of the segmented system of a number of identical pieces that are connected in parallel electrically is further analyzed, the equivalent circuit of the segmented system is obtained which is useful in the design of the sandwiched torsional transducer.

(b) The sandwiched torsional transducer was analyzed. When the lateral dimension was less than a quarter of the wavelength of the torsional vibration, the torsional vibration of the transducer was analyzed. The electromechanical equivalent circuit and the resonance frequency equations were derived, the theory and the conclusions can be used to design and calculate different sandwiched torsional transducers with different resonance frequencies and different shapes and dimensions.

(c) The sandwiched longitudinal-torsional transducer whose front metal mass is an exponential solid horn, instead of a metal cylinder, is studied. Based on the theory that the sound speeds of longitudinal and torsional vibrations in the exponential solid metal horn depend on the cross sectional radius decay coefficient, by changing the radius decay coefficient of the exponential horn, the sound speeds of longitudinal and torsional vibrations can be changed accordingly. In this book, the longitudinal and torsional vibrations in the same transducer are designed to resonate at the same frequency, and the resonance frequency equations for the longitudinal and torsional vibrations in the longitudinal-torsional transducer are derived. In the following chapters, the new compound vibrational mode transducer is described, and the results are given for both longitudinal and torsional vibrations in the transducer. It is demonstrated that this kind of transducer works well for the longitudinal, torsional and the compound vibrational modes.

(d) Based on the vibrational theory of longitudinal and torsional vibrations of ultrasonic exponential horns, by changing the decay