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Modeling of coupled longitudinal and bending vibrations in a sandwich type piezoelectric transducer utilizing the transfer matrix method

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ABSTRACT

Sandwich type piezoelectric transducers are widely employed as actuating mechanisms for ultrasonic motors and ultrasonic cutting machines due to their advantages of compact structure, no electromagnetic interference, excellent mechanical performance, and fast response. By simultaneously adopting bending piezoelectric ceramics and longitudinal piezoelectric ceramics, sandwich type piezoelectric transducers can be utilized to generate coupled longitudinal and bending vibrations. To neglect the specific and complex polarization of the bending piezoelectric ceramics, a novel sandwich type piezoelectric transducer adopting commonly rectangular longitudinal piezoelectric ceramics is proposed in this study. The proposed transducer can be stimulated to produce the coupled longitudinal and bending vibrations by applying two electrical signals with shifted phase. To reveal the dynamic behavior of the proposed transducer and reduce the computational efforts of the finite element simulation, a semi-analytical model is developed using the transfer matrix method. Although the individual longitudinal or bending vibration model has been developed for piezoelectric elements, the modeling of coupled longitudinal and bending vibrations by simultaneously considering the electrical and mechanical coefficients is still unavailable. Therefore, a new transfer matrix model is created for the composite piezoelectric beam to describe the coupled longitudinal and bending vibrations. The presented transfer matrix model is capable of optimizing the proposed transducer and is also suitable for modeling conventional sandwich type piezoelectric transducers. To validate the effectiveness of the proposed model, two case studies are conducted. First, the optimizations of the transducer are conducted to obtain suitable geometrical dimensions. Then the frequency response characteristics and vibration shapes of the transducer are computed and compared to finite element simulation results. The comparisons demonstrate that the proposed transfer matrix model is valid and can effectively reduce the computational efforts.

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1. Introduction

Ultrasonic motors acting as the typical smart piezoelectric actuators have been commercialized and applied in industrial fields, such as aerospace [1], biomedical engineering [2], robotics [3,4], and ultra-precision machining equipment [5,6]. Most of these motors are driven by piezoelectric transducers utilizing the inverse piezoelectric effect as well as the friction effect, having the advantages of fast response, no electromagnetic interference, and high positioning precision [7,8]. Thus, the piezoelectric transducer is the key to obtain the excellent performance of the ultrasonic motors. In general, piezoelectric transducers can be classified as bonded type and sandwich type according to the mounting forms of the piezoelectric ceramics (PZT). The typical configuration of the bonded type piezoelectric transducers is that the PZT plates are glued on the surfaces of the host structure by epoxy adhesive and excited to operate in the d_{31} vibration mode, resulting in the attracted merits of being easy to miniaturize and simple and compact structure [9,10]. For instance, the circular stators of the typical rotary type traveling wave ultrasonic motors are always designed as a bonded type piezoelectric transducer whose diameter can vary from millimeter scale to micrometer scale [11]. Compared to bonded type piezoelectric transducers, sandwich type transducers have a different configuration. This is because the PZT plates are usually clamped between two metal blocks with screws and generally excited to operate with their d_{33} vibration mode for sandwich type piezoelectric transducers [12]. Therefore, this type piezoelectric transducers have a higher electromechanical coupling factor than the bonded type ones, and they can avoid the cracking of the PZT plates due to high frequency vibration and high excitation voltage. In most cases, the stators of linear ultrasonic motors are designed as a sandwich type piezoelectric transducer to obtain outstanding output performance. The most significant configuration is the V-shaped sandwich type piezoelectric transducer developed by Kurosawa in 1998 for building a high power linear ultrasonic motor [13].

To simplify the structural designs of sandwich type piezoelectric transducers, the concept of coupling vibration mode was emerged [14–20]. The general coupling vibration modes include: longitudinal-bending, longitudinal-torsional, and bending-torsional coupling vibration modes. Due to the fact that the longitudinal and bending vibration modes are easy to stimulate compared to the torsional vibration mode, researchers pay more attention to the sandwich type longitudinal-bending coupling vibration piezoelectric transducer designs. In 2001, Yun et al. proposed a bolt-clamped Langevin cylindrical piezoelectric transducer operating in the longitudinal and bending hybrid vibration modes for driving slider to achieve a high power linear ultrasonic motor [15]. The prototype motor exhibited excellent performance with a maximum output mechanical force of 92 N, indicating that the sandwich type piezoelectric transducer is capable of high electromechanical factor. To achieve three-degree-of-freedom motions, Yun et al. developed a bar type sandwiched piezoelectric transducer to drive a ball rotor by exciting the first order longitudinal vibration and second order bending vibration modes [16]. On account of this operating principle, Yang et al. studied a straight-beam sandwich type piezoelectric transducer to actuate a spherical rotor with multi-degree-of-freedom motions [17]. Jin and Zhao presented a novel approach to excite an in-plane traveling wave in a ring stator by stimulating a longitudinal-flexural coupling vibration mode of a bar shaped sandwich type piezoelectric transducer [18]. Kim et al. proposed a rod type bolt-clamped piezoelectric transducer with stepped horns to drive a stage, being able to achieve nano-positioning precision [19]. This transducer was also excited to operate in the longitudinal-bending coupling vibration mode. Later, some similar sandwich type piezoelectric transducers with rectangular or cylindrical cross-section were successively developed for driving slider or rotor utilizing the longitudinal-bending coupling vibration mode [20–23]. Aiming at practical applications, the sandwich type piezoelectric transducers operating in the longitudinal-bending coupling vibration mode were also designed to assist machining process [24,25].

Although various kinds of sandwich type piezoelectric transducers presented have been developed for ultrasonic motors or ultrasonic machining, their theoretical models have not been created for studying the complicated dynamic vibration characteristics except for the resonant frequency equations for the simplest Langevin piezoelectric transducer derived by Lin [26]. This is because most transducer designs are based on the finite element method (FEM). The FEM is a popular approach to obtain accurate solutions for tuning the resonant frequencies of the longitudinal and bending vibration modes together; however, significant calculation time and large computer memory are required. In the case of composite vibration transducers, their optimizations must be preceded by adjusting the geometrical sizes using the finite element simulation manually, since the current ANSYS/Workbench software cannot conduct modal recognition. Compared to the FEM, theoretical semi-analytical solutions are capable of greatly reducing the computational efforts and realizing a flexible design and effective optimizations for piezoelectric transducers. Therefore, a suitable theoretical model is important to be developed for the transducer modeling. Another issue that should be considered is that the aforementioned sandwich type piezoelectric transducers have strict requirements regarding the manufacture, polarization, and assembly of PZT plates to stimulate the coupling vibration mode. Firstly, the longitudinal PZT and bending PZT plates are essential for these transducers to excite the corresponding longitudinal and bending vibration modes. Therefore, to assemble these PZT plates, they must be designed with a hole in their middle. This is because a certain prestress must be applied to the PZT plates during the assembly by screws. Certainly, the assembly form will result in a breakage on the PZT plates due the generation of shearing force. In addition, the bending PZT plates must be required to excite the bending vibration of the transducers. Thus, the subarea polarizations on the bending PZT plates have to be processed, causing the polarization difficulty.

To reduce aforementioned requirements, a novel sandwich type piezoelectric transducer adopting commonly rectangular longitudinal PZT plates is proposed in this paper. Four grouped complete PZT plates are mounted at the vertexes of rectangular configuration and prestressed by a preloading mechanism, and the two diagonal PZT plates are, respectively, applied