International Journal of Mechanical Sciences 138–139 (2018) 229–243

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Systematic electromechanical transfer matrix model of a novel sandwiched type flexural piezoelectric transducer

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ARTICLE INFO

Keywords:
Sandwiched piezoelectric transducer
Flexural vibration
Transfer matrix method
Systematic electromechanical model
Dynamic behavior

ABSTRACT

Sandwiched type flexural piezoelectric transducers are used in many applications due to their excellent output performances. However, the design and manufacture of traditional sandwiched type flexural piezoelectric transducers always have specific requirements on the flexural piezoelectric ceramics with complex polarizations and configurations, seriously limiting their applications. To reduce these special requirements, a novel sandwiched type flexural piezoelectric transducer in which common rectangular piezoelectric plates with a single polarization are adopted is proposed in this paper. By applying excitation signals with different temporal phases to the rectangular piezoelectric plates, the proposed transducer features the ability to generate flexural vibration, longitudinal vibration, and composite longitudinal-flexural vibration. To lower the computational efforts of the finite element analysis, a general systematic electromechanical model is carried out for the proposed transducer utilizing the transfer matrix method. The developed systematic transfer matrix model provides an available approach for simultaneously coupling the mechanical and electrical properties to adequately reveal the dynamic behavior of the proposed transducer operating in flexural vibration mode. To validate the proposed model, dynamic behaviors of the sandwiched piezoelectric transducer in flexural vibration are calculated and compared with the finite element simulation results. The results demonstrate that the proposed transfer matrix model is valid and effectively reduces the computational efforts. In addition, vibration characteristics of the transducer prototype are experimented, and results verified the feasibility of the transducer design and the effectiveness of the developed transfer matrix model.

1. Introduction

Piezoelectric transducers are widely used in many industrial fields, such as ultrasonic processing [1,2], piezoelectric actuators [3–5], robotics [6], aerospace [7], and medical engineering [8]. Piezoelectric transducers can be generally classified as surface-boned type transducers [7,9] and sandwiched (or bolt-clamped) type transducers [4] according to the assembly form and vibration mode of the piezoelectric ceramics (PZTs). In general, the surface-bonded type piezoelectric transducers utilize epoxy adhesive to fasten the piezoelectric ceramics to the surfaces of the host structure. The piezoelectric ceramics are excited to operate at the d_{31} vibration mode. For the sandwiched type piezoelectric transducers, the piezoelectric ceramics operating at the d_{33} vibration mode are mounted between two metal blocks with a predetermined pre-stress. The sandwiched type piezoelectric transducers are the preferred option to obtain high output performances, as the piezoelectric ceramics that operate at the d_{33} vibration mode have a higher electromechanical coupling factor than those operating at the d_{31} vibration mode.

In general, three kinds of vibrations are chosen as the operating vibration modes for the sandwiched type piezoelectric transducers: longitudinal vibration, flexural vibration, and torsional vibration. The sandwiched type piezoelectric transducers operating in the longitudinal vibration have been commercialized and applied in many fields [1,2,4,8] because they are easy to design and manufacture. Recently, several studies have investigated the flexural vibration piezoelectric transducers [10–20], especially the sandwiched type piezoelectric transducers with composite vibration modes. Because elliptical motion is required to be produced in the special configurations, such as straight elastic beams or rods [15–20], in which the flexural vibration is usually selected as one of the vibration modes.

Compared with sandwiched type piezoelectric transducers operating in longitudinal vibration or torsional vibration, the sandwiched type structure operating in the flexural vibration enables the trans-

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https://doi.org/10.1016/j.ijmecsci.2018.02.012
Received 18 October 2017; Received in revised form 21 January 2018; Accepted 5 February 2018

ducer to be designed with flexibility and compaction. Currently, some sandwiched type piezoelectric transducers are designed to operate in composite vibration modes suitable for practical applications. The composite longitudinal-flexural vibration, composite flexural-flexural vibration, composite longitudinal-torsional vibration, and composite flexural-torsional vibration modes represent several options. Yun et al. [10] proposed a bolt-clamped cylindrical piezoelectric transducer using the composite longitudinal-flexural vibration mode to drive a slider, achieving a high mechanical output force of up to 92 N. This cylindrical piezoelectric transducer utilized the coupling of longitudinal and flexural vibrations to generate elliptical motion trajectories at driving tips, greatly simplifying the motor configuration compared to a V-shaped linear ultrasonic motor [11]. Jin and Zhao [12] proposed a novel approach for exciting traveling waves in a circular ring based on the composite longitudinal-flexural vibration mode of a bar-shaped sandwich transducer. As a result, using the same excitation method, similar sandwich transducers [13–15] were developed and investigated for constructing traveling wave rotary ultrasonic motors. Liu et al. [16,17] developed a sandwich transducer in composite flexural-flexural vibration mode that was used to drive rotors or sliders based on the required practical applications. For precision machining, sandwich transducers in composite longitudinal-flexural vibration or flexural-flexural vibration modes have also been proposed as a tool for ultrasonic elliptical vibration cutting (UEVC) [18–20]. Using sandwich transducers, the UEVC technique enables the cutting of ferrous materials, improves the cutting system stability, and achieves high precision machining. These applications of the sandwich transducers in flexural vibration mode adequately demonstrate that the flexural vibration is an effective vibration mode for achieving actuator functions.

However, the aforementioned sandwich flexural transducers have special requirements regarding the configurations and polarizations of piezoelectric ceramics to excite the flexural vibration mode. Two types of piezoelectric ceramics are generally used to stimulate the flexural vibration mode for traditional sandwich transducers. One type is the circular or rectangular piezoelectric ceramic with a middle hole that is polarized simultaneously with negative and positive directions on the same surface; another type consists of two semi-ring or rectangular piezoelectric ceramics with opposite polarized directions that combined together to form a piece of complete flexural vibration piezoelectric ceramic. To clamp the aforementioned piezoelectric ceramics to the metal blocks with a bolt, a mounting hole must be designed on the ceramics. In addition, the assembly for most traditional sandwich piezoelectric transducers produces a shear force on the piezoelectric ceramics that can easily result in the breakage of ceramics. Therefore, the traditional sandwich transducers in flexural vibration mode have higher requirements regarding the manufacture and assembly of the flexural vibration piezoelectric ceramics than those with longitudinal vibration modes. Furthermore, the price of the flexural vibration piezoelectric ceramic is also higher. To reduce the demands on the complex polarizations and configurations of flexural vibration piezoelectric ceramics, a novel sandwiched type flexural piezoelectric transducer utilizing common rectangular longitudinal vibration piezoelectric ceramics is proposed in this paper. The proposed sandwich transducer can generate flexural vibration, longitudinal vibration, and composite longitudinal-flexural vibration based on the excitation signal with different temporal phases. Using rectangular piezoelectric ceramics with a single polarization, the flexural vibration mode can be simply excited in the proposed transducer. The transducer is also easy to assemble, which minimizes the mounting errors.

Although the finite element method (FEM) is a common approach adopted for the design of piezoelectric transducers, its drawbacks include considerable computational efforts and complicated requirements for computer hardware. Compared to the FEM, a semi-analytical model can largely reduce the computational time and achieve flexible design and optimization for the piezoelectric transducers. Therefore, an increasing number of researchers are interested in developing a theoretical model for the design and optimization of transducers. Although the sandwich flexural vibration piezoelectric transducers have been widely used in practical applications, only a few theoretical models have been put forward [21–26]. Koike et al. [21] first proposed a calculation method for a sandwich flexural transducer based on the Miklowitz solution and Timoshenko beam theory, and derived the force factor equation. To study the mechanical load impedance of a sandwich flexural transducer, an electrical equivalent circuit was proposed in reference [22]. Zhou [23] presented a design approach for a sandwich flexural transducer utilizing the transfer matrix method (TMM). In this approach, only the mechanical parameters of the transducer were considered as an objective function for studying its inherent characteristics. Lin [24,25] deduced the resonant frequency equations of sandwich transducers with composite vibration modes, such as the longitudinal-flexural vibration mode and the torsional-flexural vibration mode. Zhang [26] conducted a theoretical analysis of a traditional sandwich flexural transducer with an exponential horn for optimizing the excitation position of the flexural vibration piezoelectric ceramics. Although the aforementioned theoretical studies on the sandwich flexural piezoelectric transducers were conducted in order to obtain the resonant frequency and vibration shape calculations of the transducer, most were focused on the independent investigation of the mechanical parameters [21,23,26] or electrical parameters [22,24,25] and the coupling of the electromechanical parameters of the transducer has not yet been studied. In this study, a general systematic electromechanical model for the proposed sandwich piezoelectric transducer operating in flexural vibration mode is carried out utilizing the TMM. Using this model, the dynamic behavior of the proposed sandwich piezoelectric transducer, including electrical impedance properties, frequency response characteristics, and vibration shapes, can be easily calculated. The presented transfer matrix model is not only suitable for the proposed transducer, but can also be extended to other flexural piezoelectric transducers.

This paper is organized as follows. Firstly, the structure and operating principle of the proposed sandwich transducer are presented and explained in detail. Subsequently, a systematic electromechanical model of the transducer in flexural vibration mode is carried out using the TMM to study its dynamic behavior. In addition, the modeling results are verified by the finite element simulation results. Furthermore, a prototype of the proposed transducer with trapezoid horns is manufactured, assembled, and measured, to validate the transducer design. Finally, a conclusion is presented.

2. Structure and operating principle

2.1. Structure design

The configuration of the proposed sandwich piezoelectric transducer is shown in Fig. 1. It consists of a straight beam, eight pieces of rectangular PZT plates, and a preloading mechanism. The straight beam is designed with two rectangular grooves in the middle, and the two grooves are placed on the upper and lower surfaces of the straight beam. Additionally, both ends of the straight beam are shaped as a continuous variable cross-sectional structure, termed a solid horn, which is employed to amplify the amplitude of the transducer. Two pieces of PZT plates with opposite polarization directions along their thickness are set as one group. Two groups of PZT plates are placed at the left and right sides of the groove. The preloading mechanism includes two isosceles trapezoid blocks with a mounting hole in the middle of each, four right trapezoid blocks and one bolt. Each of the right trapezoid blocks is vertically contacted by a group of PZT plates, and an isosceles trapezoid block is set between the two right trapezoid blocks. Therefore, two groups of PZT plates, two right trapezoid blocks, and an isosceles trapezoid block are combined together to fill in the groove. By placing the bolt through the mounting holes of the isosceles trapezoid blocks, the preloading mechanism is able to apply the equivalent preloading force to the four groups of PZT plates simultaneously.