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A novel additive manufactured three-dimensional piezoelectric transducer: Systematic modeling and experimental validation

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ABSTRACT

Sandwich piezoelectric transducers are widely used in many industrial applications due to their attractive advantages of compact structure, no electromagnetic interference, and excellent output performance. V-shaped piezoelectric transducers, a typical design, have been adopted as the stator of ultrasonic motors and the machining tool of elliptical vibration surface manufacturing. However, traditional V-shaped piezoelectric transducers were designed with one contact interface to output effective vibration, limiting their applications. To achieve multi contact areas with synchronous actuation function, a novel three-dimensional sandwich piezoelectric transducer is proposed in this study, expecting to drive wheels of a robotic mobile system. Two orthogonal Langevin transducers are adopted to vertically couple in a cylinder, producing two bending vibrations with a spatial phase difference of $\pi/2$ in the cylinder. Therefore, elliptical motion is generated at surface points of two driving parts placed at both ends of the cylinder. Due to the fact that two front-end blocks of the two Langevin transducers and the cylinder form a three-dimensional configuration which hard to be manufactured by traditional machining methods, this part is printed using laser additive manufacturing. To analyze the dynamic behavior of the proposed three-dimensional transducer, an analytical model is carried out utilizing the transfer matrix method for providing systematic modeling. This developed transfer matrix model is not only capable of greatly reducing computation efforts, and it is maybe suitable for the analysis of traditional V-shaped transducers. To validate this developed transfer matrix model and confirm the feasibility of the transducer design, experimental investigations are conducted to measure the vibration characteristics of the proposed transducer prototype using a 3D laser Doppler vibrometer and are compared to the calculation results. The measured and computed resonant frequencies of the transducer are 19.975 kHz and 20.045 kHz for the symmetrical vibration mode, and 20.07 kHz and 20.06 kHz for the anti-symmetrical vibration mode, respectively. Comparisons show that calculation results match well with the experimental results, demonstrating the effectiveness of the developed transfer matrix model and the feasibility of the three-dimensional transducer design.

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1. Introduction

Piezoelectric ultrasonic motors, a promising kind of smart actuators, utilize the converse piezoelectric effect of the piezoelectric ceramics (PZT) by transferring electric energy to mechanical energy, achieving the macro motion of slider or rotor by means of the friction effect [1–3]. Piezoelectric transducers that combine PZT elements and metal bases serve as the stator, which are the core component of piezoelectric ultrasonic motors [4–6]. In terms of mounting forms of piezoelectric elements, piezoelectric transducers can be generally divided into surface-bonded type and sandwiched type. Most rotatory type piezoelectric ultrasonic motors belong to the surface-boned type, due to the fact that PZT elements are glued on the surface of a ring type metal host structure to construct the stator [7]. Sandwich piezoelectric transducers are usually employed to drive a slider to construct a high power liner ultrasonic motor, in order to achieve high output performance [8,9]. This is because sandwich piezoelectric transducers operating in the d_{33} vibration mode of PZT elements offer higher electromechanical transformation efficiency compared to the surface-boned type transducer working with the d_{31} vibration mode [10].

In general, sandwich piezoelectric transducers can be designed to operate in single vibration mode or multi vibration modes according to requirements of practical applications. A typical example of a single mode sandwich piezoelectric transducer is the Langevin transducer operating in longitudinal vibration mode. This kind of transducer has been commercialized and applied in many industrial fields due to its simple structure and excellent output performance [11]. Currently, research has mainly been focused on the multi-mode sandwich piezoelectric transducers, as they can be designed to achieve actuator function. Generally, this type of sandwich piezoelectric transducer operates in the coupling vibration modes, such as composite longitudinal-longitudinal vibration [12], composite longitudinal-bending vibration [13,14], composite bending-bending vibration [15], composite bending-torsional vibration [16], and composite longitudinal-torsional vibration [17]. Compared to the bending and torsional vibrations, the excitation of longitudinal vibration has a lower requirement on PZT elements, being more easily adopted as the operating vibration mode of multi-mode sandwich transducers. The V-shaped sandwich piezoelectric transducer initially proposed by Kurosawa in 1998 is the most typical longitudinal-longitudinal coupling vibration transducer used to drive sliders to construct a linear ultrasonic motor [18]. Two Langevin piezoelectric transducers with a fixed angle are connected together at a joint tip to structure the V-shaped piezoelectric stator, and the two longitudinal vibration modes are, respectively, stimulated in these two Langevin transducers and then coupled in the joint tip. Thus, symmetrical and anti-symmetrical vibration modes are formed in the V-shaped piezoelectric transducer, resulting in an elliptical motion of the joint tip. Due to the utilization of the Langevin transducers, the design and assembly of V-shaped piezoelectric transducers become simple. And only longitudinal PZT elements are required to build the transducer, therefore, lowering the requirements on the flexural or torsional PZT elements compared to other composite vibration transducers. Subsequently, to decrease the excitation voltage, modified V-shaped piezoelectric transducers operating in the same complex vibration modes were developed by utilizing piezoelectric stacks [19,20]. To eliminate the critical dimension limitation of the V-shaped piezoelectric transducer in the application of semiconductors for driving stages, Asumi et al. conducted the miniaturization of the initial V-shaped transducer [21]. Suzuki et al. developed a V-shaped transducer with an acute angle between the two Langevin transducers for medical bed application [22]. Due to the excellent output performance, the V-shaped transducer has been further improved and employed as machining tools for elliptical vibration surface texturing manufacturing [23,24].

The aforementioned V-shaped piezoelectric transducers present the advantages of compact structure, no electromagnetic interference, and excellent output performances; however, they are designed with only one contact interface to output effective vibration, limiting their applications. To achieve multi contact areas with synchronous actuation function, a novel three-dimensional sandwich piezoelectric transducer is proposed in this study, expecting to drive two wheels of a robotic mobile system. Inspired by the V-shaped configuration, two orthogonal Langevin transducers are designed in our proposed transducer to produce two longitudinal vibrations. Compared to traditional V-shaped transducers, the proposed three-dimensional transducer adopts a cylinder to substitute the joint tip of the two Langevin transducers. Therefore, the coupling vibration generated by the two Langevin transducers are transferred to the entire cylinder to achieve the same elliptical motion of surface points of two driving parts placed at both ends of the cylinder, with the result that the two driving parts present the same driving characteristic. As connections between the two Langevin transducers and the cylinder construct the three-dimensional configuration of the proposed transducer, the front-end blocks of the two Langevin transducers and the cylinder are designed as one part. To eliminate the manufacturing errors caused by traditional machining methods, the three-dimensional part is printed by laser additive manufacturing, solving the fabrication issue of three-dimensional transducers with complex configuration. In addition, the clamped block used to connect the two Langevin transducers in the traditional V-shaped transducer is eliminated in our design, simplifying the transducer configuration and preventing the difficult assembling problem caused by the manufacturing errors.

In most cases, traditional V-shaped transducers have been designed based on the finite element method (FEM) [18–24]. The FEM can provide a relatively accurate solution; however, plenty of computational time and specific computer hardware are required. Especially for the coupling of two vibration modes, the tuning between their resonant frequencies must be manually processed using the commercial ANSYS software, as this software cannot conduct the modal recognition to select the expected vibration modes of the transducer during optimization. The semi-analytical approach is increasingly adopted as the solution to conduct piezoelectric transducer designs and optimizations within a fairly short time. Until now and as a