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A new topological structure for the Langevin-type ultrasonic transducer

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ABSTRACT

In this paper, a new topological structure for the Langevin-type ultrasonic transducer is proposed and investigated. The two cylindrical terminal blocks are conically shaped with four supporting plates each, and two cooling fins are disposed at the bottom of terminal blocks, adjacent to the piezoelectric rings. Experimental results show that it has larger vibration velocity, lower temperature rise and higher electroacoustic energy efficiency than the conventional Langevin transducer. The reasons for the phenomena can be well explained by the change of mass, heat dissipation surface and force factor of the transducer. The proposed design may effectively improve the performance of ultrasonic transducers, in terms of the working effect, energy consumption and working life.

1. Introduction

The development of various applications of power ultrasound requires ultrasonic transducers with larger maximum vibration velocity and energy-efficiency, and lower temperature rise [1–3]. Larger maximum vibration velocity leads to stronger acoustic pressure in liquid, and thus the acoustic cavitation effect will be strengthened [4,5]. High energy efficiency decreases the operation cost of sono-reactors [6]. Lower temperature rise in the transducers increases the transducer lifetime and decreases the heat transferred into the treated samples such as the biological materials [1].

Langevin transducers are often utilized to generate low-frequency and high-power ultrasound [1,7]. P. Langevin designed and improved the classic sandwich-type ultrasonic transducer half a century ago [8], which utilizes the terminal clamping masses to increase the maximum vibration displacement of the piezoelectric components and to increase the operation stability [9,10]. Since then, many designs have been concentrated on the solid horn structure (e.g. conical, exponential, stepped, et al.), which can be used to amplify the vibration displacement of Langevin transducers [11–14]. Peshkovsky et al. summarized the design principles of the ultrasonic horn based on his “five-element” theory and invented the bar-bell horn which has a large gain factor [4–6]. S. Lin analyzed the relationship between the vibration amplitude and ultrasonic transducer’s geometrical dimensions and proposed the optimized methods to improve the radiation power [15–18]. Recently, J.A. Gallego-Juárez et al. proposed and investigated a radiator structure with properly designed slots for acquiring high acoustic power capacity, high efficiency and controlled radiation patterns [19–22]. Besides those, Rubio et al. applied functionally graded material technique to design piezoelectric transducers for acquiring little stress concentration and wide bandwidth [23]. Nakamura et al. designed an airborne ultrasonic transducer composed of a poly-based vibrator and high-intensity ultrasound can be generated [24].

In this work, a novel ultrasonic transducer structure, which is achieved by optimizing the mass distribution of the terminal blocks of a Langevin transducer, is reported. In the structure, the two cylindrical terminal mass blocks are conically shaped with four supporting plates each, and two cooling fins are disposed at the bottom of the terminal mass blocks, adjacent to the piezoelectric rings. A prototype is designed with the assistance of the finite element method (FEM), and fabricated to verify the proposed design. The results show that, at the same driving voltage and resonance, the proposed transducer has larger vibration amplitude, acoustic output power and electroacoustic energy efficiency, and lower temperature rise than the traditional Langevin transducers. Physical reasons for the transducer’s improved performance are also analyzed and discussed. The transducer proposed in this work may be used to effectively improve the treatment effects, energy efficiency and lifetime of various sono-reactors.

2. Structure design

Fig. 1(a) shows the configuration of a traditional Langevin transducer (TLT) which consists of two terminal mass blocks (the front mass block and back mass block), one bolt and two piezoelectric rings (outer diameter 40 mm × inner diameter 16 mm × thickness

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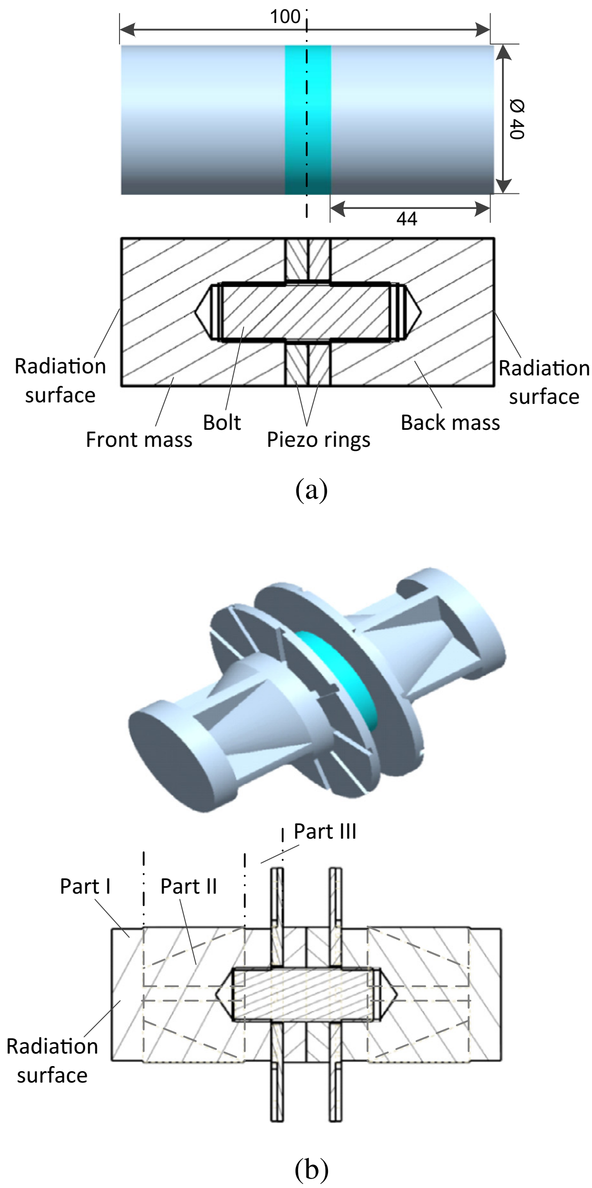

Fig. 1. Configuration of (a) traditional Langevin transducer (TLT), and (b) mass optimized Langevin transducer (MOLT).

6 mm). The components are disposed as shown in Fig. 1(a), and clamped together by the bolt. Two piezoelectric rings are stacked with opposite polarization directions in order to excite the longitude vibration mode in the axial direction. When the TLT operates at resonance frequency of the 1st order longitudinal mode, ultrasound energy is radiated from the end surface of the terminal mass block. The size of the TLT is 100 mm (length) × 40 mm (diameter), and the length of the terminal mass block is 44 mm.

Lots of works in ultrasonic transducers use the tapered front mass to enhance the vibrating performance at the expense of the size of the radiation face [11–14]. Being different from those works, we propose the mass optimized transducer (MOLT) in this work, which uses the same piezoelectric rings and possesses the same radiation face size with the TLT shown in Fig. 1(a). Fig. 1(b) shows the structure of the proposed transducer. The structure difference between the TLT and MOLT is in the terminal mass blocks. As shown in Fig. 1(b), the MOLT's terminal mass blocks can be divided into three parts: part I is a circular mass plate with a radiation face which has the same area as that of the TLT; part II is a cone-shaped mass block with four supporting plates uniformly disposed on the cone surface between parts I and III; part III is a cylinder with a circular ring as heat sink.

PZT-5H, which can be used as the hard piezoelectric material for transmitting transducers [25,26], is used in the transducer. Bronze is chosen as the electrodes, and steel for the transducer's other metal parts. Detailed material property constants used in the computation are listed in Table 1 [27,28].

3. Finite element analyses

Vibration and thermal characteristics of the transducers have been analyzed by COMSOL MULTIPHYSICS FEM software. In the first step, the 3-dimensional transducer model was built by Pro Engineering software and then transferred into COMSOL. In the second step, material of each part of the transducers was defined. In the third step, the models were meshed into elements, and boundary conditions were applied. In the fourth step, vibration characteristics were computed by using the eigen frequency module and frequency domain module. In the last step, thermal characteristics were computed by the calculation module Heat Transfer in Solids. By the above calculating process, both the TLT and MOLT were modeled and analyzed for a comparison. In the calculation, unless otherwise specified, driving voltage applied on the Langevin transducers was 40 $V_{p\text{-}p}$ and the initial temperature was 25 °C (298 K).

In the vibration analyses, the 1st longitudinal vibration modes of both transducers were analyzed, and the calculated vibration modes are shown in Fig. 2, respectively. Calculated resonance frequency for the TLT is 21.3 kHz and that for the MOLT is 22.2 kHz, which means that the new structure of the MOLT shifts the resonance frequency by 4.2%. According to the calculation, it is observed that vibration amplitude of the MOLT (2.5×10^{-6} m) at resonance is two times higher than that of the TLT (0.8×10^{-6} m) also at resonance for the same voltage, which indicates that vibration magnitude is enhanced for the MOLT's structure by removing some unnecessary mass in the terminal mass blocks.

In the thermal analyses, power loss density obtained from the vibration calculation was used as the heat source for computing the temperature field distribution. Fig. 3 shows the steady state temperature field of the TLT and MOLT, respectively. The colored iso-surfaces denote the calculated temperature value, and the arrows denote the direction of heat flux. Generally speaking, piezoelectric rings are the hottest structures in both TLT and MOLT. From the TLT's result, it can also be seen that temperature difference between the maximum (307 K) and minimum values (300 K) is 7 K, and all heat in the transducer transfers to the radiation faces. Comparatively, the MOLT's temperature difference is 4 K and heat dissipates mainly through the cooling fins, which indicates that thermal characteristic is improved for the MOLT by optimizing the mass distribution.

Table 1
Material property constants for the ultrasonic transducers.

		PZT-5H	Steel
Density	(kg/m^3)	7600	7840
Young's modulus	(N/m^2)		19.86×10^{10}
Poission's ratio		0.31	0.29
Damping coefficient		5.5×10^{-4}	1.09×10^{-4}
Specific heat	(J/kg K)	491	640
Thermal conductivity	(W/m K)	1.5	83.5
Dielectric loss factor		0.3%	
Elastic stiffness constant c_{11}	(N/m^2)	12.7×10^{10}	
Piezoelectric constant d_{33}	(pC/N)	593	