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Piezoelectric ultrasonic transducer for longitudinal-flexural vibrational mode-conversion

Xiaoli Zhang [a,b,*], Bo Liang [c]

[a] School of Materials Science and Engineering, Shaanxi Normal University, No.199, Chang'an South Road, Xi'an, Shaanxi 710062, PR China
[b] Department of Electronic & Information Engineering, Ankang University, No.92, Yucai Road, Ankang, Shaanxi 725000, PR China
[c] Department of Chemistry & Chemical Engineering, Ankang University, PR China

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ABSTRACT

A new type of piezoelectric ultrasonic transducer for longitudinal-flexural vibrational mode-conversion is proposed. The mode-conversion transducer has a back metal mass, longitudinally polarized piezoelectric ceramic pieces, and a circular metal plate. The longitudinal vibration of the piezoelectric vibrator drives the circular metal plate to produce flexural vibration. The analytical method for designing this type of mode-conversion transducer is mainly given in this paper, and the numerical simulation and the experimental measurement are used to verify this method. The performance analysis of the mode-conversion transducer is focused on comparing frequencies and mode shapes. Based on equivalent lumped mass and elastic parameters, the equivalent circuit and resonance frequency of the mode-conversion transducer are given. The vibrational modes and the harmonic response of the transducer are simulated via the numerical method. The results show satisfying concurrence among the analytical theory, numerical simulation, and experimental measurement. The suitability of this type of mode-conversion transducer for ultrasonic liquid processing, which requires high power and a large radiation area, will be investigated in the future.

1. Introduction

Ultrasound has been widely used for non-destructive testing, welding, soldering, machining and ultrasonic cleaning [1–4]. The ultrasonic transducer is one of the main parts of ultrasonic equipment. Given their different applications, ultrasonic transducers also have different vibrational modes and loads. Ultrasonic transducers can be divided into extensional, torsional, flexural, and mode-conversion vibration transducers based on vibrational mode; and the load of the transducers may be gas, liquid, or solid [5]. Compound mode transducers, such as longitudinal-radial, longitudinal-torsional, and longitudinal-flexural transducers have been used in underwater sound and power ultrasound applications [6–8].

Ultrasonic liquid processing technology is one of the main applications of power ultrasound. In traditional ultrasonic cleaning equipment, the sandwich piezoelectric ultrasonic transducer radiates ultrasound directly into the cleaning tank through the tank bottom. However, the radiation area of a single sandwich transducer is significantly smaller. If several similar transducers are used at the bottom of a cleaning tank, the consistency of their performance is difficult to adjust, which leads to poor uniformity of the cleaning sound field. Therefore, this type of transducer has certain restrictions for ultrasonic cleaning applications [9].

In order to design ultrasonic transducers with large radiation area in power ultrasonics conveniently, a new type of piezoelectric transducer for longitudinal-flexural vibrational mode-conversion, which consists of a back metal mass, longitudinally polarized piezoelectric ceramic pieces and a circular metal plate in flexural vibration, is proposed in the present paper. However, the sound speeds of the longitudinal and flexural vibrations are different at the same frequency. The resonance frequencies of the whole transducer system generally do not coincide with the resonance frequencies of system parts. Therefore, the longitudinal and flexural vibrations are difficult to resonate if considered separately. Besides, in general case, a half-wave transducer can be considered to consist of two quarter-wave vibrators, and the resonance frequency of the transducer can be given by using the resonance frequency equations of two quarter-wave vibrators. But, for the mode-conversion transducer, its front and back masses are not equal section elastic masses, so the analysis of the individual parts is comparatively complicated [5].

* Corresponding author at: School of Materials Science and Engineering, Shaanxi Normal University, No.199, Chang'an South Road, Xi'an, Shaanxi 710062, PR China.
E-mail address: zxlxlzhang@163.com (X. Zhang).

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In the following analysis, for this type of mode-conversion transducer, the electro-mechanical equivalent circuit method is mainly given. Firstly, the equivalent lumped parameters for a circular plate in flexural vibration are obtained for the free boundary condition, and its equivalent circuit is derived. The equivalent circuit of the mode-conversion transducer system is then given. Secondly, the vibrational mode and frequency characteristics of the mode-conversion transducer are simulated via the numerical method. Finally, some of the piezoelectric ultrasonic transducers of the vibrational mode-conversion are designed and manufactured; their resonance frequencies and vibrational displacement distributions are measured and compared with the theoretical results.

2. Theoretical analysis of the piezoelectric ultrasonic transducer for longitudinal-flexural vibrational mode-conversion

The geometrical diagram of a piezoelectric transducer for longitudinal-flexural vibrational mode-conversion is presented in Fig. 1. In the mode-conversion transducer, the piezoelectric longitudinal vibrator, which has a back metal mass and longitudinally (that is to say, polarized direction is thickness direction of piezoelectric ceramic pieces) polarized piezoelectric ceramic pieces, drives a circular metal plate to produce flexural vibration, which radiates acoustic waves into the fluid medium.

Let h and a be the thickness and radius of the thin circular plate, respectively. p identical circular piezoelectric pieces can be found in the longitudinal vibrator. Generally, p is an even number. l_0, r_1 and r_2 are the thickness, outer radii and inner radii of each piece. The thickness and radius of the back metal mass are l_b and R_b, respectively.

2.1. Equivalent lumped parameters of a circular plate in axisymmetrical flexural vibration for the free boundary condition

In the following analysis, the thickness of the circular plate is assumed to be significantly less than its radius. The shearing strain and the rotary inertia are ignored in this case, and the classic thin plate theory can be used [10]. The transverse displacement for the axisymmetrical flexural vibration of a circular plate can be expressed based on the linear elasticity theory as [5].

$$\zeta(r,t) = \xi(r)\cdot\exp(\mathrm{j}\omega t) = [A\mathrm{J}_0(kr) + B\mathrm{I}_0(kr)]\exp(\mathrm{j}\omega t) \tag{1}$$

The flexural moment and transverse shearing force of the thin circular plate can be expressed as follows:

$$M_r = -D\left(\frac{\partial^2\zeta}{\partial r^2} + \frac{\sigma}{r}\frac{\partial\zeta}{\partial r}\right) \tag{2}$$

$$Q_r = -D\left(\frac{\partial^3\zeta}{\partial r^3} + \frac{1}{r}\frac{\partial^2\zeta}{\partial r^2} - \frac{1}{r^2}\frac{\partial\zeta}{\partial r}\right) \tag{3}$$

where $\mathrm{J}_0(kr)$ is the first-kind Bessel function of order zero, and $\mathrm{I}_0(kr)$ is the first-kind modified Bessel function of order zero, where r is the radius of the thin circular plate. j is the imaginary unit, and $\mathrm{j} = \sqrt{1}$. $k^4 = \rho h\omega^2/D$, $D = Eh^3/12(1-\sigma^2)$, where k and D are the wave number and flexural rigidity of the plate [5], respectively. ρ, E, σ and ω are the density, Young's modulus, Poisson's ratio and angular frequency, respectively. A and B are two constants that can be determined by the boundary condition of the plate.

When the boundary of the plate is free, the flexural moment and transverse shearing force at the boundary are zero. The following equations can be obtained based on Eqs. (2) and (3):

$$A\left[k\mathrm{J}_0(ka) - \frac{1-\sigma}{a}\mathrm{J}_1(ka)\right] = B\left[k\mathrm{I}_0(ka) - \frac{1-\sigma}{a}\mathrm{I}_1(ka)\right] \tag{4}$$

$$-A\mathrm{J}_1(ka) = B\mathrm{I}_1(ka) \tag{5}$$

where $\mathrm{J}_1(ka)$ and $\mathrm{I}_1(ka)$ are the first order Bessel functions.

The normal function of the normal vibration of order n can be expressed as

$$\zeta_n(r,t) = \xi_n(r)\cdot\exp(\mathrm{j}\omega_n t) = [A_n\mathrm{J}_0(k_n r) + B_n\mathrm{I}_0(k_n r)]\exp(\mathrm{j}\omega_n t) \tag{6}$$

Therefore, the vibrational velocity can be obtained as follows:

$$v_n(r,t) = \mathrm{j}\omega_n[A_n\mathrm{J}_0(k_n r) + B_n\mathrm{I}_0(k_n r)]\exp(\mathrm{j}\omega_n t) \tag{7}$$

2.1.1. The equivalent mass M_n of the plate in the n th flexural vibration

In the thin plate, the mass of the volume element of a radial coordinate $(r, r+dr)$ is $2\pi\rho hrdr$, and the kinetic energy of the normal vibration of order n can be expressed as

$$dE_{kn} = \frac{1}{2}(2\pi\rho hrdr)v_n\cdot v_n^*$$

Based on Eq. (7), the kinetic energy of the circular plate in the n th flexural vibration can be obtained as follows:

$$E_{kn} = \int_0^a dE_{kn} = -\pi\rho h\omega_n^2\int_0^a [A_n\mathrm{J}_0(k_n r) + B_n\mathrm{I}_0(k_n r)]^2 rdr \tag{8}$$

The vibration velocity at the center of the circular plate can be derived from Eq. (7) in the following manner:

$$v_n = \mathrm{j}\omega_n(A_n + B_n)\exp(\mathrm{j}\omega_n t)$$

When the center of the circular plate is chosen as the reference point of the equivalent mass, the equivalent kinetic energy of the n th flexural vibration can be written as

$$E'_{kn} = \frac{1}{2}M_n v_n\cdot v_n^* = -\frac{1}{2}M_n(A_n + B_n)^2\omega_n^2 \tag{9}$$

where M_n is the equivalent mass at the center of the circular plate in the n th flexural vibration. Let $E'_{kn} = E_{kn}$. The equivalent mass at the center of the circular plate can be obtained as follows:

$$M_n = \frac{2m}{a^2(A_n + B_n)^2}\int_0^a [A_n\mathrm{J}_0(k_n r) + B_n\mathrm{I}_0(k_n r)]^2 rdr \tag{10}$$

where m is the mass of the plate, $m = \pi a^2 h\rho$.

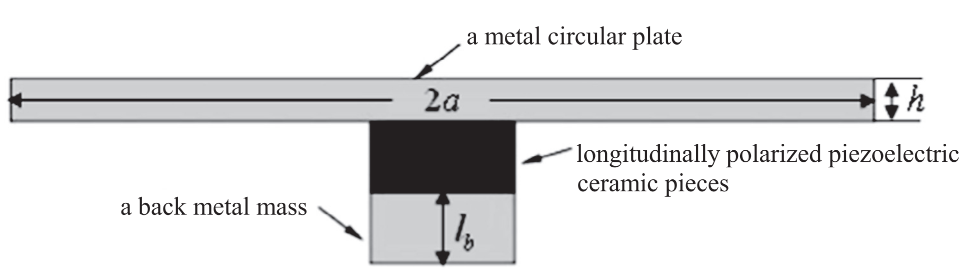

Fig. 1. Geometrical diagram of a piezoelectric ultrasonic transducer for longitudinal-flexural vibrational mode-conversion.