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Study on tangentially polarized composite cylindrical piezoelectric transducer with high electro-mechanical coupling coefficient

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ABSTRACT

In this work, we proposed an effective way to fabricate a tangentially polarized composite cylindrical transducer with high electro-mechanical coupling coefficient (EMCC) by radially connecting an inner tangential polarized piezoelectric tube with an outer metal ring. The resonance frequency and EMCC of the proposed transducer are calculated according to frequency equations, which are obtained from the equivalent circuit of the transducer, and the results indicate that EMCC of the tangentially polarized cylindrical transducer is much higher than that of the cylindrical transducer polarized in radial direction. Furthermore, the Finite Element Method (FEM) model of the transducer is established and used for numerical simulation of the vibration models and the optimum configuration parameters. On the basis of those theoretical results, serials of prototype transducers are manufactured with an inner tangential polarized piezoelectric tube connecting with different outer metal cylindrical shells. The admittance characteristics of the fabricated transducers measured by Impedance Analyzer clearly demonstrate that the resonance frequencies of the transducers are in good agreement with those of simulation results, and the effective EMCC of transducers varies with the material of metal cylindrical shell, in which aluminum metal shell possesses the highest EMCC.

1. Introduction

With the rapid development of electronic, computer and materials science, high power piezoelectric ultrasonic transducer is more and more widely used in the fields of aviation, navigation, national defense, biotechnology, optical fiber communications and electronics [1–8]. Lots of high power piezoelectric ultrasonic transducers with composite structure have been successfully designed and used, such as longitudinal composite transducer, longitudinal sandwich transducer, radial composite cylindrical piezoelectric transducer, and radial sandwich cylindrical transducer [9–20]. Piezoelectric cylindrical tube has received increasing attentions due to its stable performance, no directivity in horizontal direction and higher receiving sensitivity. In order to improve sound radiation area, composite cylindrical piezoelectric transducer is proposed, many theories and experimental works have been developed to improve the energy conversion efficiency of the transducer [21–23]. For example, Lu obtained a formula to estimate the transverse frequencies of the piezoelectric cylindrical shells [24]. Lin designed a kind of radial sandwiched piezoelectric transducer using analytical and numerical method [25]. He also proved that the transducer polarized in axially direction has larger sound radiating area [26–28]. Ebenezer and Kim studied the radial vibration of a radial polarized piezoelectric transducer under some assumptions [29,30]. Liu got the electromechanical model for a thin-walled cylindrical radial composite piezoelectric ceramic transducer [31]. Aronov et al. studied the effects of coupled vibrations in piezoelectric circular tubes with energy method [32,33]. According to polarization direction acted on piezoelectric tube, the composite piezoelectric ultrasonic transducer can be classified into radial polarization, axial polarization, and tangentially polarization transducer. To the best of our knowledge, the existed studies mainly focus on fabrications of cylindrical composite piezoelectric transducers with the manner of radial polarization and axial polarization, tangentially polarized composite cylindrical piezoelectric transducer has never been designed and studied. However, recent studies indicated tangentially polarized stripe-electroded piezoelectric tube possesses a higher effective electro-mechanical coupling coefficient (EMCC) compared with those of radial polarized and axial polarized piezoelectric tubes [34–36]. On the basis of those works, the present study aims to design a novel tangentially polarized composite cylindrical transducer with high EMCC by radially connecting an inner tangential polarized piezoelectric tube with an outer metal ring. The performance of

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the designed transducer is studied by equivalent circuit and finite element methods. In the following sections, the equivalent circuit and the frequency equation of the transducer is deduced and then the vibration characteristics of the transducer are analyzed by finite element simulation. Finally, prototype transducers are made and the performances of the transducers are measured experimentally.

2. The equivalent circuit of the tangentially polarized hybrid piezoelectric cylindrical transducer

Fig. 1 shows the structure of the tangential polarized cylindrical transducer. The inner part of the transducer is a tangentially polarized piezoelectric ring, which has outer radius b, inner radius c and height l. The piezoelectric ring consists of 12 rectangular silver electrodes which cover the inner and outer walls of the tube. There are six positive electrodes and six negative electrodes. The positive electrodes and negative electrodes are alternately arranged at equal intervals and the polarization direction denoted by arrows in Fig. 2(a) is approximately parallel to the tangential direction of the tube. The polarization direction of each segment coincides with the polarity of the excitation electric field. The electrical connection of the transducer is shown in Fig. 2(b), where six positive electrodes are connected in parallel to serve as the positive pole and six negative electrodes are connected in parallel to serve as the negative pole of the transducer. The outer part of the transducer is metal tube, which has outer radius a and inner radius b. When the height of the cylindrical transducer is less than its diameter, the radial vibration can be regarded as an ideal plane radial vibration.

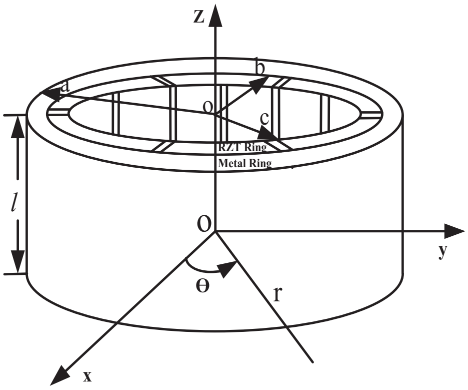


Fig. 1. The structure of the tangentially polarized cylindrical transducer.

Based on the structure of the transducer shown in Fig. 1, the piezoelectric equations can be written as:

$$\xi_r/r_0 = S_{33}^E T_\theta + d_{33}E_\theta \tag{1}$$

$$D_2 = d_{33}T_\theta + \varepsilon_{33}^T E_\theta \tag{2}$$

where subscript 3 represents the circumferential direction, $r_0 = (b+c)/2$ is mean radius of the cylinder ring, S_{33}^E is elastic compliance constant, d_{33} is piezoelectric strain constant, ε_{33}^T is dielectric constant, E_θ is tangential electric field, T_θ is shear stress, and ξ_r is radial displacement.

The mass of the piezoelectric tube can be expressed as $2\rho\pi w r_0 l$, in which w is the thickness of the piezoelectric tube. Let radial displacement and the radial vibration velocity be ξ_r and $d\xi_r/dt$, respectively, then the wave equation in radial direction can be written as:

$$\rho\frac{d^2\xi_r}{dt^2} = -\frac{T_\theta}{r_0} - \frac{F_r}{Aw} \tag{3}$$

where $A = 2\pi r_0 l$ denotes the lateral area and F_r is the external force exerted to the outer surface of the piezoelectric tube in radial direction. From Eq. (1), we have:

$$T_\theta = \frac{\xi_r}{r_0 s_{33}^E} - \frac{d_{33}}{s_{33}^E}E_\theta \tag{4}$$

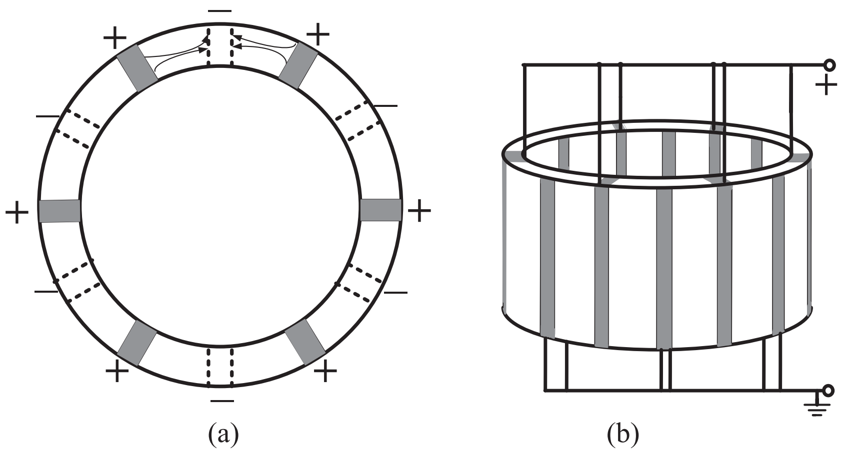
Based on Eqs. (3) and (4), we can obtain the radial wave equation, that is:

$$\rho\frac{d^2\xi_r}{dt^2} + \frac{\xi_r}{r_0^2 s_{33}^E} = \frac{d_{33}}{r_0^2 s_{33}^E}E_\theta - \frac{F_r}{Aw} \tag{5}$$

Let $\xi_r = \xi_{r0}\exp(j\omega t)$, then we have $\dot{\xi}_r = j\omega\xi_r$, $\ddot{\xi}_r = j\omega\dot{\xi}_r$. If each patch connects in parallel, the tangential electric field intensity E_θ can be expressed as $E_\theta = V/L_C = nV/2\pi r_0$, where $L_C = 2\pi r_0/n$ is the thickness of each piezoelectric patch and n is the number of ceramic patches. Then the radial equation can be written as:

$$(j\omega m + 1/(j\omega C_m))\dot{\xi}_{r2} + F_r = \varphi V \tag{6}$$

Here, $C_m = r_0 s_{33}^E/2\pi wl$, $\varphi = d_{33}nlwY_0^E/r_0$, and $Y_0^E = 1/s_{33}^E$ are elastic compliance constant, electromechanical conversion coefficient and phase modulus of the piezoelectric tube, respectively. According to Eqs. (2) and (4), we can deduce the electric displacement D_θ, that is



(a) (b)

Fig. 2. The structure of the piezoelectric ring. (a) Polarization direction and (b) electrical connection.