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Optimization Design and Load Characteristics of the Ring-Type Piezoelectric Ceramic Transformer

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Summary
A new type of ring-type piezoelectric ceramic transformer consisting of two concentric piezoelectric ceramic rings polarized axially and radially is analyzed. When the electric load impedance is considered, the electromechanical characteristics of the piezoelectric transformer are studied. The dependency of the voltage gain, the efficiency (the ratio of the output over the input power) and the effective electromechanical coupling coefficient of the piezoelectric transformer on the geometrical dimensions are analyzed. Meanwhile, the load dependency of the electromechanical parameters of the transformer is also investigated. It is concluded that the electromechanical characteristics of the piezoelectric transformer are closely related with the geometrical dimensions and the load electrical impedance. The conclusions can be used for the optimization design of the ring-type piezoelectric ceramic transformers in the engineering applications.

PACS no. 43.35.-c, 43.38.-p

1. Introduction

Piezoelectric transformers have a history of about half a century. Generally speaking, piezoelectric transformers can be classified into three main categories based on their vibration modes, which are the high voltage or Rosen-type piezoelectric transducer [1, 2, 3], low voltage or thickness vibration mode piezoelectric transformer [4, 5], and the radial vibration mode piezoelectric transformer [6, 7, 8, 9]. In order to increase the step-up or step-down ratio, either the primary piezoelectric actuator or the secondary piezoelectric transducer can be made up of more than one layer of piezoelectric materials. This kind of piezoelectric transformer was called multilayer piezoelectric transformer [10, 11, 12, 13].

For the performance description of piezoelectric transformers, the equivalent circuit method and the finite element method have been used [14, 15, 16, 17]. In general cases, the lumped parameter equivalent circuit is widely used for simplifying the analysis of the complicated electromechanical coupling in the piezoelectric transformers. However, the abilities of these simplified models are limited to some extent. For example, it is usually difficult to give the exact relationship between the lumped parameters and the material parameter, the geometrical shape and dimension of the real piezoelectric transformers. On the other hand, the lumped parameter equivalent circuit is only suitable for the performance description of the piezoelectric transformer in the vicinity of resonance.

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In the present paper, the piezoelectric transformer composed of two concentric piezoelectric rings which are polarized axially and radially is studied. In fact, the two piezoelectric ceramic rings in the piezoelectric transformer are two ultrasonic transducers, one converts the electric energy into the mechanical energy, and the other converts the mechanical energy into the electric energy. The piezoelectric ceramic rings polarized axially and radially are the main components for the commonly used ultrasonic transducers [18, 19, 20]. This kind of piezoelectric ceramic transducers are the main sound generating and receiving devices, which nowadays are widely used in underwater acoustics, ultrasonics and medical ultrasonics [21, 22]. In this paper, when the load impedance is considered, the distributed parameter electromechanical equivalent circuit is obtained. The dependency of the electromechanical characteristics on the geometrical dimension, the frequency and the load impedance is investigated. Meanwhile, some prototypes of the piezoelectric transformers are designed and made, and the impedance-frequency response and the resonance/anti-resonance frequencies are measured.

2. Theoretical analysis of the electromechanical characteristics of the piezoelectric transformer in radial vibration with load impedance

The diagrammatic sketch of a piezoelectric transformer in radial vibration is illustrated in Figure 1. In the figure, the inner piezoelectric ceramic ring is polarized in its thickness direction and is used as the input part, the outer piezo-

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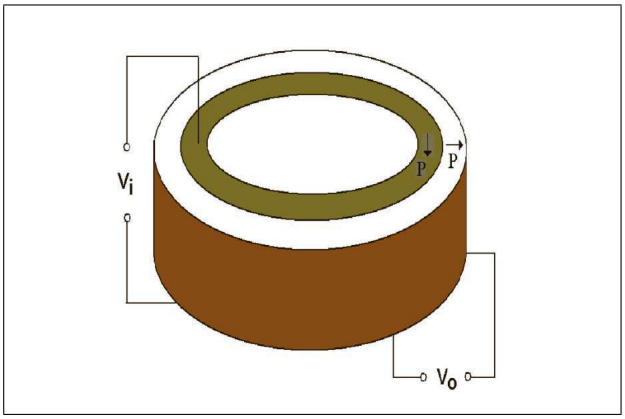


Figure 1. Diagrammatic sketch of a piezoelectric transformer in radial vibration.

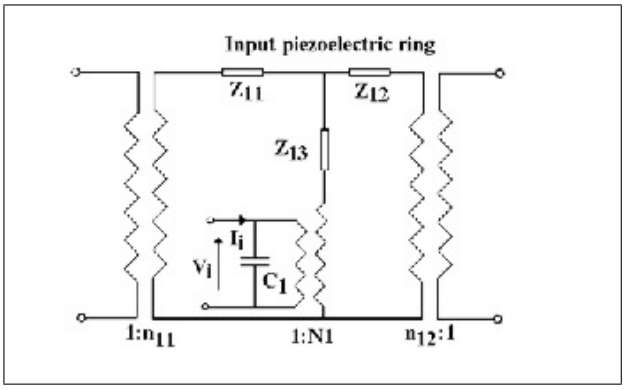


Figure 2. Electromechanical equivalent circuit of the thickness polarized piezoelectric ring in radial vibration.

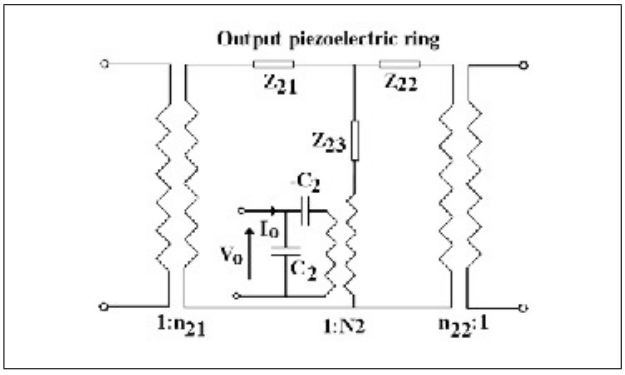


Figure 3. Three-port electromechanical equivalent circuit of an output piezoelectric ceramic ring polarized in the radial direction.

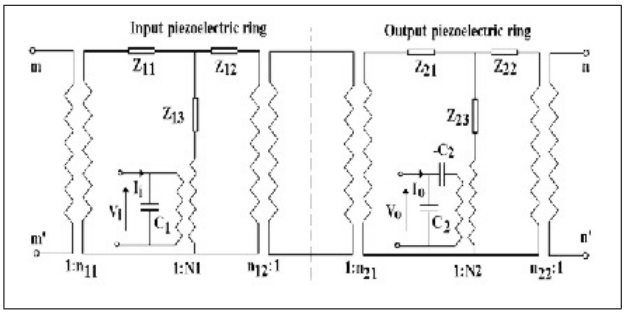


Figure 4. Electromechanical equivalent circuit for a piezoelectric ceramic transformer composed of two concentric piezoelectric rings in radial vibration.

electric ring is polarized in the radial direction and is used as the output part. When the input voltage is applied to the upper and lower surfaces of the input piezoelectric ceramic ring, it will produce radial vibration. The radial vibration will accordingly causes the output piezoelectric ring to vibration. Based on the piezoelectric effect, an output voltage will be produced at the inner and outer cylindrical surfaces. By means of changing the geometrical dimensions of the two piezoelectric rings, the voltage step-up or down can be realized and the optimization design of the piezoelectric transformer completed.

Let the height, the inner radius and the outer radius of the input piezoelectric ceramic ring be h, a and b. In the case of plane stress, the three-port electromechanical equivalent circuit can be obtained as shown in Figure 2. The related physical parameters and their physical meaning and expressions in Figure 2 can be found in our previous work [23].

For the radially polarized output piezoelectric ring with height h, the inner radius b and the output radius c, its three-port electromechanical equivalent circuit is shown in Figure 3. The related physical parameters and their physical meaning and expressions in Figure 3 can be found in our previous work [24, 25].

From Figures 2 and 3, it can be seen that the electromechanical equivalent circuit for a radially polarized piezoelectric ceramic ring is different from that of a thickness polarized piezoelectric ceramic ring. For the thickness polarized piezoelectric ring, since the polarization orientation is in the height direction of the ring and vertical to the radial vibrational displacement, the radial wall thickness of the piezoelectric ring has no obvious effect on the radial vibration of the ring. For this vibrational mode, the effective electromechanical coupling k_p was used and it was defined as the vibrational mode of transverse effect. For the radially polarized piezoelectric ceramic ring, since the polarization orientation is parallel to the radial vibrational displacement, the radial wall thickness of the ring has obvious effect on the radial vibration, and this vibrational mode is often defined as the vibrational mode of longitudinal effect. For this kind of vibrational mode, its electromechanical coupling coefficient is similar to k_{33} or k_t. On the other hand, because of the interaction between the radial electric field and the radial mechanical vibration, a negative capacitance is produced for the radially polarized piezoelectric ring.

At the contacting cylindrical surface between the input and the output piezoelectric ceramic rings, the radial force and velocity are continuous. Based on Figures 2 and 3, the electromechanical equivalent circuit for the piezoelectric transformer can be obtained as shown in Figure 4.

In Figure 4, the inner and the outer cylindrical surfaces of the piezoelectric transformer are free of external forces, therefore, the mechanical terminals m-m' and n-n' in Figure 4 are short circuited. When the electrical output termi-

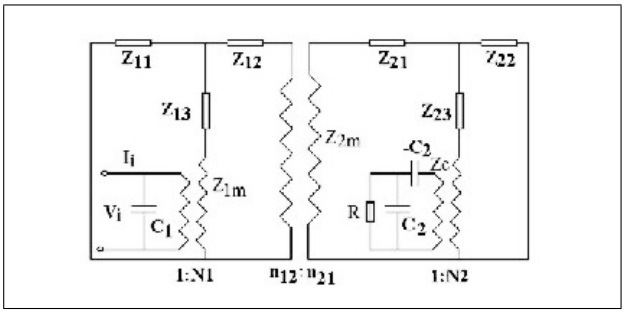


Figure 5. Simplified electromechanical equivalent circuit of a piezoelectric transformer with load resistance R.

nals of the piezoelectric transformer are loaded with resistance R, Figure 4 can be reduced to Figure 5. In the figure, R represents the load electric resistance.

Based on the electromechanical equivalent circuit shown in Figure 5, the resonance/anti-resonance frequency equation and electromechanical parameters of the piezoelectric transformer can be obtaied.

From Figure 5, the electric impedance between the primary terminals of the electromechanical transformer of the output piezoelectric ring can be obtained,

$$Z_c = \frac{1}{\omega^2 C_2 R - \mathrm{j}\omega C_2}. \tag{1}$$

The reflected mechanical impedance of the output piezoelectric ring is expressed as

$$Z_{2m} = \frac{(Z_{12} + Z_{22})(Z_{23} + N_2^2 Z_c) + Z_{21} Z_{22}}{Z_{23} + N_2^2 Z_c + Z_{22}}. \tag{2}$$

The mechanical impedance between the mechanical terminals of the input piezoelectric transformer can be given as

$$Z_{1m} = \frac{(Z_{11} + Z_{13})(Z_{12} + \frac{n_{12}^2}{n_{21}^2} Z_{2m}) + Z_{11} Z_{13}}{Z_{12} + \frac{n_{12}^2}{n_{21}^2} Z_{2m} + Z_{11}}. \tag{3}$$

The input electric impedance of the piezoelectric transformer is obtained as the following expression,

$$Z = \frac{Z_{1m}}{\mathrm{j}\omega C_1 Z_{1m} + N_1^2}. \tag{4}$$

From equation (4), the resonance frequency equations can be obtained by letting the imaginary part of the input electric impedance equal to zero,

$$Im\{Z\} = 0, \tag{5}$$

and the anti-resonance frequency equation can also be obtained by letting the imaginary part of the input electric admittance be equal to zero,

$$Im\{1/Z\} = 0. \tag{6}$$

From equations (5) and (6), when the material parameters and the geometrical dimensions are given, the resonance/anti-resonance frequency of the transformer at different vibrational modes can be obtained.

From Figure 5, the voltage gain of the piezoelectric transformer which is defined as the ratio of the output voltage over the input voltage can be derived out in the following expression,

$$\begin{aligned} Mv = \frac{V_o}{V_i} = N_1 & \frac{Z_{11}(Z_{12} + \frac{n_{12}^2}{n_{21}^2} Z_{2m})}{(Z_{11} + Z_{13})(Z_{12} + \frac{n_{12}^2}{n_{21}^2} Z_{2m}) + Z_{11} Z_{13}} \\ & \cdot \frac{Z_{22}(Z_{23} + N_2^2 Z_c)}{(Z_{21} + Z_{22})(Z_{23} + N_2^2 Z_c) + Z_{21} Z_{22}} \\ & \cdot \frac{\frac{n_{12}}{n_{21}} Z_{2m})}{Z_{12} + \frac{n_{12}^2}{n_{21}^2} Z_{2m}} \frac{N_2 Z_c}{Z_{23} + N_2^2 Z_c} \big(-\mathrm{j}\omega C_2 R \big) \end{aligned} \tag{7}$$

And the efficiency of the piezoelectric transformer which is defined as the output power over the input power can be obtained as

$$\eta = \frac{P_o}{P_i} = \frac{\frac{V_o^2}{R}}{\frac{V_i^2}{Z}} = Mv^2 \frac{Z}{R}. \tag{8}$$

From Equations (7)–(8), it can be seen that the voltage gain and efficiency are two complicated expressions. They are closely related with the material parameters, the geometrical dimensions, the vibrational modes and the working frequency of the piezoelectric transformer.

3. Optimization design and the dependency of the electromechanical characteristics on the geometrical dimensions and the load electric impedance of the piezoelectric transformer

In this section, the dependency of the resonance/anti-resonance frequency, the voltage gain, the efficiency and the effective electromechanical coupling coefficient of the piezoelectric transformer on the geometrical dimensions and the load electric resistance is analyzed. The piezoelectric material for the piezoelectric ceramic rings is an equivalent of PZT-4, its standard material parameters are used and are as follows:

$\rho = 7.5 \cdot 10^3\,\mathrm{kg/m^3}$, $e_{31} = -5.2\,\mathrm{N/mV}$,
$e_{33} = 15.1\,\mathrm{N/mV}$, $\varepsilon_{33}^S = 5.62 \cdot 10^{-9}\,\mathrm{F/m}$,
$c_{11}^E = 13.9 \cdot 10^{10}\,\mathrm{N/m^2}$, $c_{12}^E = 7.78 \cdot 10^{10}\,\mathrm{N/m^2}$,
$c_{13}^E = 7.43 \cdot 10^{10}\,\mathrm{N/m^2}$, $c_{33}^E = 11.5 \cdot 10^{10}\,\mathrm{N/m^2}$,
$s_{11}^E = 12.3 \cdot 10^{-12}\,\mathrm{m^2/N}$, $s_{12}^E = -4.05 \cdot 10^{-12}\,\mathrm{m^2/N}$,
$d_{31}^E = -123 \cdot 10^{-12}\,\mathrm{C/N}$, $\varepsilon_{33}^T/\varepsilon_0 = 1300$,
$\varepsilon_0 = 8 - 842 \cdot 10^{-12}\,\mathrm{C^2/(Nm^2)}$. $\tau = (b-a)/(c-a)$,

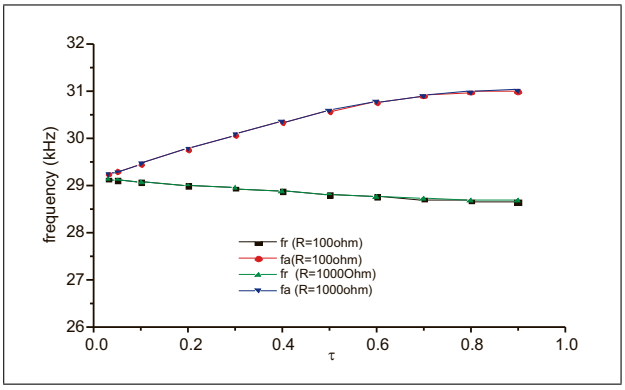


Figure 6. Dependency of the resonance/anti-resonance frequency on the geometrical dimensions of the transformer with different load resistances.

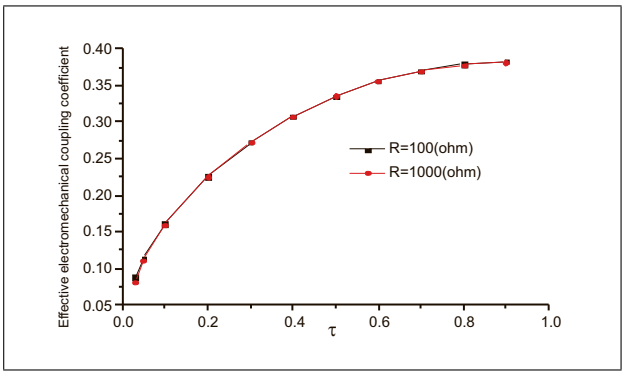


Figure 7. Dependency of the effective electromechanical coupling coefficient on the geometrical dimensions of the transformer with different load resistances.

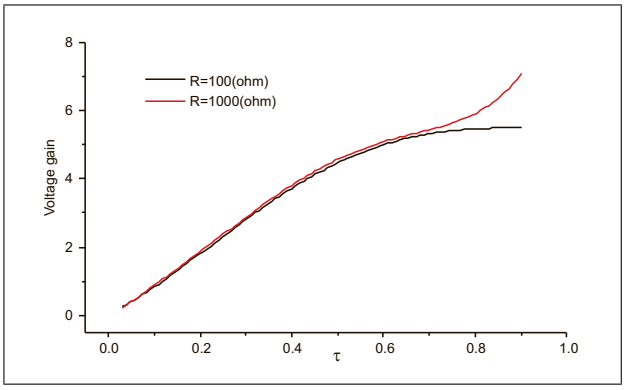


Figure 8. Dependency of the voltage gain on the geometrical dimensions of the transformer with different load resistances.

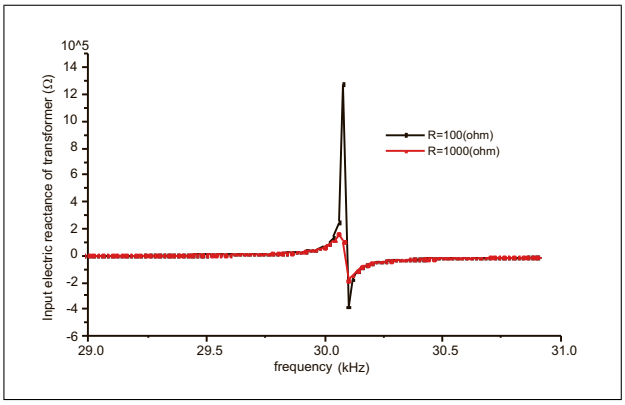


Figure 9. Frequency response of the input electric reactance of the piezoelectric transformer with different load electric resistances.

which represents the ratio of the radial thickness of the input piezoelectric ceramic ring over the total radial thickness of the piezoelectric transformer. It can be seen that there are two limiting cases. When $\tau = 0$, there is no the input piezoelectric ring, the transformer becomes a radially polarized piezoelectric ring; When $\tau = 1$, there is no the output piezoelectric ring, the transformer becomes a piezoelectric ring polarized in the thickness direction.

3.1. Theoretical relationship between the electromechanical parameters and the geometrical dimensions

Based on the analytical expressions in the above section, the dependency of the resonance/anti-resonance frequency, the voltage gain and the effective electromechanical coupling coefficient on the geometrical dimensions are studied and the theoretical results are illustrated in Figures 6–8. In the theoretical analysis, the geometrical dimensions of the piezoelectric transformer are as follows. $a = 0.01$ m, $c = 0.03$ m, $h = 0.005$ m.

It can be seen from Figures 6–8 that the load resistance has little effect on the resonance/anti-resonance frequency. However, the geometrical dimensions have obvious effect on the voltage gain and the effective electromechanical coupling coefficient. When the thickness ratio is increased, the anti-resonance frequency, the voltage gain and the effective electromechanical coupling coefficient are all increased, while the resonance frequency is decreased. These conclusions can be used in the performance analysis and optimization design of the piezoelectric transformer on the geometrical dimensions.

3.2. Dependency of the electromechanical characteristics of the piezoelectric transformer on the frequency with different load resistances

For a piezoelectric transformer with definite geometrical dimensions, its electromechanical parameters are dependent on the frequency. The relationship between the input electric reactance, the voltage gain and the efficiency of the piezoelectric transformer with the frequency are analytically simulated and shown in Figures 9–11. In the theoretical calculation, the geometrical dimensions of the piezoelectric transformer are $a = 0.01$ m, $b = 0.016$ m, $c = 0.03$ m and $h = 0.005$ m.

From the above analytical figures, it can be seen that the piezoelectric transformer is a kind of typical frequency selective device. Its input electric impedance is similar to that of a resonant piezoelectric device. At the resonance and anti-resonance frequency, the voltage gain and the efficiency have maximum values. Therefore, the piezoelec-

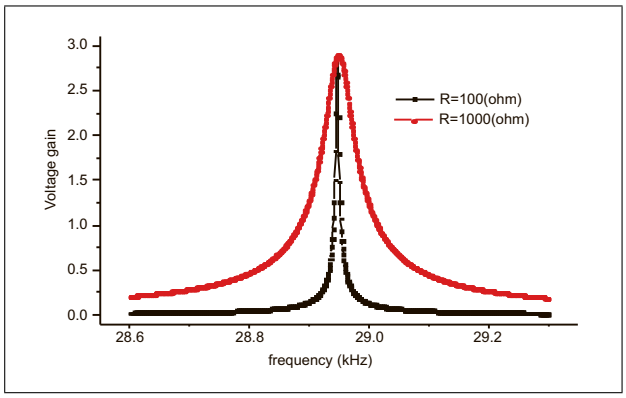


Figure 10. Theoretical relationship between the voltage gain and the frequency with different load resistances.

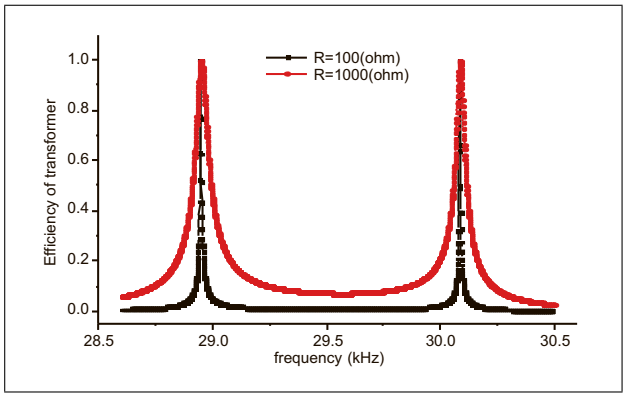


Figure 11. Theoretical relationship between the efficiency and the frequency with different load resistances.

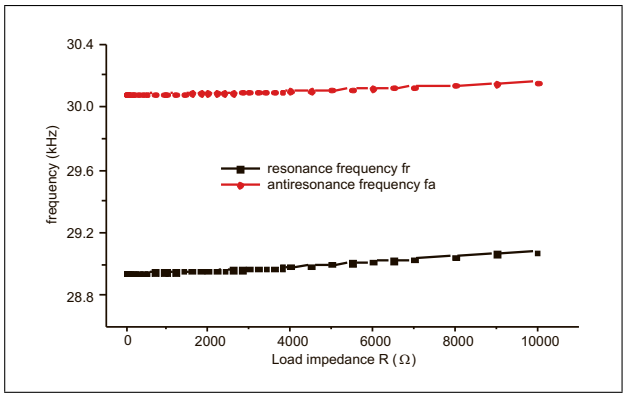


Figure 12. Theoretical relationship between the resonance/anti-resonance frequency and the load electric resistance.

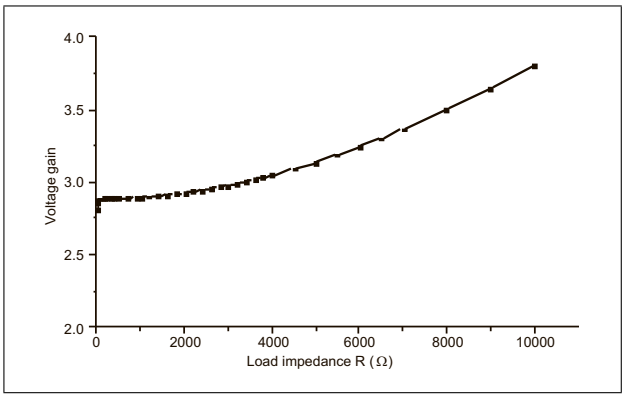


Figure 13. Relationship between the voltage gain and the load electric resistance.

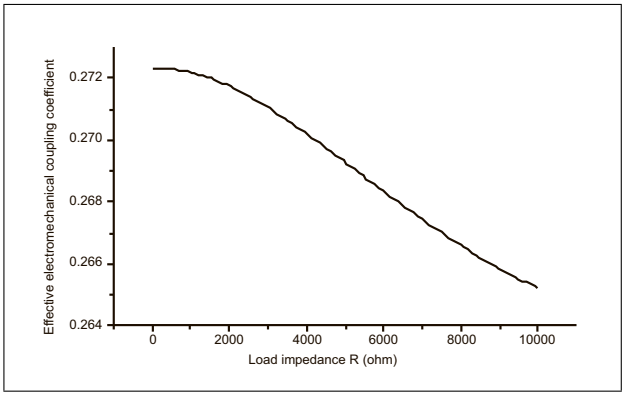


Figure 14. Theoretical curve between the effective electromechanical coupling coefficient and the load electric resistance.

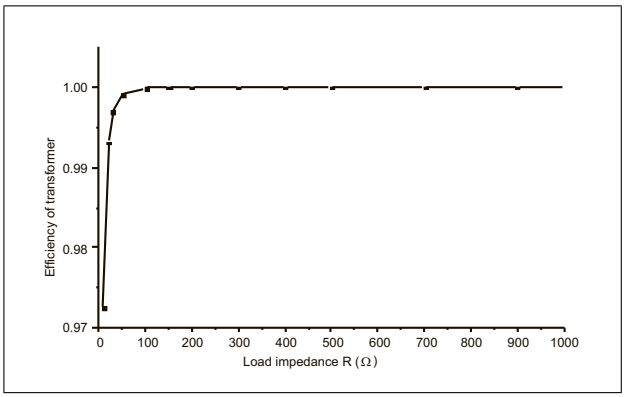


Figure 15. Dependency of the efficiency of the piezoelectric transformer on the load electric resistance.

tric transformer must be operated on its resonance/anti-resonance frequency. On the other hand, it can be seen that when the load resistance is increased, the input electric impedance of the piezoelectric transformer is decreased.

3.3. Analysis of the load characteristics of the piezoelectric ceramic transformer

The load electric resistance will affect the characteristics of the piezoelectric transformer. The dependency of the resonance/anti-resonance frequency, the voltage gain, the efficiency and the effective electromechanical coupling coefficient on the load electric resistance is studied and the theoretical relationship is illustrated in Figures 12–15.

From the above results, it can be concluded that the load electric impedance has different effects on the electromechanical characteristics of the piezoelectric transformer. When the load electric impedance is increased, the voltage gain and the efficiency of the piezoelectric transformer are increased, while the effective electromechanical coupling coefficient is decreased. Meanwhile, it can be

seen that the load impedance has no obvious effect on the resonance/anti-resonance frequency.

In the above analysis, the theoretical dependency of the electromechanical characteristics of the piezoelectric ceramic transformer on the frequency, the geometrical dimensions and the load electric resistance are studied. Some theoretical conclusions are obtained and can be used in the optimization design. It should be pointed out that, however, in these analysis, the mechanical and dielectric loss in the piezoelectric transformer are not considered. Therefore, the absolute figures for the input electric impedance, the voltage gain and the efficiency have no practical meaning. Their changing rules on the frequency, the geometrical dimensions and the load electric resistance have guiding significance for engineering design of the piezoelectric ceramic transformers.

4. Numerical simulation and experimental results of the piezoelectric transformer in radial vibration

In order to verify the theoretical analysis, some real prototypes of the piezoelectric transformers in radial vibration are designed and made. The impedance-frequency response of the transformer is measured and the resonance/anti-resonance frequencies are obtained by 6500B Precision Impedance Analyzer made by Wayne Kerr Electronics of West Sussex in UK. The prototypes of the piezoelectric transformers and the experimental set-up for the measurement of the electric impedance are shown in Figure 16. The measured impedance-frequency curve of a piezoelectric transformer is shown in Figure 17. In the figure, the upper figure displays the modulus of the input electric impedance, and the bottom figure is the phase of the input electric impedance of the piezoelectric transformer. The abscissa axis in the figure is the frequency in logarithmic coordinate; the vertical coordinate represents the modulus and the phase of the input electric impedance. The modulus of the impedance is also in logarithmic coordinates.

On the other hand, for comparison, the finite element method is also used to simulate the radial vibration of the piezoelectric transformer. In the numerical simulation, the transformer material is the same as that in the above theoretical analysis. The geometrical dimensions of the transformer are listed in Table I. The analytical, numerically simulated and the measured resonance/anti-resonance frequencies of the transformers are listed in Tables II–III. In the tables, f_r and f_a are the analytical resonance/anti-resonance frequencies; f_{nr} and f_{na} are the numerical resonance/anti-resonance frequencies, and f_{mr} and f_{ma} are the experimental resonance/anti-resonance frequencies.

$$\Delta_1 = \left| f_r - f_{rm} \right| / f_{rm}, \qquad \Delta_2 = \left| f_{nr} - f_{rm} \right| / f_{rm},$$
$$\Delta_3 = \left| f_a - f_{am} \right| / f_{am}, \qquad \Delta_4 = \left| f_{na} - f_{ma} \right| / f_{ma}.$$

It can be seen that the analytical resonance/anti-resonance frequencies are in good agreement with the numerical and

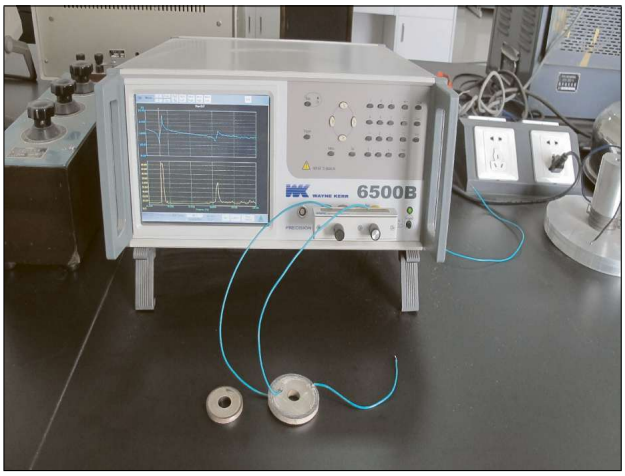


Figure 16. Photo of the piezoelectric transformers and the experimental set-up for the impedance and frequency measurement.

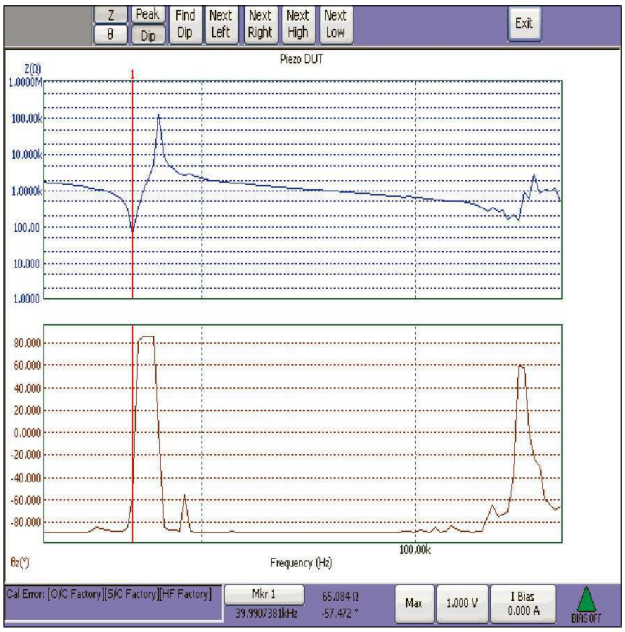


Figure 17. Experimental impedance-frequency curve for a piezoelectric ceramic transformer.

experimental results. Table IV list the effective electromechanical coupling coefficient of the piezoelectric transformer at the first and second radial vibrational modes, where k_{effc}, k_{neffc} and k_{meffc} are the analytical, numerical and experimental effective electromechanical coupling coefficient,

$$\Delta_5 = \left| k_{effc} - k_{meffc} \right| / k_{meffc},$$
$$\Delta_6 = \left| k_{neffc} - k_{meffc} \right| / k_{meffc}.$$

It is obvious that the relative error for the effective electromechanical coupling coefficient is comparatively large. The reason for this error can be explained as follows. First, in the theoretical analysis, the mechanical and dielectric losses in the piezoelectric transformer are neglected; while in the numerical simulation and experimental measurement of the transformer, the loss factor in the piezoelec-

Table I. Geometrical dimensions of the piezoelectric transformers.

a (mm)	b (mm)	c (mm)	h (mm)	τ
7.5	19	21	5	0.85

Table II. Analytical, numerical and experimental resonance frequencies of the piezoelectric transformers at the first and second radial vibrational mode. f in kHz, Δ in %.

mode	f_r	f_{nr}	f_{mr}	Δ_1	Δ_2
1	40.07	39.99	39.90	0.43	0.23
2	138.45	135.05	135.78	1.97	0.54

Table III. Analytical, numerical and experimental anti-resonance frequencies of the piezoelectric transformers at the first and second radial vibrational mode. f in kHz, Δ in %.

mode	f_a	f_{na}	f_{ma}	Δ_3	Δ_4
1	43.13	42.71	43.52	0.89	1.86
2	151.45	146.55	147.54	2.65	0.67

Table IV. Analytical, numerical and experimental effective electromechanical coupling coefficient of the piezoelectric transformers at the first and second radial vibrational mode Vibrational mode.

mode	k_{effc}	k_{neffc}	k_{meffc}	Δ_5 (%)	Δ_6 (%)
1	0.370	0.351	0.399	7.27	12.0
2	0.405	0.388	0.391	3.58	0.77

tric transformer is considered. Second, the mechanical and dielectric losses have more obvious effect on the effective electromechanical coupling coefficient than on the resonance/anti-resonance frequencies of the piezoelectric transformer. Third, in the analytical and numerical simulation, the standard material parameters are used, they are more or less different from the real material parameters.

In the above analysis, when the output end of the transformer is open circuited, the frequency characteristics and the voltage transformation ratio of the piezoelectric transformer is studied. In the theoretical analysis, the mechanical and dielectric losses in the transformer are not considered and therefore the energy conversion efficiency of the transformer is not studied. In future work, the load characteristics, the power conversion efficiency and the effect of the losses on the electromechanical characteristics of the piezoelectric transformer will be further studied.

5. Summary and conclusions

The ring-type piezoelectric transformer composed of two concentric piezoelectric rings polarized in the thickness and radial direction is studied. Based on the electromechanical equivalent circuit, the resonance/anti-resonance frequency equations are given. The analytical expressions for the voltage gain, the efficiency and the effective electromechanical coupling coefficient are theoretically obtained. The dependency of the electromechanical characteristics on the frequency, the geometrical dimensions and the load electric resistance are analyzed. To sum up the above analysis, the following conclusions can be obtained.

1. The load electric resistance has no obvious effect on the resonance/anti-resonance frequency of the piezoelectric ceramic transformer. When the load electric resistance is increased, the voltage gain and the efficiency are increased, while the effective electromechanical coupling coefficient is decreased.
2. The ring-type piezoelectric ceramic transformer is a kind of typical frequency selective device. At the resonance and anti-resonance frequency, the voltage gain and the efficiency have maximum values. Therefore, the piezoelectric ceramic transformers must be operated near the resonance frequency.
3. The geometrical dimensions have obvious effect on the electromechanical characteristics of the piezoelectric transformers. When the radial thickness ratio is increased, the anti-resonance frequency, the voltage gain and the effective electromechanical coupling coefficient are all increased, while the resonance frequency is decreased.
4. In the present research, the load electric impedance of the transformer is considered and its effect on the electromechanical characteristics is also analyzed. However, the mechanical and dielectric loss in the piezoelectric transformer is ignored. There are two main reasons for this consideration. First, the piezoelectric ceramic material used for the piezoelectric transformers is an equivalent of PZT-4. This kind of piezoelectric material has high mechanical and electrical quality factor, and therefore, the mechanical and dielectric losses are low, especially when the piezoelectric transformer is excited by low electric signal. Second, the mechanical loss and the dielectric losses in the piezoelectric transformer are very difficult to formulate and calculate in analytical method, therefore, it is difficult to determine and give the absolute value. On the other hand, it should be pointed out that when the input electric power and the electric exciting signal of a piezoelectric transformer is high, the mechanical and the dielectric losses will become large and obvious. In this case, the losses cannot be ignored in the analysis of the characteristics of the high power piezoelectric transformers. In the future research, the effect of the losses on the piezoelectric transformer will be further studied.

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