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To cite this article: Yi Xuan *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **470** 012043

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Design and Simulation Technology of Piezoelectric Ultrasonic Transducer with Sandwich Composite Horn

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Abstract. The structural characteristics of piezoelectric ultrasonic transducer with sandwich composite horn are expounded, the vibration characteristics are theoretically analyzed, the velocity distribution equation and stress distribution equation of transducer under longitudinal vibration are obtained, the frequency equation is given, and the piezoelectric ultrasonic transducer with compound amplitude-changing rod is designed. Then the modal analysis and harmonic response analysis of the transducer are carried out by using the finite element simulation software Workbench, comparison between the results obtained and the theoretical values, the error is very small, which meets the need of engineering practice and verifies the correctness of the derivation design.

1. Introduction

An ultrasonic transducer is an energy conversion device that converts alternating electrical signals into acoustic signals or acoustic signals into electrical signals in the range of ultrasonic frequencies[1]. At present, the transducer is mainly divided into two types: magnetostrictive transducer and piezoelectric transducer. Because the electro-acoustic conversion efficiency of piezoelectric transducer is much higher than that of magnetostrictive transducer, piezoelectric transducer is generally used in ultrasonic transducer. In ultrasonic vibration system, the transducer and the amplitude-change rod are usually connected as a whole by bolts, and the length is usually the wavelength of a longitudinal wave. Many scholars at home and abroad have studied this structure[2-4].

In this paper, an analytical method is used to design a transducer with a variable amplitude bar, which can greatly improve the energy transfer efficiency of the transducer and reduce the redundancy of the whole vibration system. Then the design of the transducer is simulated by finite element software to verify the consistency between the design and the simulation results.

2. Piezoelectric ultrasonic transducer with sandwich composite horn

2.1. structural analysis

The structure of the sandwich piezoelectric ultrasonic transducer is shown in Figure 1, including: front cover plate, piezoelectric ceramic, electrode, back cover plate, prestressed bolt and insulating pipe. Piezoelectric ceramic stack consists of a plurality of piezoelectric ceramic wafer mechanical series, with independent positive and negative electrodes. The electrical parallels between ceramic chips are opposite to the polarity of



adjacent ceramic plates. A flange is used to connect the transducer to the external mechanism to meet the needs of practical application of power ultrasound.

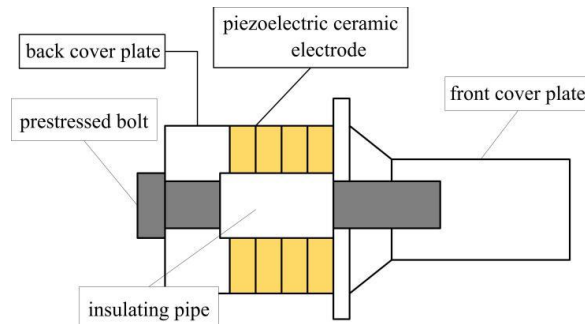


Figure 1. Structure diagram of piezoelectric ultrasonic transducer with sandwich composite horn.

Its main characteristics are [5-6]: (1) Piezoelectric ceramics have great compressive strength, prestressing force is given by prestressed bolt, on the one hand, the stability of transducer can be enhanced when the environmental strength changes; On the other hand, it ensures that the components are in a compression state under the condition of high power drive, thus avoiding the rupture caused by the expansion of the ceramic plate. (2) The number and connection of the piezoelectric ceramic pieces are open to choice. Thus the transducer can be designed in a wide range of impedance and frequency. (3) Changing the material and size of the front and rear metal cover plate can effectively control the performance parameters such as the front and back vibration speed ratio and the effective electromechanical coupling coefficient of the transducer.

2.2. Theoretical analysis

When an object vibrates in an elastic medium, it will cause the vibration of the medium. For all solids, the vibration wave can be regarded as an elastic body. There is an elastic relation between the points of the medium, and the vibration of the object propagates in the elastic medium. It is assumed that there is a uniform thin rod with arbitrary variable cross section and mechanical loss is omitted. When the cross sectional area of the rod is much smaller than the wavelength the plane longitudinal wave propagates along the axis of the rod. As shown in Figure 2, any variable cross-section bar, the axis of symmetry is x , optionally, a small volume element $(x, x + dx)$, the tensile stress acting on it is $\frac{\partial \xi}{\partial x} dx$.

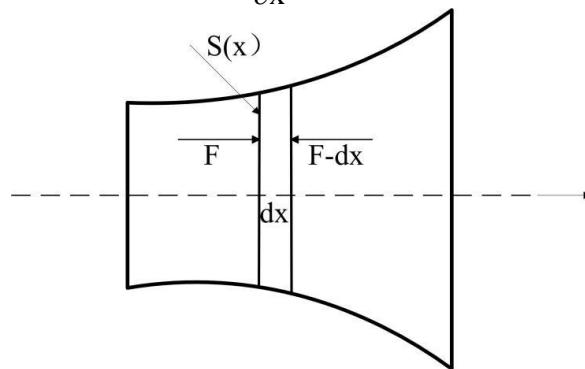


Figure 2. Any variable cross-section bar.

According to Newton's law, the kinetic equation can be obtained:

$$\frac{\partial(S\sigma)}{\partial x} dx = S\rho \frac{\partial^2 \xi}{\partial t^2} dx \quad (1)$$

In the form, S is the cross-sectional area function of the bar, ξ is particle displacement function, σ is stress function, ρ is density of rod material, E is young's modulus.

Under the condition of resonance, the wave equation of longitudinal vibration of the rod with variable cross section can be obtained:

$$\frac{\partial^2 \xi}{\partial x^2} + \frac{1}{S} \times \frac{\partial S}{\partial x} \times \frac{\partial \xi}{\partial x} + k^2 \xi = 0 \quad (2)$$

In the form, k is circular wave number, ω is circular frequency, c is the velocity of the longitudinal wave propagating through the rod.

The vibration velocity equation of the longitudinal vibration of the rod with variable cross section can be obtained by taking the equation (2):

$$\frac{\partial^2 v}{\partial x^2} + \frac{1}{S} \times \frac{\partial S}{\partial x} \times \frac{\partial v}{\partial x} + k^2 v = 0 \quad (3)$$

2.2.1 uniform equal-circle cross-section bar. If the area is uniform and equal, the equation of vibration velocity of a rod with uniform section can be obtained:

$$\frac{\partial^2 v}{\partial x^2} + k^2 v = 0 \quad (4)$$

The general solution of equation (4) is:

$$v(x) = A \sin kx + B \cos kx \quad (5)$$

The elastic force and stress are:

$$F(x) = \frac{ES}{j\omega} \frac{\partial v}{\partial x} = -j\rho c S (A \cos kx - B \sin kx) \quad (6)$$

$$\sigma(x) = \frac{E}{j\omega} \frac{\partial v}{\partial x} = -j\rho c (A \cos kx - B \sin kx) \quad (7)$$

2.2.2 Circular section conical bar. The large end radius of the circular section conical rod is R_1 , the small end radius is R_2 , the length is l , and the expression of the radius and area of the section at any position is as follows:

$$R(x) = R_1(1 - \gamma x) \quad (8)$$

$$S(x) = S_1(1 - \gamma x)^2 \quad (9)$$

$$\gamma = \frac{R_1 - R_2}{R_1 l} \quad (10)$$

Replace equation (9) with equation (3):

$$\frac{\partial^2 v}{\partial x^2} + \frac{2\gamma}{\gamma x - 1} \frac{\partial v}{\partial x} + k^2 v = 0 \quad (11)$$

By solving equation (11), the general solution of vibration velocity of conical rod with circular section is obtained as follows:

$$v(x) = \frac{1}{x - 1/\gamma} (A \sin kx + B \cos kx) \quad (12)$$

The elastic force and stress are:

$$F(x) = -j\rho c S \left\{ A \left[\frac{1}{x - 1/\gamma} \cos kx - \frac{1}{k(x - 1/\gamma)^2} \sin kx \right] - B \left[\frac{1}{x - 1/\gamma} \sin kx + \frac{1}{k(x - 1/\gamma)^2} \cos kx \right] \right\} \quad (13)$$

$$\sigma(x) = -j\rho c \left\{ A \left[\frac{1}{x - 1/\gamma} \cos kx - \frac{1}{k(x - 1/\gamma)^2} \sin kx \right] - B \left[\frac{1}{x - 1/\gamma} \sin kx + \frac{1}{k(x - 1/\gamma)^2} \cos kx \right] \right\} \quad (14)$$

2.3. Dimension Design

The following analysis is made on the sandwich type piezoelectric ultrasonic transducer with compound amplitude change rod. The model is simplified as shown in Figure 3. The 1 is the rear cover plate, the 2 is the piezoelectric ceramic plate, the 3,4,5 is the composite horn, and as the front cover plate, the joint surface is

located on the joint surface of the piezoelectric ceramic stack and the front cover plate. It is assumed that the front surface vibration velocity of the transducer oscillator is v_f and that the rear surface vibration velocity is v_b .

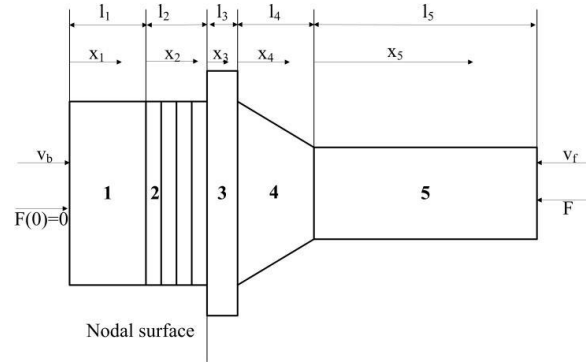


Figure 3. Model schematic diagram of piezoelectric ultrasonic transducer with sandwich composite horn.

The frequency equation on both sides of the nodal plane is derived below. First consider the left part of the nodal plane. The boundary conditions are as follows:

$$\begin{cases} v_2(l_2) = 0 \\ v_2(0) = v_1(l_1) \\ F_2(0) = F_1(l_1) \\ v_1(0) = v_b \\ F_1(0) = 0 \end{cases} \quad (15)$$

Substituting equations (5)(6)(7) gives the frequency equation on the left side of the nodal plane:

$$\tan k_1 l_1 \tan k_2 l_2 = \frac{Z_2}{Z_1} = \frac{\rho_2 c_2 S_2}{\rho_1 c_1 S_1} \quad (16)$$

The right part of the nodal plane with boundary conditions as follows:

$$\begin{cases} v_3(0) = 0 \\ v_3(l_3) = v_4(0) \\ F_3(l_3) = F_4(0) \\ v_4(l_4) = v_5(0) \\ F_4(l_4) = F_5(0) \\ v_5(l_5) = v_f \\ F_5(l_5) = -Z_w v_f = 0 \end{cases} \quad (17)$$

Substituting equations(12)(13)(14) gives the frequency equation on the left side of the nodal plane:

$$\begin{aligned} \frac{Z_5}{Z_4} \tan k_5 l_5 &= \frac{Z_4 k_4 (l_4 - 1/\gamma)}{Z_3 k_4 \cot k_3 l_3 \sin k_4 l_4 - \gamma Z_4 \sin k_4 l_4 + Z_4 k_4 \cos k_4 l_4} \times \\ &\times \left[\left(\frac{Z_3 k_4 \cot k_3 l_3 - \gamma Z_4}{Z_4 k_4} \right) \left(\frac{k_4 (l_4 - 1/\gamma) \cos k_4 l_4 - \sin k_4 l_4}{k_4 (l_4 - 1/\gamma)^2} \right) \right] \\ &\times \left[\frac{k_4 (l_4 - 1/\gamma) \sin k_4 l_4 + \cos k_4 l_4}{k_4 (l_4 - 1/\gamma)^2} \right] \end{aligned} \quad (18)$$

The forward and rear vibration speed ratio of the transducer is deduced below, we can see that the boundary condition at the node is the continuity of elastic force from figure 3:

$$F_2(l_2) = F_3(0) \quad (19)$$

Substituting equation (6)(15)(17):

$$\begin{aligned} \frac{v_f}{v_b} &= \left(Z_3 k_4 \cot k_3 l_3 \sin k_4 l_4 - \gamma Z_4 \sin k_4 l_4 + Z_4 k_4 \cos k_4 l_4 \right) \times \\ &\times \frac{Z_2 \cos k_1 l_1 \sin k_3 l_3}{\gamma Z_3 Z_4 k_4 \sin k_2 l_2 (l_4 - 1/\gamma) \cos k_5 l_5} \end{aligned} \quad (20)$$

Figure 3 shows the dimensions of the sandwich composite horn piezoelectric ultrasonic transducer, as shown in Table 1. The diameter of the large end of the conical segment of the front cover plate is 50 mm, and the diameter of the small end is 20 mm. In the table, the length of the front cover plate is calculated by equation (16) (18) except the length of the back cover plate 1 and the length of the front cover plate cylinder 5. The other dimensions are all given dimensions. Table 2 is a list of material parameters.

Table 1. Dimensions of ultrasonic transducer parts

Component		Parameter			
		External diameter /mm	Bore size /mm	Length /mm	Material
Back cover plate		50	18	16.5	Steel
Piezoelectric Ceramic chip		50	20	6.0	PZT-8
Electrode sheet		50	20	0.2	Brass
Front cover plate	Flange plate	65	18	5.0	TC4
	Conical segment			16.5	TC4
	Cylindrical segment	20		46.5	TC4

Table 2. Material parameter table

Material	Parameter			
	Elastic modulus /Gpa	Density /kg*m-3	Poisson ratio	Acoustic velocity /m*s-1
Steel	209	7800	0.28	5150
PZT-8	65	7600	0.31	2950
TC4	110	4430	0.33	5000

3. Numerical simulation analysis of piezoelectric ultrasonic transducer with sandwich composite horn

3.1. The establishment of finite element model

According to the design experience, the overall structure of the transducer is often simplified to a certain extent in the analysis process, and the influence of bolts and electrodes is ignored in this analysis, that is, the front cover plate of the transducer when modeling. Both the back cover plate and the piezoelectric ceramic plate are considered as solid bodies, and the parallel connection of piezoelectric elements in the circuit is not considered. The finite element analysis of the designed transducer is carried out by workbench. After a series of preprocessing, such as simplification of transducer model and definition of performance parameters, the model was meshed and the finite element model was established. The finite element model of the transducer is shown in Figure 4.

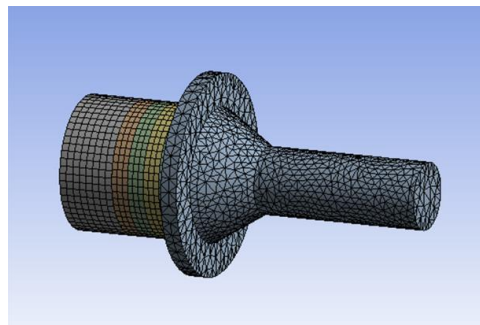


Figure 4. Finite element model of transducer.

3.2. Modal analysis technique

In modal analysis of the transducer, the positive and negative electrodes are briefly connected to obtain the resonant frequency of the transducer, that is, all the nodes on the surface of the piezoelectric plate are coupled

with the voltage degree of freedom and the coupling voltage. In addition, the displacement constraint of the degree of freedom is applied on the nodal surface of the transducer. In modal analysis, a direct solver controlled by program is used. The order of solution is 10 and the frequency of solution is 15-25 kHz. The natural frequency and vibration mode are shown in Table 3.

Table 3. Natural frequency and vibration mode of transducer

Order	Natural frequency	Mode of vibration
1	18394	winding
2	18399	winding
3	19695	direction
4	20482	winding
5	23384	winding
6	23434	winding

It can be seen from Table 3 that the natural frequency and mode shape of the third mode meet the requirements of the design. The first to sixth order modal analysis clouds are shown in Figure 5.

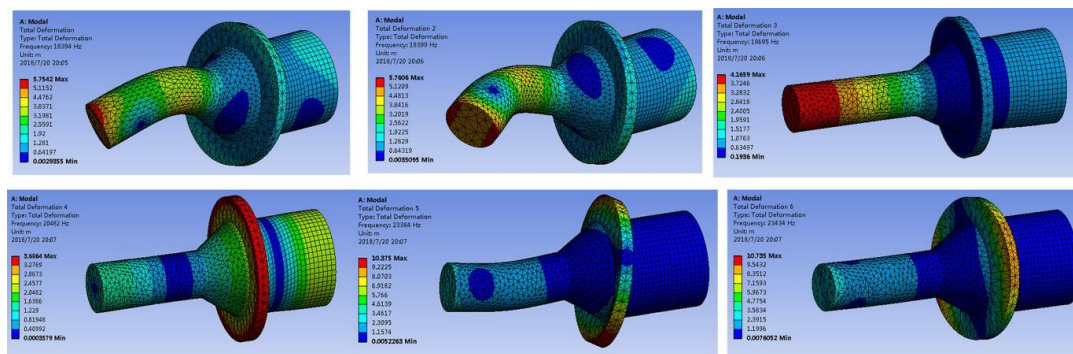


Figure 5. First to sixth order Modal Analysis of Transducers

Table 3 and figure 5 show that the frequency of longitudinal vibration of the transducer is 19695 Hz, which is close to its theoretical design value 20000Hz, and its error is about 1.52%. This shows that the theoretical design of the transducer holds true.

3.3. Harmonic response analysis technique

In the case of external excitation, harmonic response analysis is a method to determine whether resonance can occur in the frequency range of a mechanism. The harmonic response of the designed transducer is analyzed, and the voltage applied on the electrode is the load of harmonic response analysis. A sinusoidal alternating voltage is applied to the piezoelectric ceramic stack, a 0 V voltage is applied to the negative electrode and a 100 V alternating voltage is applied to the positive electrode. According to this excitation method, the front end amplitude of the front cover plate of the transducer varies with the frequency, as shown in Figure 6.

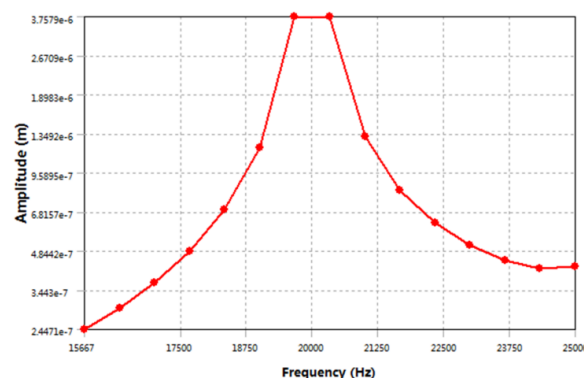


Figure 6. Harmonic response analysis curve of transducer

From Figure 6, it can be seen that when the frequency is 20333Hz, the center node displacement of front end of front cover plate of the transducer is the largest, and the amplitude of longitudinal vibration can reach about 4 micron, which has met the requirement of the required amplitude for ultrasonic vibration application. At the same time, in the safe range of excitation voltage, according to the different process requirements, without replacing the transducer, the value of the transducer excitation voltage can be adjusted by the ultrasonic power supply, and the amplitude of the front face of the front cover plate of the transducer can be finally adjusted.

4. Conclusion

Using the boundary condition analysis method, the vibration characteristics of the sandwich-type composite horn piezoelectric ultrasonic transducer are theoretically analyzed, and the vibration velocity distribution equation, stress distribution equation and resonance frequency equation of the transducer are obtained. The size parameters of the transducer are solved, which solves the problem of the design of the piezoelectric horn transducer of the composite horn.

The finite element simulation software Workbench is used to analyze the harmonic response of the theoretically designed transducer. The results show that the natural frequency of the longitudinal vibration of the transducer is within 2% of the theoretical value, which verifies the theory. The correctness. Subsequent processing will be performed to produce the actual transducer, further verifying the correctness of the theoretical design.

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