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Performance Analysis and Prospect of Piezoelectric Ultrasonic Transducers Based on Vibration Modes

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Abstract: With the maturity of ultrasonic transducer technology, as a traditional ultrasonic transducer, piezoelectric ultrasonic transducer has leaped into the public view. This article briefly summarizes the development of ultrasonic transducers and the classification of piezoelectric ultrasonic transducers. In practical applications, different piezoelectric ultrasonic transducers are mostly selected based on the different sound source vibrations in the application scenarios. The principle analysis and structure introduction of longitudinal vibration type ultrasonic transducers, longitudinal bending vibration mode conversion type ultrasonic transducers, and torsional vibration piezoelectric ceramic ultrasonic transducers are conducted respectively, and the application fields are pointed out. Besides, heat dissipation is an important link that affects the energy transfer efficiency of piezoelectric ultrasonic transducers. For traditional air-cooled heat dissipation and phase change heat dissipation, the heat dissipation ability is investigated and analyzed separately, and the advantages and disadvantages of the two are compared. It is concluded that phase change heat dissipation can effectively solve the impact caused by excessive temperature difference inside the transducer, while traditional heat dissipation methods cannot solve this problem.

Keywords: Piezoelectric ultrasonic transducers, Longitudinal vibration, Torsional vibration, Bending vibration, Heat dissipation characteristics.

1. Introduction

The flexibility and suitability of sound transmission bring natural advantages to the long-distance detection of ocean and rail, and the piezoelectric ultrasonic transducer is now widely used. Due to the different vibration forms required in different situations, various types of piezoelectric ultrasonic transducers have been developed, among which the longitudinal vibration ultrasonic transducer is the most mature. Taking the long-distance rail detection as an example, when cracks appear in the rail connection, the mechanical energy generated by the sound vibration is converted into electrical signal by the ultrasonic transducer and sent to the terminal, which is received by the staff for inspection. This method greatly reduces human resources and overhaul time, and can detect track problems in time. It is an efficient and feasible detection method. However, there are still some problems in this field, such as low heat dissipation efficiency and low energy transfer efficiency of coupled ultrasonic transducer. This review will introduce three typical ultrasonic transducers based on different vibration modes, analyze their heat dissipation characteristics, and summarize and prospects.

2. The Proposal of Ultrasonic Transducer

Ultrasonic transducers have the ability to convert acoustic and electrical energy into each other, and are an indispensable part of the ultrasonic field.

Material is an important factor affecting the transformation and development of ultrasonic transducers, which limits the strength, power capacity, and stability of transducers, causing the ups and downs of different types of transducers. The earliest ultrasonic transducer was a sandwich type ultrasonic transducer proposed by P. Langevin for underwater exploration in 1917. It was composed of quartz crystals as piezoelectric materials and two steel plates clamped on both sides[1].Subsequently, in 1933, the laminated magnetostrictive transducer, due to its superior properties in various aspects, replaced the craze of Langevin transducers. In the 1950s, due to the successful development of electrostrictive materials, piezoelectric ceramics, and other materials, Langevin transducers rose again and still occupy an important position.

3. Classification of Piezoelectric Ultrasonic Transducers

Piezoelectric ceramic ultrasonic transducers can be classified according to their shape, vibration mode, and energy conversion form. If classified by component shape, it can be divided into thin plate shape, circular sheet shape, circular ring shape, circular tube shape, circular rod shape, thin shell spherical shape, piezoelectric thin film, etc[1], Vibration modes can be divided into telescoping vibration, bending vibration, torsional vibration, and composite vibration formed by coupling three basic vibrations in pairs, In the terms of energy conversion, emission type refers to electrical acoustic conversion type ultrasonic transducer, reception type refers to acoustic electrical conversion type ultrasonic transducer, and emission reception composite type ultrasonic transducer. In different situations, the vibration mode is an important way to distinguish the applicable fields of different types of ultrasonic transducers. Therefore, this article focuses on using the vibration mode as a classification standard to introduce three types of piezoelectric ultrasonic transducers: telescopic vibration, bending vibration, and torsional vibration.

Telescopic vibration is divided into radial, longitudinal, and tangential vibrations. This article will mainly introduce the most common longitudinal vibration type ultrasonic transducers.

Bending vibration is usually applied in combination with longitudinal vibration. This article will focus on the design theory and vibration mechanism of longitudinal and bending mode conversion ultrasonic transducers.

Torsional vibration will focus on the Langevin type, which is a sandwich type ultrasonic transducer. Compared to telescoping vibration transducers, the research theory of piezoelectric torsional vibration transducers still needs further development and improvement.

3.1. Longitudinal vibration sandwich piezoelectric ultrasonic transducer

The longitudinal vibration sandwich piezoelectric ultrasonic transducer, also known as the Langevin composite transducer, is composed of a front cover plate, a rear cover plate, a piezoelectric ceramic stack, metal electrodes, and prestressed bolts, as shown in Figure 1. Traditional design theories limit its ability to vibrate in one dimension only in the longitudinal direction, and its radial dimension needs to be smaller than its longitudinal dimension[2]. Due to its high power and efficiency, longitudinal vibration sandwich piezoelectric ultrasonic transducers are often used in high-power ultrasonic fields, such as long-distance rail inspection, ultrasonic welding, or underwater sound transmission

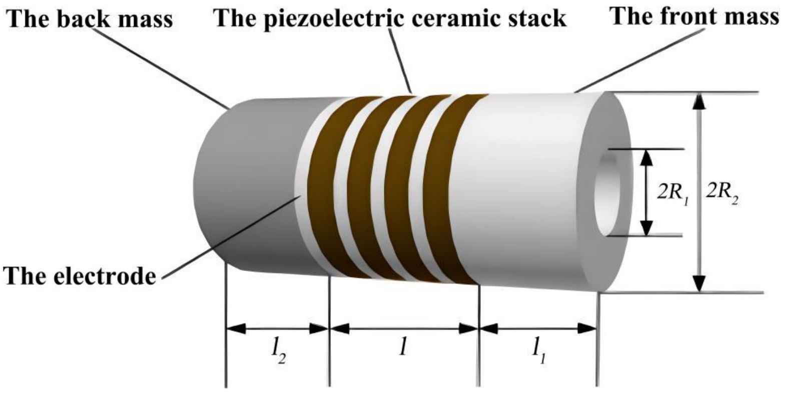

Figure 1. Simplified structure diagram pf a sandwich piezoelectric ultrasonic transducer

3.2. Longitudinal and bending vibration mode conversion ultrasonic transducer

Composite vibration ultrasonic transducers have a wider range of applications, and bending vibration ultrasonic transducers have been widely used due to their small size, easy to change the direction of energy transmission, and strong load capacity，such as ultrasonic welding, ultrasonic scalpel, ultrasonic vibration turning, and ultrasonic motor[3]. The longitudinal and bending vibration mode conversion ultrasonic transducer is a composite bending vibration transducer composed of a sandwich longitudinal vibration transducer and a bending vibration thin disk. As shown in Figure 2, the longitudinal vibration transducer and the disk are linked by a horn, which gathers energy and better couples acoustics and machinery, greatly enhancing the efficiency of vibration energy conversion.

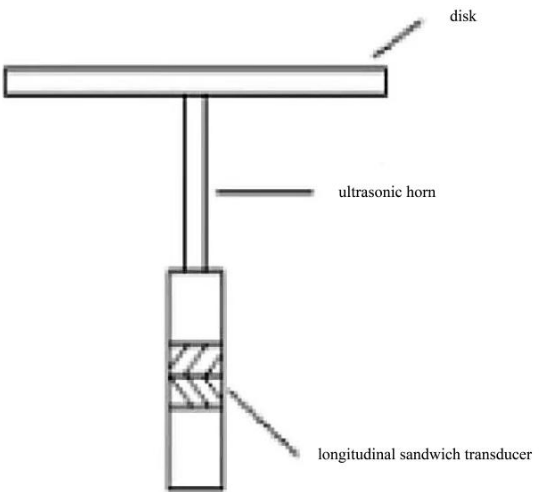

Figure 2. Structure of a longitudinal and bending vibration mode conversion ultrasonic transducer.

3.3. Torsional vibration piezoelectric ceramic ultrasonic transducer

The torsional vibration piezoelectric ceramic ultrasonic transducer is often used in rotary devices such as ultrasonic motors. It is a tangentially polarized piezoelectric torsional transducer with electrodes attached to the top and bottom[4]. Figure 3 is a simplified diagram of a torsional vibration ultrasonic transducer. An excitation electric field is applied in the polarization direction, that is, in the tangential direction. Under the excitation of the applied electric field, the transducer generates torsional vibration to achieve the purpose of mutual conversion of mechanical and electrical energy.

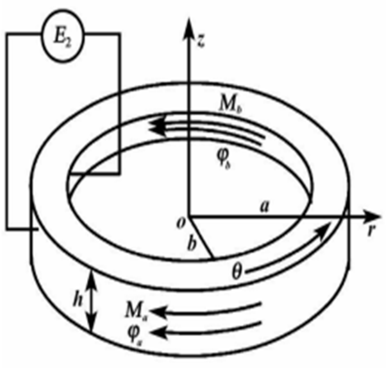

Figure 3. Schematic diagram of a torsional vibration piezoelectric ceramic ultrasonic transducer.

4. Heat Dissipation Characteristics of Piezoelectric Ceramic Ultrasonic Transducers

Temperature is an important factor that causes the stability of ultrasonic transducers to decrease. As an insulating material, piezoelectric ceramic materials have poor thermal conductivity. High temperatures can cause changes in the input impedance, capacitance, and other electromechanical parameters of the transducer, resulting in frequency drift and mistermination, and lead to a serious decline in the electromechanical conversion efficiency of the transducer. Moreover, long periods of high temperatures can even cause depolarization of piezoelectric ceramic ceramics. Therefore, heat dissipation of piezoelectric ceramic ultrasonic transducers is an important part of maintaining their stable operation. Heat dissipation can be divided into water cooling, air cooling, and phase change heat dissipation. This review will focus on the most mature longitudinal vibration piezoelectric ceramic ultrasonic transducers, introducing and comparing them in both forced air cooling and heat pipe cooling.

4.1. Air cooled heat dissipation - flange fin

Air cooling is also known as gas cooling. Document[5]introduces a simulation example of air cooling. Firstly, under forced convection conditions, simulation is conducted for lateral and axial wind respectively. Taking the same wind speed of 8 m/s and ambient temperature of 20 °C, the distribution diagram shown in Figure 4 and Figure 5 can be obtained. The analysis shows that the average wind speed in the lateral wind field is higher than that in the axial wind field, making it easier to achieve the cooling effect; In addition, when using lateral wind, the maximum temperature and average temperature are lower than those of axial wind. When using axial wind, the average temperature of the transducer is 89 °C, while when using lateral wind, the average temperature of the transducer is 80 °C, which shows that lateral wind has more advantages for heat dissipation[5].

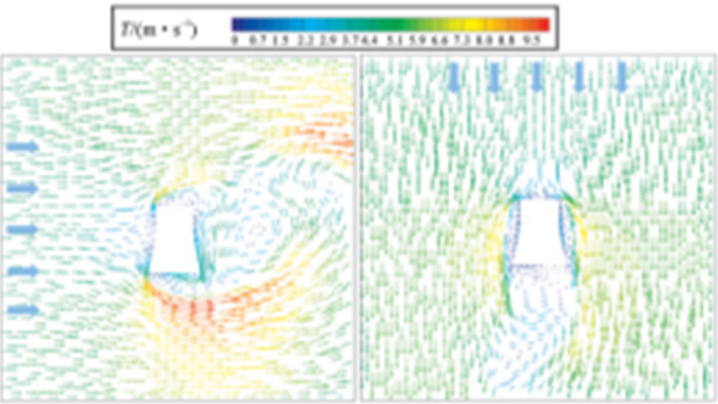

Figure 4. Simulation of flow distribution under different blowing directions.

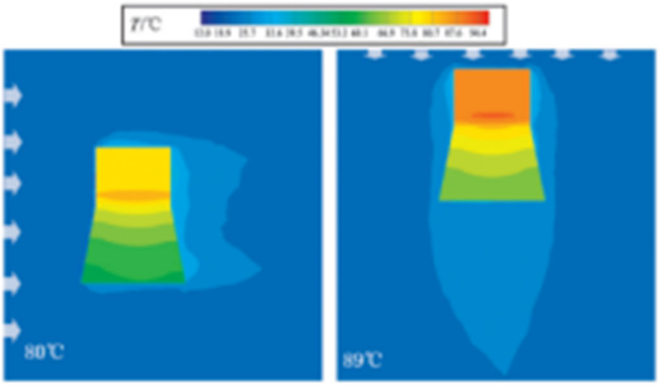

Figure 5. Simulation of temperature distribution under different blowing directions.

For forced convection heat dissipation methods with different wind speeds, their heat dissipation efficiency and average heat dissipation temperature also differ. Under the same conditions, take a wind speed of 2m/s-15m/s for simulation respectively, as shown in Figure 6, it is obvious that the average temperature of the piezoelectric sheet decreases with the increase of wind speed, and it can be observed that regardless of axial or lateral wind, the slope of the curve decreases with the increase of speed. Therefore, the greater the wind speed, the smaller the impact on heat dissipation. Combining heat dissipation efficiency and energy conservation concepts, it is appropriate to choose a wind speed range of 5 to 8 m/s[5].

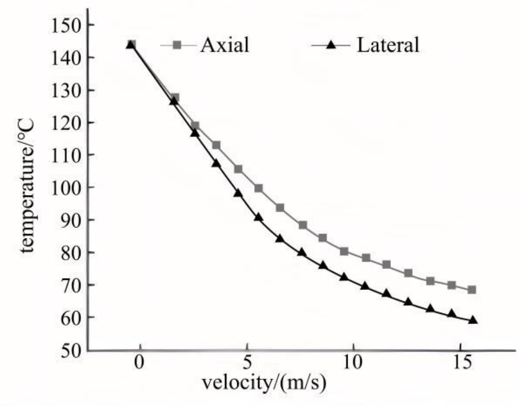

Figure 6. Effect of wind speed on the average temperature of piezoelectric sheets

Increasing the heat dissipation area of a transducer is another way to increase heat dissipation efficiency. Under the above-mentioned wind speed conditions, add a flange and fin to the ultrasonic transducer, as shown in Figure 7. Select a brass plate with a thickness of 2 mm and an outer diameter of 80 mm as the flange material, a height of 20 mm and a width of 16 mm as the heat sink, and weld the heat sink to the flange, select a suitable location, and adopt the design method of centering the nodal plane, that is, the piezoelectric ceramic center is the displacement nodal plane, The effect of installing a heat dissipation device at this location on the vibration characteristics of the transducer can be negligible. Under the same conditions, from Figure 8, it can be seen that the gas cooling method of installing flange fins can reduce the operating temperature by about 42% (from 134 ℃ to 78 ℃) , which can effectively increase the heat transfer efficiency of the transducer.

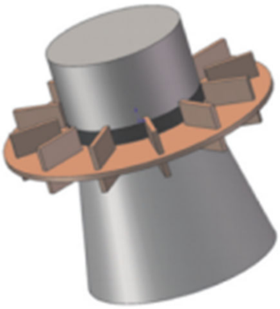

Figure 7. Finned transducer

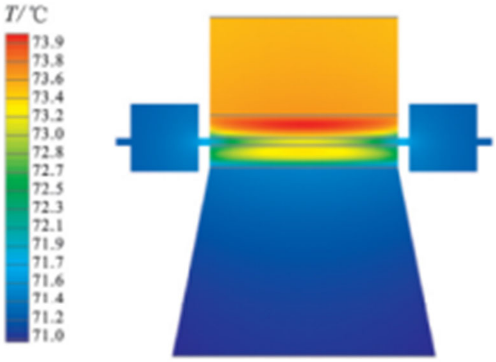

Figure 8. Temperature distribution of finned transducers

To sum up, in the wind speed range of 5-8m/s, installing flange fins in the middle of piezoelectric ceramics and using lateral wind for forced air cooling can greatly alleviate the impact of temperature issues on the ultrasonic transducers.

4.2. Phase change heat dissipation - heat pipe

Traditional heat dissipation methods, such as wind cooling, water cooling, and semiconductor heat dissipation, still cannot solve the problem of excessive temperature difference inside the transducer and that inside and outside the piezoelectric ceramic chip. However, the heat pipe heat dissipation method can effectively solve the above problems by utilizing the high-density heat dissipation characteristics of the heat pipe to quickly and stably derive heat from the interior of the transducer.

The basic working idea of a heat pipe is to achieve rapid heat transfer through the absorption or release of heat through the phase change of the working liquid in the pipe. The heat pipe mainly consists of a tube shell, an end cover, and a heat absorbing core, and can be divided into three sections: a heat absorbing section, a condensing section, and an adiabatic section. The working liquid vaporizes or re condenses at the heat absorbing section and the condensing section, that is, releases or absorbs heat, while the adiabatic section plays a role in transferring heat. Generally, the working liquid is filled and sealed in the heat absorbing core. One section of the heat pipe is heated (the heat absorbing section). The working liquid in the heat absorbing core inside the pipe vaporizes and evaporates under negative pressure, and under the effect of pressure difference, it passes through the insulation section and flows to another section (the condensing section). In this process, the gas releases heat again and condenses back into a liquid state, which is refluxed to the heat absorption section by capillary force, forming a closed cycle that can stably and efficiently achieve heat transfer. Reference[6]introduces simulation of typical heat pipe cooling technologies. Thermal imaging was performed on ultrasonic transducers with no load of 20 W, 30 W, and 40 W, respectively, and a working time of 10 minutes. Temperature measurements were arranged in both axial and radial dimensions for comparative analysis. As can be seen from Figure 9, under the same power condition, the axial temperature of the ultrasonic transducer without heat pipe heat dissipation reaches the highest temperature at the center position. Under the same power condition, the ultrasonic transducer with heat pipe heat dissipation reaches the lowest temperature at the center, and its temperature fluctuation is smaller than that of the transducer without heat pipe, which verifies the feasibility and advantages of heat pipe heat dissipation[6].

On the other hand, according to the analysis in Figure 10, under the same power condition, the radial temperature distribution of the ultrasonic transducer with heat pipe heat dissipation is lower and more uniform than that of the ultrasonic transducer without heat pipe heat dissipation, further verifying that the heat pipe effectively reduces the operating temperature of the ultrasonic transducer. In addition, the highest temperature point of the ultrasonic transducer with heat pipe heat dissipation tends to move towards the edge, which shows that the heat pipe can effectively transfer heat and prevent adverse effects caused by excessive internal temperature.

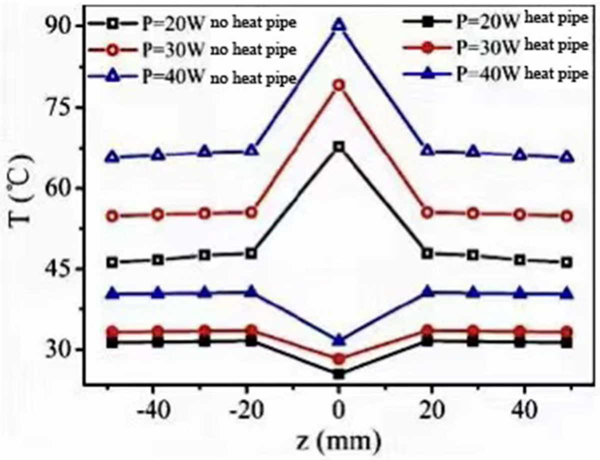

Figure 9. Axial temperature distribution field of heat pipe transducer and non-radiating transducer

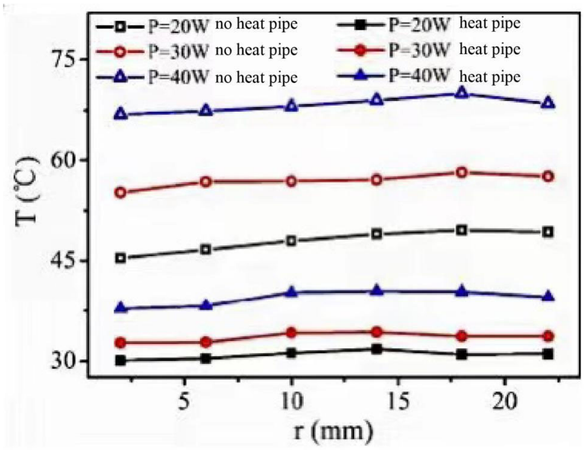

Figure 10. Radial temperature distribution field of heat pipe transducer and non-radiating transducer

5. Conclusion

Piezoelectric ceramic ultrasonic transducer derives traditional piezoelectric ultrasonic transducer based on longitudinal, torsional and bending vibration in three-dimensional plane and several vibration-coupled ultrasonic transducers due to different vibration requirements in application. However, although the former technology is relatively mature, the application of single ultrasonic transducer is too limited and it is difficult to make achievements for situations with diverse vibration requirements. Although the latter can adapt to many vibration situations, its output efficiency is low and the technology is not mature enough. Therefore, improving the efficiency of the vibration-coupled ultrasonic transducer and producing the ultrasonic transducer with good adaptability in the situation of high vibration demand are the future development direction.In terms of improving efficiency, the heat dissipation characteristics of transducer are also worth improving. Compared with traditional heat dissipation methods, such as air cooling and water cooling, the emergence of new heat pipe heat dissipation is the trend.

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