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Optimization on ultrasonic plastic welding systems based on two-dimensional phononic crystal

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ABSTRACT

Large-sized tools are needed for plastic welding of large objects. However, the displacement distribution at the radiation surface of the tools is not uniform due to the strong lateral vibration. In this paper, two-dimensional (2D) phononic crystal (PnC) is introduced by processing periodically arranged grooves in large-sized tools. This method is different from the traditional experience-based grooving method. The lateral vibration is suppressed due to the characteristic of PnC. In this paper, six kinds of ultrasonic plastic welding systems based on 2D PnC with different groove width and height are designed. The vibration characteristics of ultrasonic plastic welding systems were simulated and experimented. The band gaps of large-sized tools are analyzed. The results show that the lateral vibration is suppressed when the operating frequency of the ultrasonic plastic welding system is within the band gap of the large tool. The displacement distribution at the radiation surface of the tools is more uniform. A theoretical support is provided for the design of large-sized ultrasonic plastic welding systems.

1. Introduction

The great majority kinds of thermoplastic plastics are welded in less than 1 s by the ultrasonic plastic welding system which has the advantages of fast, efficient and economical [1–3]. It has been extensively used in automobile, medical, pharmaceutical and other industries. At the working frequency, the tool of ultrasonic plastic welding system should be in longitudinal vibration mode, and its output radiation surface should have uniform longitudinal vibration displacement distribution [4]. In the welding process of large objects, the ultrasonic plastic welding system is required to export large ultrasonic power. Therefore, large-sized tool with lateral dimensions greater than 1/4 of the wavelength is required. In the condition of operative mode, the distribution of the displacement at the radiation surface of large-sized tool is uneven due to the strong coupling between the longitudinal and lateral vibration [5,6]. In order to make the longitudinal displacement distribution at the radiation surface of the tools uniform, adopting a vibration control method to eliminate the influence of lateral vibration is necessary. For instance, the vibration of tool is controlled by grooving, adding additional elastomer and other methods, to achieve the requirement that the radiation surface of the tool is similar to the motion of the piston.

It is difficult to obtain a rigorous analytical solution for large-sized grooved tool because of its complex shape. Therefore, the numerical methods such as the finite element method (FEM) are generally used. However, it is based on experience for the most part. Although, as mentioned earlier, the grooving of the tool can be designed using FEM, it would be desirable to find a theory to supported this behavior.

Recently, Ronda et al. proposed the application of the principles behind phononic materials to attenuate or even stop the lateral resonances, producing in this way a piezoceramic resonator adequate for operation in the thickness mode with an in-phase vibration surface [7,8]. The concept of PnC was proposed by Kushwah et al. for the first time in the research of Ni/Al two-dimensional solid periodic composite media [9]. PnC is a kind of functional material with periodic structure [10,11]. It has the characteristic of frequency bandgaps [12,13]. The generation reason of bandgaps is that, waves of some frequency cannot be propagated due to the influence of the periodic arrangement structure of the material with the process of elastic waves passing through PnC [14–16]. The unique bandgap vibration characteristics of PnC enable its vibration in the bandgap to be prohibited or suppressed [17,18]. This characteristic makes it widely used in the field of vibration suppression [19,20]. For instance, Lu reports the first demonstration of PnC in suspended lithium niobate thin films, which exhibit band gaps for tailoring the performance of laterally vibrating devices [21]. Wen et al. applied PnC to straight beam structures to suppress bending vibration [22]. Aragón et al. used PnC to suppress lateral vibration in resonators [7,8].

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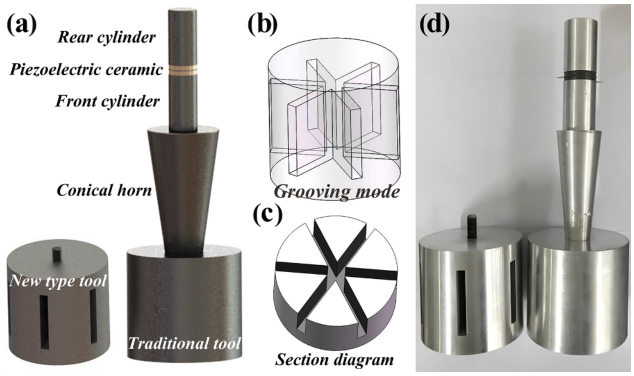

Fig. 1. The traditional ultrasonic plastic welding systems and the new type tool. (a) Model schematic diagram. (b) Perspective diagram. (c) cross-sectional drawing. (d) physical picture.

Here, a new type of large-sized ultrasonic plastic welding system is designed based on the theory which the elastic waves can be suppressed in the bandgap range of 2D PnC. 2D PnC is formed by processing periodically arranged grooves on large-sized tools. Because periodic grooves are formed along the radial direction, the radial wave cannot propagate. So that the longitudinal vibration displacement distribution at the radiation surface of the tools is effectively improved due to suppressing the lateral vibration. Six different structures of tools were simulated and compared. It is concluded that the band gap analysis of PnC can help us design the grooving mode and size of large-sized tools.

2. Materials and methods

The large-sized ultrasonic plastic welding system consists of a sandwich piezoelectric transducer, a conical horn and a large-sized cylindrical tool. A new type tool is presented in this paper. The traditional ultrasonic plastic welding system and the new type tool are shown in Fig. 1 which Fig. 1(a) is the schematic diagram and the Fig. 1(d) is the physical picture. In this research, six models are established. For convenience of comparison, the sandwich transducer and the conical horn are the same for six models. Aluminum is used for the front and rear metal cylinders of sandwich transducer, conical horn and tool. The material of piezoelectric ceramic is PZT-4. The front and rear metal cylinders of sandwich transducer are equal cross-section cylinders with diameter of 39 mm and height of 58 mm. The number of piezoelectric ceramic crystals is 2 with the height, inner diameter and outer diameter of 5, 20 and 38 mm, respectively. The upper surface diameter, the lower surface diameter and the height of the conical horn are 54, 30 and 128 mm, respectively. The tool in model 1 is a groove-free tool with a diameter of 120 mm and a height of 110 mm. Tools of models 2, 3, 4, 5 and 6 are grooved, and the way of grooving are shown in the illustrations in Fig. 1(b) and (c) which are perspective and cross-sectional drawing of new tools, respectively. Tools in model 2, 3, 4, 5 and 6 are the same size as those in model 1, but with grooves on them. Groove widths of model 2, 3 and 4 are 8, 10 and 12 mm, respectively, with the heights of 70 mm. Groove heights of model 5 and 6 are 60 and 80 mm with the widths of 10 mm.

These models were studied numerically and experimentally. For numerical study, the piezoelectric device module and solid mechanics module are used to calculate the vibration modes of ultrasonic plastic welding system and the band gap of the tool, respectively, using the material properties of Aluminum 6063-T83 and PZT-4 included in COMSOL library.

Wayne Kerr's 6500B precision impedance analyzer was used to measure the impedance and the out-of-plane mechanical amplitude was recorded by laser vibration measurement. The instrument for vibration measurement experiment is Polytec's PSV-400 full-field scanning laser vibrometer.

3. Results and discussion

In this paper, a new type of large-sized ultrasonic plastic welding system is designed, which utilizes the characteristics of PnC to suppress lateral vibration. The PnC prohibits or suppresses the propagation of elastic waves in the bandgap range. The ultrasonic plastic welding system has a fixed working frequency, that is, its resonance frequency. Therefore, it is necessary to design the working frequency within the bandgap range of the tool in order to restrain the lateral vibration of large-sized tools. Generally, the plane wave expansion method is used to calculate the band gap of ideal PnC. In practical applications, PnC are all finite periodic structures. The research group of Wen, National Defense University of Science and Technology has calculated the vibration band gaps of ideal 2D PnC by the plane wave expansion method and the vibration transmission characteristics of Finite-Period 2D PnC with the same parameters by FEM [22]. The vibration band gaps obtained by the FEM and the plane wave expansion method are basically the same. Considering that the finite period structure is adopted in this study, the finite element software COMSOLMultiphysics®5.3a is used to analyze the vibration transmission characteristic curve of the tools.

3.1. FEM modelling

The resonant frequency of ultrasonic plastic welding system is affected by grooving. In order to analyze the change of resonance frequency before and after grooving, the piezoelectric device module of COMSOL Multiphysics is used to build models 1 and 3. The resonance frequency of ultrasonic plastic welding system is calculated, and its modal diagram is shown in Fig. 2.

The resonance frequencies of model 1 and model 3 are 20,370 Hz and 20,469 Hz. Using the same method, the resonance frequencies of model 2, 4, 5 and 6 are calculated, which are 20,903 Hz, 19,956 Hz, 20,445 Hz and 20,667 Hz, respectively, as shown in Fig. 3. The

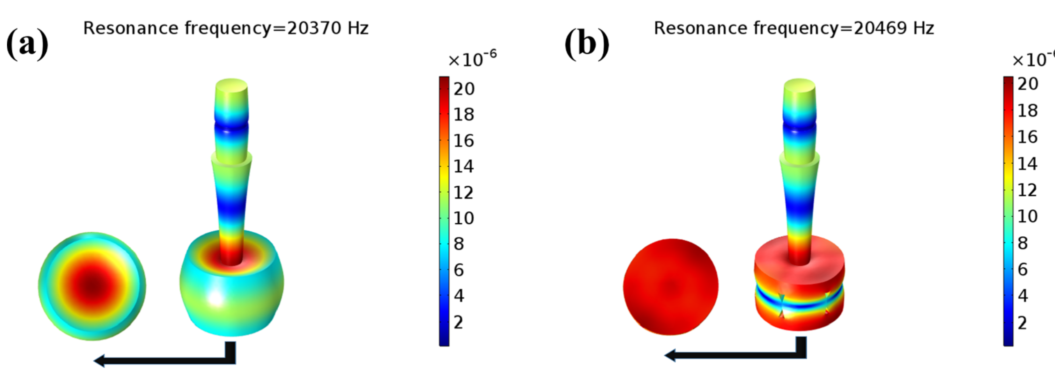

Fig. 2. Vibration modes of ultrasonic plastic welding system. (a) Model 1. (b) Model 3.

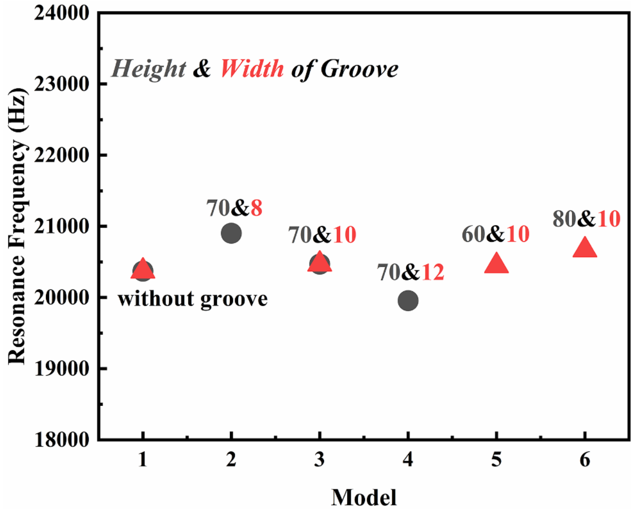

Fig. 3. Resonance frequency of ultrasonic plastic welding system.

resonance frequencies of the six models are all around 20 kHz. Therefore, the band gap of the tool near 20 kHz is selectively analyzed. Because periodic grooves are formed along the radial direction, when the operating frequency of the ultrasonic plastic welding system is in the band gap of the tool, the radial wave propagation is suppressed due to unique vibration band gap characteristics of PnC. Compared with Fig. 2(a) and (b), it is obvious that the lateral vibration of tool has been suppressed after grooving, and the radiation surface of the new type tool is similar to the motion of the piston.

Five tools model with grooves mentioned above is established. The acceleration excitation of 1 m/s^2 is added uniformly along the radial direction on a Finite-Period 2D PnC to make the vibration propagate in 2D PnC. The vibration transmission characteristic curve of the Finite-Period 2D PnC can be obtained by calculating the output response. Here, the vibration transmission characteristic curves of tools based on different groove height and width are calculated. The calculation range is 1 to 30 kHz, and the step size is 0.1 kHz. The effect of groove height and width on the bandgap of 2D PnC through comparative analysis is obtained, as shown in Fig. 4, where (a) corresponds to different groove widths, (b) corresponds to different groove heights.

The criterion for determining the band gap range is that the vibration transmission rate is less than 1. The variation of groove height and width has a great influence on the band gap of 2D PnC, as shown in Fig. 4. The bandgap moves to low frequency with the increase of groove width. Similarly, the same rule can be found with the increase of grooving height. There are many band gaps in the frequency range considered according to the definition of bandgap. As mentioned

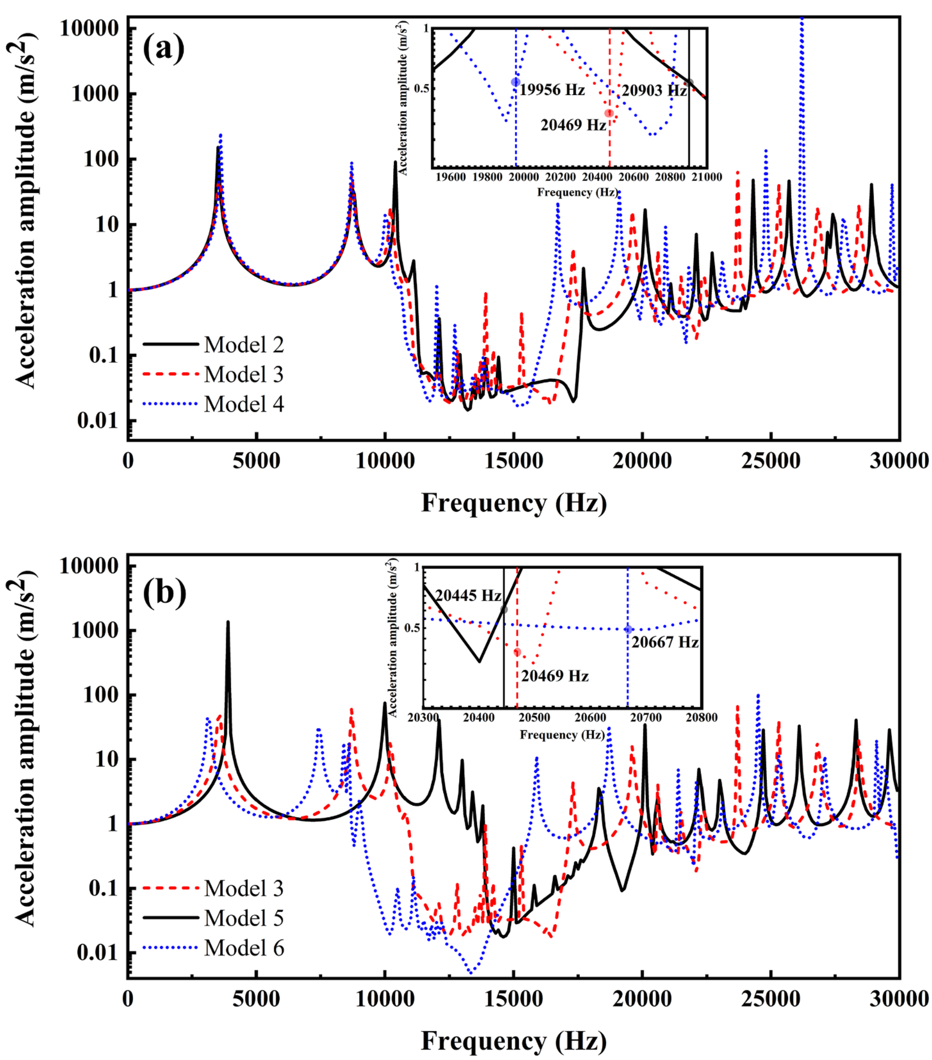

Fig. 4. Vibration transmission characteristic curve of the new type tool. (a) The vibration transmission characteristic of Model 2, 3 and 4. Inset, the band gap near resonance frequency. (b) The vibration transmission characteristic of Model 3, 5 and 6. Inset, the band gap near resonance frequency.

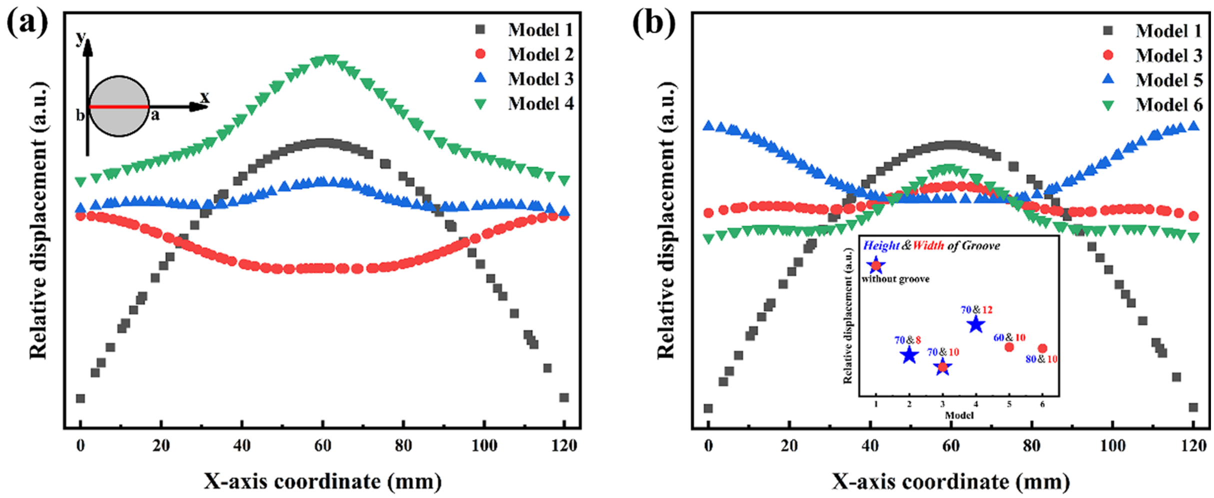

Fig. 5. Longitudinal displacement distribution of radiation surface in ultrasonic plastic welding system. (a) Model 1, 2, 3 and 4. Inset, the schematic diagram of calculation principle for the displacement distribution at the radiation surface of the tools. (b) Model 1, 3, 5 and 6. Inset, the maximum change in relative displacement.

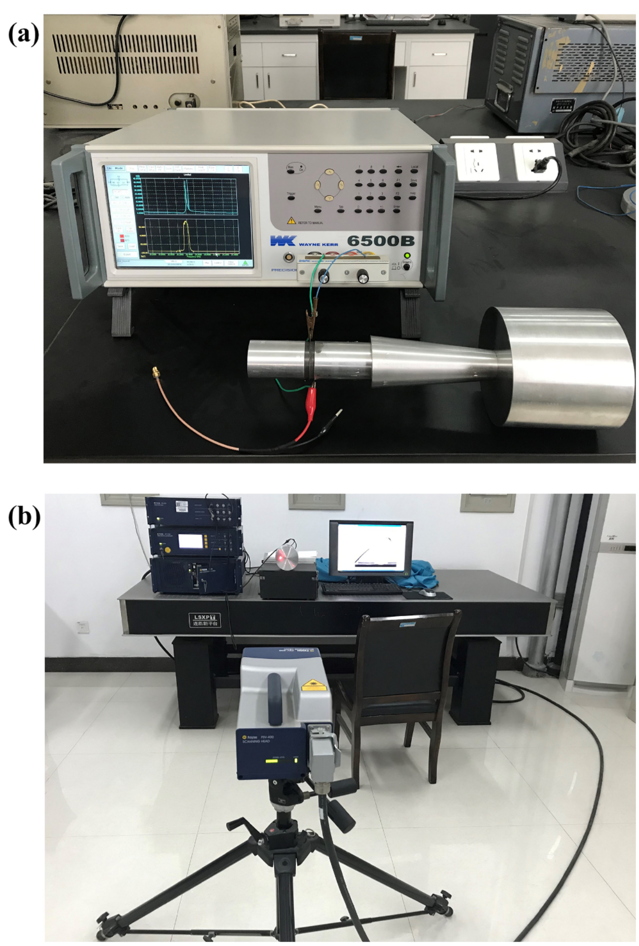

Fig. 6. Experimental setup for measuring the ultrasonic plastic welding system. (a) Precision impedance analyzer. (b) Full-field scanning laser vibrometer.

Table 1
Resonance frequencies of ultrasonic plastic welding system.

f_r (Hz)	f_{er} (Hz)	f_r' (Hz)	f_{er}' (Hz)
20,370	20,284	20,469	20,433

earlier, the bandgap near 20 kHz is selectively analyzed. The attenuation degree is weak because of the small number of cycles. Shown in the inset of Fig. 4(a) and (b) are the position of the resonant frequency on the vibration transfer characteristic curve of the ultrasonic plastic welding system. Both as shown in Fig. 4(a) and (b), model 3 is located at the place with the greatest attenuation.

In order to observe the displacement distribution at the radiation surface of the tools more clearly after calculating the vibration modes, one of the diameters is selected, as shown in Fig. 5(a) inset. The displacement distribution along the diameter on the surface of the large-sized tool is computed with FEM at the working frequency, as shown in Fig. 5, where (a) corresponds to different groove widths, (b) corresponds to different groove heights. The difference between the maximum and minimum relative displacements of all models is calculated, as shown in Fig. 5(b) inset.

As can be seen from Fig. 5, the displacement distribution at the radiation surface of the tools after grooving is more uniform than that without grooving due to the formation of 2D PnC. Although the attenuation of bandgap is weak, it is still effective for suppressing lateral vibration. It can be seen from Fig. 4 that the working frequency of model 3 is located at the largest attenuation of band gap, so that the displacement distribution is the most uniform. It is found that the more the vibration attenuation is at the resonance frequency, the more uniform the displacement will be. However, the suppression effect of model 4 is poor because the width of grooving is too large, the longitudinal vibration is coupled with other vibration modes. Therefore, these situations should be avoided when designing new type tools.

The difference between the maximum and the minimum relative displacements of Model 3 is the smallest, because the operating frequency is situated at the maximum of bandgap attenuation, as shown in the inset of Fig. 5(b). The results show that PnC can effectively suppress lateral vibration. When the operating frequency is within the bandgap range, the propagation of elastic wave in this direction is restrained, thus the lateral vibration of the tool is suppressed. Meanwhile, the improved uniformity of displacement distribution is related to the attenuation of vibration transmission curve corresponding to the resonance frequency of the tools.

3.2. Experimental results

Subsequently, experiments were carried out to further demonstrate the suppressing of lateral vibration of the new type tool. The materials of model 1 and 3 are hard aluminums and PZT-4. The metal front and

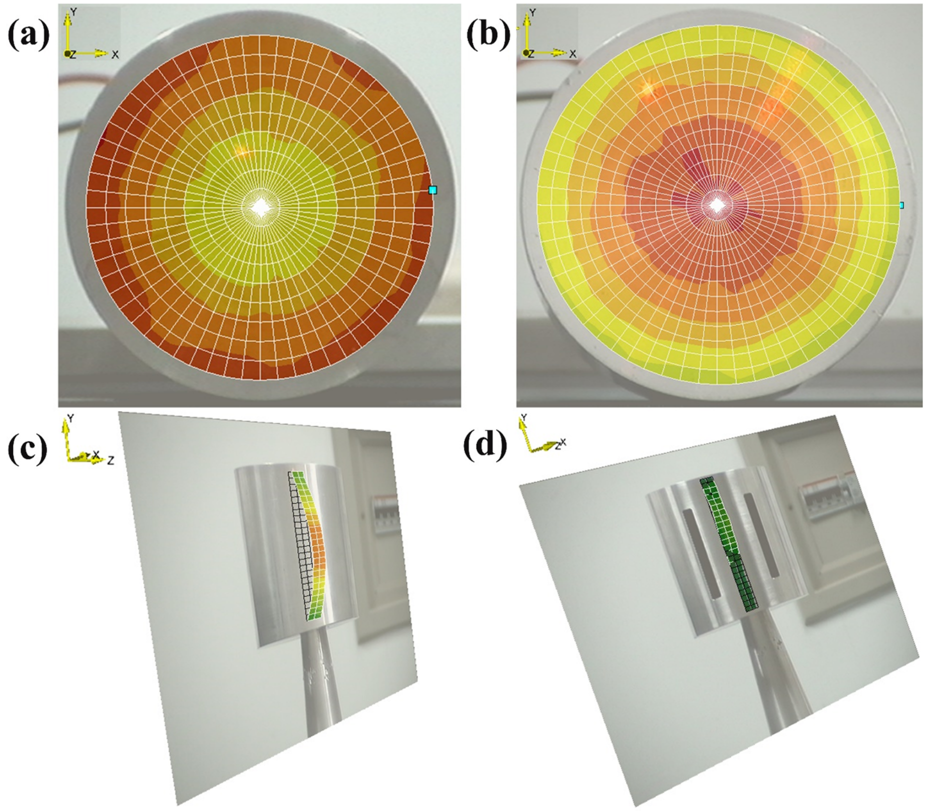

Fig. 7. The displacement distribution of the model 1 and model 3. (a, b) Longitudinal displacement distributions of model 1 and model 3, respectively. (c, d) Lateral displacement distributions of model 1 and model 3, respectively.

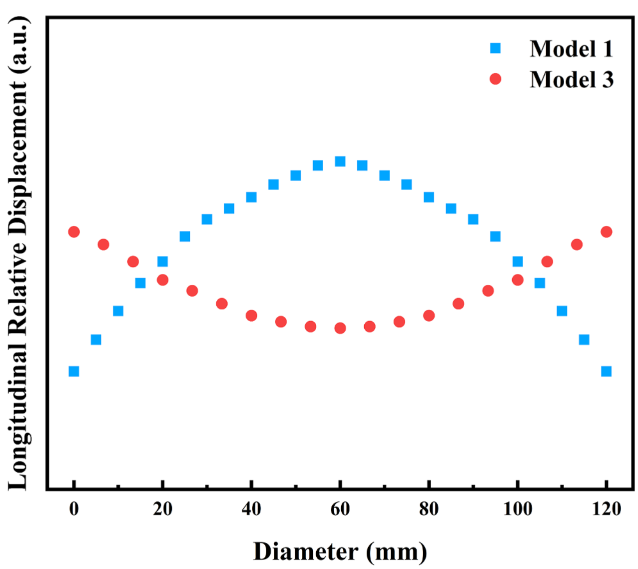

Fig. 8. The relative longitudinal displacement of model 1 and 3 along the diameter.

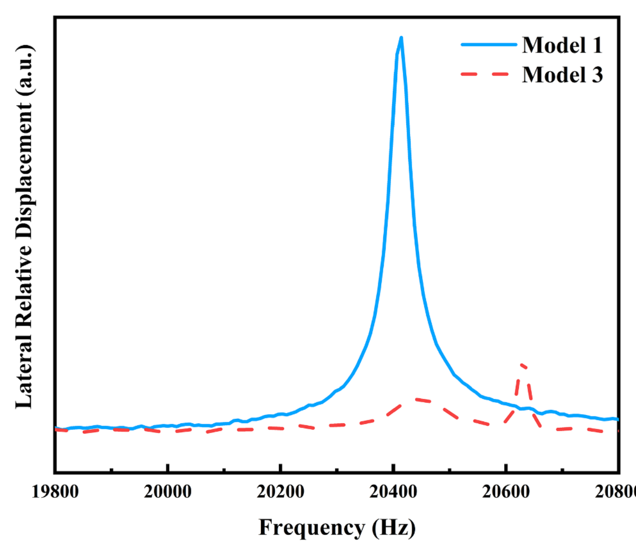

Fig. 9. The frequency response curve of lateral relative displacement of model 1 and 3.

rear cylinders, horns and tools are connected by M12 steel screw. Firstly, the resonance frequencies of model 1 and model 3 are measured by 6500B precision impedance analyzer, as shown in Fig. 6(a). The numerical and experimental resonance frequencies of traditional and new large-sized ultrasonic plastic welding system are listed in Table 1, where f_r and f_{er} are the numerical and experimental resonance frequencies of model 1, f_r' and f_{er}' are the numerical and experimental resonance frequencies of model 3.

Then, the displacement distributions of model 1 and model 3 tools are measured by PSV-400, as shown in Fig. 6(b). Fig. 7(a) and (b) show the mechanical displacement at the radiation surface of the tools of model 1 and model 3, respectively. When the laser is directed to the side of the tool, the mechanical displacement of lateral vibration was measured. Fig. 7(c) and (d) show the lateral mechanical displacements of the tool sides of model 1 and model 3, respectively.

Comparing the longitudinal mechanical displacement distributions at the radiation surface of the tools between model 1 and model 3, model 3 is more uniform, as is shown in Fig. 7(a) and (b). Comparing model 1 with model 3, it is found that model 1 has strong lateral vibration, while lateral vibration of model 3 is suppressed due to the introduction of PnC, as is shown in Fig. 7(c) and (d).

In order to further observe the difference after grooving, a series of points along the diameter direction at the radiation surface were selected to determine the longitudinal relative displacement. The mechanical displacement distributions along the diameter direction of model 1 and 3 are measured and shown in Fig. 8. Meanwhile, the frequency response curves of lateral vibration displacement amplitude of model 1 and 3 are measured and shown in Fig. 9.

As can be seen from Fig. 8, the displacement distribution along the diameter of model 3 is more uniform than that of model 1. The peak value of model 3 decreases significantly near 20 kHz by comparing with model 1, as shown in Fig. 9. It is shown that the lateral vibration can be effectively suppressed by the PnC in the bandgap range. Therefore, the lateral vibration of large-sized tool is suppressed by introducing PnC tools.

4. Conclusion

Traditional large-sized ultrasonic plastic welding system has been modified based on the PnC working principle. This is achieved by transforming the tool into PnC by drilling arranged periodically grooves to stop the lateral vibration of the large-sized tool. The vibration transmission characteristic curves and vibration modes of tools with different groove widths and heights are studied by FEM. Electrical and vibration tests were also carried out to compare the traditional and new ultrasonic plastic welding systems. It is concluded that the new tools based on two-dimensional PnC have band gap. The height and width of grooves have effect on the bandgap. When the operating frequency of the ultrasonic plastic welding system is within the bandgap of the new tool, the lateral vibration of the large tool can be suppressed. The more the vibration attenuation is at the resonance frequency, the more uniform the displacement will be. It shows that the application of PnC in the tools of ultrasonic plastic welding system can optimize its design, and provide a theoretical support for the design of large-sized ultrasonic plastic welding system.

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