Design and finite element analysis of longitudinal vibrating stepped ultrasonic horn

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Abstract. In this paper, a longitudinal vibration stepped ultrasonic horn was designed, and the size parameters of the ultrasonic horn were designed by theoretical calculation. In order to verify the rationality of the ultrasonic horn design, the finite element analysis software was used to perform a modal analysis on the horn, and the vibration mode and natural frequency of the ultrasonic horn within the design frequency range were obtained. The modal analysis results show that the natural frequency of the longitudinal vibration of the horn had a large error from the design frequency. Therefore, the size of the horn was optimized to make the natural frequency of the ultrasonic horn conform to the design frequency requirements. In addition, the optimized ultrasonic horn reduces the maximum stress which improves the safety and service life of the horn.

1. Introduction

At present, ultrasonic processing technology plays an extremely important role in the preparation of the composite materials[1]. For example, in the in-situ synthesis process of Al-Ti-C grain refiner, ultrasonic treatment technology can improve the wettability of Al-C interface, and improve the structure and properties of the composite materials [2-5]. However, the amplitude of ultrasonic vibration system is usually only 5 μm in the actual ultrasonic processing technology[6], which is far from the required amplitude. Therefore, it is necessary to design an ultrasonic horn to amplify the output amplitude of the transducer in the ultrasonic vibration system, which can be satisfy the technical requirements of ultrasonic processing of large amplitude vibration.

The main function of the ultrasonic horn is to amplify the displacement or velocity of mechanical vibration, which concentrate the ultrasonic energy on a smaller radiation surface. The natural frequency and vibration mode of the horn can be obtained by modal analysis with finite element method[6, 7], and the size of the horn can be optimized according to the modal analysis results, which can obtain an excellent performance of the horn. Modal analysis provides an effective method for the design and performance check of the horn.

In this paper, the size design of the ultrasonic horn was completed through theoretical calculation, and the modal analysis of the horn to verify the rationality of the ultrasonic horn size design. In addition, modal analysis was used to optimize the size of the ultrasonic horn, and the final design of the ultrasonic horn was realized.
2. Materials and methods

The design principle of the stepped ultrasonic horn is mainly divided into two steps: first, the size parameters of horn are calculated according to the theoretical design; second, the finite element analysis method are used to perform modal analysis which can verify the vibration pattern and natural frequency of the ultrasonic horn. The stepped ultrasonic horn is composed of two different cross-sectional areas. Figure 1 is the structural design diagram of the stepped ultrasonic horn. When the simple harmonic vibration was applied on the stepped ultrasonic horn, the longitudinal wave vibration equation at variable cross-section can be described as follows[6, 8]:

$$\frac{\partial^2 \xi}{\partial x^2} + \frac{1}{s} \frac{\partial s}{\partial x} \frac{\partial \xi}{\partial x} + K^2 \xi = 0$$

(1)

Where, $K$ is circular wave number, $\xi$ is the displacement function of the particle, $\xi = \xi(x)$; $S$ is the cross-sectional area function of the ultrasonic horn, $S=S(x)$. $c$ denotes the acoustic speed of horn material,

$$c = \left(\frac{E}{\rho}\right)^{1/2}$$

(2)

$E$ and $\rho$ are the young’s modulus and density of the ultrasonic horn material.

![Structural design diagram of the stepped ultrasonic horn.](image)

When the displacement node is at $x=0$, the horn is in the resonant state, At present, $a=b=\lambda/4$, and the length of the ultrasonic horn can be expressed as:

$$L = a + b = 2a = \lambda/2$$

(3)

Table 1 is the size parameters of the horn based on theoretical calculations

| Horn | $E$ (GPa) | $\rho$ (kg/m$^3$) | $c$ (m/s) | $a$ (mm) | $b$ (mm) | $L$ (mm) |
|------|----------|-------------------|-----------|----------|----------|----------|
| Value | 209      | 7.84              | 5760      | 72       | 72       | 144      |

3. Results

3.1. Modal analysis

After the modal analysis of the horn, four groups of frequency values were obtained in the frequency range of 15 kHz ~ 28 kHz, which were 20424 Hz, 20428 Hz, 22130 Hz and 27938 Hz respectively. In order to determine whether the vibration patterns of the four groups of frequencies meet the design requirements, the frequency values were input into the model for vibration patterns verification. Figure 2 is the cloud diagram of the 10 ~ 13 modes of the ultrasonic horn. Figure 2(a) shows the vibration mode of the horn with the natural frequency of 20424 Hz, and the vibration mode is bending vibration along the Z-axis; Figure 2(b) shows the vibration mode of the horn with the natural frequency of 20428 Hz, and the vibration mode is bending vibration along the Y-axis; Figure 2(c) shows the vibration mode of
the horn with the natural frequency of 22130 Hz, and the vibration mode is the longitudinal vibration along the X-axis; Figure 2(d) shows the vibration mode of the horn with the natural frequency of 27938 Hz, and the vibration mode is bending vibration along the Z-axis. It can be seen from Figure 2 that only when the natural frequency of the horn is 22130 Hz, the vibration mode is longitudinal vibration, which satisfy the requirements of longitudinal vibration of the horn.

Figure 2. The vibration mode diagram of horn (a) 20424 Hz (b) 20428 Hz (c) 22130 Hz (d) 27938 Hz.

Figure 3 shows the cloud diagram of stress and strain during longitudinal vibration of the ultrasonic horn. It can be seen from the figure that the stress concentration and strain are concentrated at the abrupt change of the cross section. The maximum stress and the maximum strain are 123 MPa and 3.31×10⁻², respectively.

Figure 3. The Stress and strain cloud diagram of the horn (a) stress (b) strain.

### 3.2. Horn optimization

However, many factors will affect the inconsistency between the frequency of the horn and the design value, such as processing errors, uneven distribution of material structure and theoretical calculations. Therefore, it is necessary to modify and optimize the ultrasonic horn. Figure 4 shows the stress and strain cloud diagram of the optimized horn. It can be seen from the figure that after optimization of the horn, the maximum stress and maximum strain are 81.4 MPa and 2.77×10⁻², respectively. Compared with the original horn, the stress and strain of the optimized horn are reduced, which improves the safety and service life of the horn.
4. Conclusion
The size parameters of the ultrasonic horn are designed through theoretical calculations, and the frequency and vibration mode of the horn are verified by modal analysis. The results show that the natural frequency of the horn is 22130 Hz, the vibration mode is longitudinal vibration, which satisfy the requirements of longitudinal vibration of the horn. After the optimization of the horn, the maximum stress and strain of the horn are reduced, which improves the safety and service life of the horn.

Acknowledgments
This work was supported by National Natural Science Foundation of China under Grant number11574043.

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