Theoretical and experimental research on a new rotating standing wave ultrasonic motor

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Abstract. In this paper, a new rotating standing wave ultrasonic motor with multiple driving teeth is proposed. Using the method of adding additional teeth, the correction of the B06 surface of the ultrasonic motor vibrator is expected, the design of the optimum position of the drive tooth is realized. At the same time, a method of reducing the stiffness of the rotor is proposed, and the flexibility is met, the integrated design of the rotor and the pressure device can be realized by removing the disc spring. The accuracy of the finite element analysis is verified by the vibration test of the prototype oscillator. The finite element analysis of the main structure parameters of the influence oscillator mode and natural frequency is carried out. It provides theoretical basis for the design and machining of vibration.

1. Introduction
Ultrasonic motor is a kind of direct driver[1]. If it is designed reasonably and applied properly, ultrasonic motor and electromagnetic motor can learn from each other and get more extensive and effective application[2-3]. Standing wave rotary ultrasonic motor, as a necessary supplement to traveling wave ultrasonic motor, has attracted more and more attention in recent years because of its advantages of simple driving and control circuit and small auxiliary devices[4]. Based on the driving principle of classical linear standing wave ultrasonic motor, a new type of rotary standing wave ultrasonic motor with multiple driving teeth is proposed in this paper.

2. Working principle of rotary standing wave ultrasonic motor
The vibrator of the standing wave type ultrasonic motor using bending vibration mode is excited into a simple standing wave mode, and the particle on the vibrator vibrates approximately in a straight line[5-7]. In order to facilitate the analysis, the annular vibrator is developed into a straight beam form, as shown in Figure 1, assuming that the guide rail is fixed and the vibrator itself moves. A number of teeth are machined on the vibrator according to a certain configuration[8-9]. According to the different position of the vibrator teeth relative to the stationary wave peak, the left oblique upward or right oblique upward collision force is formed, which pushes the mover to make a one-way linear motion.
FIGURE 1 Working principle of the oscillation. In figure (a), the vibrator tooth is on the right side of the antinode, and the displacement of the tooth end is as shown in the figure. The upper beam vibrator tooth exerts a right oblique upward force on the guide rail, and the lower beam vibrator tooth exerts a right oblique downward force on the guide rail, and the reaction force of the guide rail on the vibrator pushes the vibrator to move to the left. Similarly, in figure (b), the vibrator tooth is on the left side of the antinode, and the vibrator moves to the right. In order to realize the positive and negative movement of the vibrator, the key of the design is to determine the position of the vibrator teeth relative to the bending mode: generally, the driving teeth of the vibrator should be designed on the same side of the wave crest of the bending mode, so as to move the vibrator along the specified direction. When the bending mode is changed so that the driving tooth of the vibrator is on the other side of the corresponding mode peak, the driving tooth will move the vibrator in the opposite direction.

If the elastomer with standing wave is bent into a circular ring and some convex teeth are processed, as shown in FIGURE 2, the piezoelectric ceramic ring with good polarization is pasted below, and a metal ring (namely rotor) is placed on it. Assuming that the vibrator is fixed, the ring is rotated continuously. This is the operating principle of the rotating standing wave ultrasonic motor.

3. Modal design of rotary standing wave ultrasonic motor
The main performance of rotary ultrasonic motor depends on the vibration characteristics of the vibrator, so the design of the vibrator is very important in the whole design process. Among them, modal analysis is a powerful tool to optimize the design of the vibrator. Through the modal analysis of the vibrator, the structural size of the vibrator can be revised continuously, so as to find the required vibration shape and the corresponding resonance frequency.

In order to make the motor rotate continuously, there should be at least one tooth in one standing wave length. In this paper, two driving teeth are set in each standing wave length of the vibrator ring. The two groups of convex teeth processed in a certain way work alternately in a vibration cycle, which can reduce the wear of the teeth and improve the output efficiency of the motor. When the wave number of B06 bending mode on the circumference is 6, the number of driving teeth is 12, as shown in Figure 2.
FIGURE 2 Oscillator of rotary standing wave ultrasonic motor.

As for the drive tooth distribution of the vibrator shown in FIGURE 2, it is found through finite element calculation that the same drive tooth is always located at the wave peak of one bending mode of B06 or the pitch diameter of another bending mode of B06, which is not the optimal position to be designed. The B06 bending mode of the vibrator is shown in FIGURE 3. The experimental results of the amplitude distribution of the oscillator are consistent with the finite element calculation, as shown in FIGURE 4.

FIGURE 3 B06 mode diagram of the oscillator.

The appearance of vibration modes as shown in FIGURE 3 can be explained as the stiffness of the toothed parts on the oscillator ring is greater than that of the toothless parts, and it is not easy to bend. These special symmetrical parts must become the key points of the symmetric mode, namely the peak (or trough) or pitch diameter. The mode shown in FIGURE 3 is undoubtedly ineffective for the driving of the standing wave ultrasonic motor, because the oscillators' circumferential and axial amplitudes are in extreme conditions, which cannot form an effective driving force for driving the rotor to rotate along the set direction. By changing this mode and applying it to the standing wave ultrasonic motor, only under the non-resonant excitation can we obtain the bending mode where the driving teeth are not at the peak or pitch diameter. This working mode has been confirmed by the author's experiments.

FIGURE 4 Relative amplitude distribution of the finite element modal analysis of the oscillator.
However, the ideal vibration amplitude can be obtained only when the ultrasonic motor works under resonant conditions.

In view of this, this paper adopts the structural modification of the vibrator to fundamentally design the ideal bending mode, so that the driving teeth of the vibrator can be on the same side of the corresponding wave peak to realize the periodic shifting of the rotor.

The practice of finite element calculation shows that if the width of the upper teeth of the vibrator is different, the influence of the different width of the vibrator teeth on the position of the tooth in the bending mode is different. According to the importance of the influence of tooth width, the author uses the method of adding additional teeth to carry out modal control, that is, adding wider but lower height correction teeth near the working driving teeth (the amplitude of each part of the vibrator is within the micron level, and the height difference of the teeth is about 1 mm, which will not affect the working of the driving teeth) to improve the bending mode, as shown in FIGURE 5. According to the structural parameters in Table 1, the finite element analysis shows that the wide and lower additional teeth all stay at the peak or pitch diameter of the wave, while the driving teeth stay at the desired ideal position, that is, the left (or right) side of the wave's abdomen. The corresponding bending mode of B06 is shown in FIGURE 6.

Table 1. Main structural parameters of circle-ring vibrator (unit: mm).

| Ring Elastomer | Outer Radius | Inner Radius | Thickness H |
|---------------|--------------|--------------|-------------|
| Drive tooth   | Height th1   | Width (degree) |
| 20            | 14           | 3.2          |
| 2.1           | 6            |
| Additional tooth | Height th2  | Width (degree) |
| 0.6           | 4            |

![FIGURE 5 Oscillator with additional teeth for rotating standing wave ultrasonic motor.](image5)

![FIGURE 6 Modal diagram of B06 with additional teeth.](image6)

The exact position of the oscillator driving teeth and the additional teeth in the finite element bending mode is shown in FIGURE 7. The short segment of the diagram represents the additional teeth, and the long segment represents the driving teeth.
FIGURE 7 Relative amplitude distribution of finite element modal analysis with additional tooth oscillator.

In order to improve the unfavorable energy transfer between the original stator and the rotator, in this design, the stiffness of the rotator is reduced by evenly distributing the holes along the circumference direction while ensuring sufficient mechanical strength, so as to meet the flexible requirements of the rotator. The structure of the front and back faces of the rotator is shown in FIGURE 8.

4. Finite Element Analysis and Prototype Test of Rotor

The two bending vibration modes of finite element analysis are shown in FIGURE 8. The two natural frequencies are 20326Hz and 20327Hz respectively, with a frequency difference of 1 Hz.

FIGURE 8 Rotor configuration.

The pre-pressure of the structure is mainly applied to the stator by the flexible deformation of the rotor, not by the disc spring. Therefore, the disc spring can be removed to simplify the motor structure and achieve an integrated and beautiful design of the rotor. It also eliminates the energy loss caused by the relative sliding between the disc spring and the rotor.

The structural assembly diagram of the motor is shown in FIGURE 9.

FIGURE 9 Brief Diagram of Motor Assembly Structure.

1. Shell 2. Rotor 3. Vibrator 4. Piezoelectric Ceramic 5. Shell Screw 6. Base 7. Vibrator screw 8. Output Shaft 9. Adjusting Shim 10. Circlip

FIGURE 10 shows the physical picture of the ring oscillator and the prototype experimental device.
A prototype was manufactured and tested. The experiment result shows that the work frequency of the motor were 50.50 kHz and 50.60 kHz, the frequency difference is 100Hz. And when the excitation voltage is 260 V and the excitation frequency is 50.55 kHz, no-load speed motor positive and negative two directions respectively 395 r/min and 401 r/min, achieved the same drive motor speed under the same frequency.

5.Conclusion

Based on the driving principle of classical linear standing wave ultrasonic motor, a new type of rotating standing wave ultrasonic motor with multiple driving teeth is presented in this paper. The oscillator of the motor can match the optimal position of the driving teeth under the pre-designed out-of-plane bending mode. Using a pair of orthogonal modes of the same order and same frequency of the oscillator, the forward and reverse motion of the motor can be achieved. It has simple driving and control circuit. Small auxiliary device and other prominent advantages. The stiffness of the rotator is reduced by evenly distributing the holes in the circumferential direction to meet the flexible requirements. The disc spring can be removed to achieve the integrated design of the rotator and the compression device, and the energy loss caused by the relative sliding between the disc spring and the rotator can also be eliminated. Experiments on the prototype show that the same speed of the motor is driven in both positive and negative directions at the same frequency, and the output moment is 19.32Nmm.

Acknowledgments

“This work was supported in part by the Scientific research project of Liaoning Province in 2019 (Project No. L2019014); Natural Science Foundation Project of Liaoning Province in 2018 (Project No. 20180550960); Liaoning Natural Science Foundation joint fund project (2020-YKLH-28); Yingkou enterprise doctor entrepreneurship and innovation project(QB-2019-07); Scientific research project of Liaoning Province in 2020 (Project No. L2020007); Supported by Program for Excellent Talents of Science and Technology in Yingkou Institute of Technology(RC202003); Liaoning Natural Science Foundation joint fund project (2021-YKLH-07);
REFERENCES

[1] Zhao Chunsheng. Ultrasonic motors technologies and applications[M]. Beijing: Science Press, 2007: 313-314.

[2] Jin Jiamei, Zhao Chunsheng. Linear stepping ultrasonic motor[J]. Journal of Electroceramics, 2008, 20: 193-196.

[3] Chen Chao, Shi Yunlai, Zhang Jun, et al. Novel linear piezoelectric motor for precision position stage[J]. Chinese Journal of Mechanical Engineering, 2016, 29(2): 378-385.

[4] Li Yubao, Shi Yunlai, Zhao Chunsheng, et al. Research on linear ultrasonic motor with high speed and large thrust force[J]. Proceedings of the CSEE, 2008, 28(33): 49-53.

[5] Liu Jianfang, Yang Zhigang, Cheng Guangming, et al. A study of precision pzt line step motor[J]. Proceedings of the CSEE, 2004, 24(4): 102-107.

[6] Shi Shengjun, Chen Weishan, Liu Junkao, et al. Ultrasonic linear motor using longitudinal and bending multimode bolt-clamped langevin type transducer[J]. Proceedings of the CSEE, 2007, 27(18): 30-34.

[7] Wang Liang, Shu Chengyou, Jin Jiamei, et al. Dynamical characteristics of sandwich-type piezoelectric actuator for driving track[J]. Journal of Mechanical Engineering, 2017, 53(5): 128-135.

[8] Jūnas V, Kazokaitis G, Maeika D. Design of Unimorph Type 3DOF Ultrasonic Motor[J]. Applied Sciences, 2020, 10(16): 5605.

[9] Zhang Bailiang, Yao Zhiyuan, Jian Yue, et al. Structural design of a novel plate-shaped linear ultrasonic motor based on bending mode[J]. Journal of Vibration And Shock, 2019, 38(1): 118-125.