Design of two-way self-moving linear ultrasonic motor

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Abstract. This paper designs a two-way self-moving linear ultrasonic motor. The ultrasonic motor is composed of a diamond-shaped metal elastic body, a piezoelectric ceramic sheet and a parallel guide rail. There is a slight gap between the driving foot and the parallel guide rail on both sides of the metal elastic body, and the grounded aluminum tube is sandwiched between the diamond-shaped metal elastic body. By exciting the piezoelectric ceramic sheets on both sides of the elastic body, the first-order bending vibration mode is excited to realize the bidirectional movement of the motor. Based on the analysis of the working principle of the ultrasonic motor, the finite element harmonic response analysis of the ultrasonic motor was carried out. A prototype is made for mechanical properties experiments. Experiments show that under the excitation of 200Vpp, the forward and reverse frequency of the ultrasonic motor is 18.18KHz and 18.07KHz, and the forward and reverse no-load speed is 43.76mm/s and 43.14mm/s. The no-load speed is close to.

1. Introduction

Linear ultrasonic motor (LUSM) is a linear actuator that uses the inverse piezoelectric effect of piezoelectric ceramics[1]. It has the advantages of simple and flexible structure, high power density, no noise, self-locking and no electromagnetic interference[2-3]. In addition, it has the characteristics of directly generating linear motion and driving force, high precision of positioning and speed control, flexible structure design, and easy realization of miniaturization and weight reduction of the device.

Aiming at the problem that the cost of ultrasonic motor is too high, the forward and reverse speeds are too large, the wear is serious, and the asymmetric mode is driven, this paper proposes a two-way self-moving linear ultrasonic motor[4-5]. The ultrasonic motor adopts a symmetrical diamond structure (hereinafter referred to as a diamond-shaped ultrasonic motor), and has the advantages of small volume, simple mechanical structure and driving circuit, strong anti-interference force, single-mode driving, two-way self-propelling and equal no-load speed. Adapted to the needs of special tasks for micro-miniature robots.

2. Structure of diamond-shaped ultrasonic motor

The structure of the diamond-shaped ultrasonic motor is shown in Figure 1. It consists of a diamond-shaped metal elastomer and four pieces of piezoelectric ceramic sheets. The diamond-shaped structure is provided with two driving feet on both sides. The diamond-shaped ultrasonic motor drives the foot end to generate tangential vibration parallel to the moving direction of the ultrasonic motor under the excitation of the high-frequency voltage signal. Since the diamond-shaped ultrasonic motor is
symmetrical along the Y-Z plane, its centre of gravity remains unchanged at the centre of the structure, ensuring that the diamond-shaped ultrasonic motor is linearly driven along the Y-axis under the external excitation signal to avoid left and right offset. A lightweight grounded aluminum tube is sandwiched between the diamond-shaped ultrasonic motor structure.

Figure 1. Structure of diamond-shaped ultrasonic motor.

The arrangement of the piezoelectric ceramic sheets is as shown in Figure 1. The method of bonding with the metal elastic body has two sets of four piezoelectric ceramics. A small gap is kept between the drive foot and the guide rails on both sides. The piezoelectric ceramic is polarized in the thickness direction, and the vibration of the elastic body is excited by the inverse piezoelectric $d_{31}$ effect, and the electrode piece is placed in the middle of each group of piezoelectric ceramics for external excitation signal. The bidirectional drive of the diamond-shaped ultrasonic motor is controlled by the forward excitation signal and the reverse excitation signal respectively, and the positive and negative excitation signals are used to excite the diamond-shaped ultrasonic motor generate the first-order bending mode in the X-Y plane.

Figure 2. The scheme of PZT’s arrangement location.

3. Operating mechanism of diamond-shaped ultrasonic motor

In the design of the diamond-shaped ultrasonic motor, the driving premise is that a certain gap must be maintained, so that after the external excitation signal is connected, a wedge-shaped groove is formed between the contact surface of the driving foot and the guide rail. Under the excitation of the external high-frequency voltage, the driving foot will produce a continuous oblique collision with the guide rail to drive the movement of the diamond-shaped ultrasonic motor. The external positive excitation signal
is taken as an example to analyze the operating mechanism of the diamond-shaped ultrasonic motor, as shown in Figure 3:

At (b), Side A of the driving foot collides with the guide rail at a speed $V_A$. After the oblique collision, the tangential component of the velocity causes the diamond-shaped ultrasonic motor to produce a self-propelled motion in the Y direction. At (c), the piezoelectric ceramic piece recovers its length, and the foot end and the guide rail are restored in parallel. At (d), the piezoelectric ceramic piece is stretched in the longitudinal direction, and the driving foot is swung. Due to the presence of the gap, Side B of the driving foot has a tendency to obliquely collide with the guide rail at a speed $V_B$. However, since the diamond structure is obliquely connected to the driving foot, there is a fixed angle $\beta$ ($\beta \neq 90^\circ$), and At(a), the point O is the end point of the piezoelectric ceramic, not the symmetrical point of the structure, causing $OA > OB$. Under the gap $\Delta$, Side B has no oblique collision with the guide rail. At (e), the piezoelectric ceramic piece recovers its own length, and the foot end and the guide rail are restored in parallel, which is the same as (a) state. Under the external positive excitation signal, Side A will produce a continuous oblique collision with the guide rail, and the speed tangential component will output the diamond ultrasonic motor in the positive direction of the Y axis. In summary, the symmetrical vibration-driven asymmetrical oblique collision on both sides of the driving foot is a dynamic factor that causes the diamond-shaped ultrasonic motor to move along the guide rail.

4. Simulation and mechanical characteristics experiment

4.1 Harmonic response analysis of diamond-shaped ultrasonic motor

The harmonic response analysis of the diamond-shaped ultrasonic motor is carried out, in which the piezoelectric ceramic piece adopts the SOLID226 unit and the metal elastic body adopts the SOLID187 unit. The excitation voltage amplitude and the driving frequency are used as parameters to simulate the relationship between the driving frequency $f$ and the terminal amplitude $A$ when the excitation voltage is constant at the end of the piezoelectric vibrator. When the excitation voltage is 220V, the simulation result is shown in Figure 4:
Figure 4 shows that when the driving voltage is 220V, at $f=19.36\text{KHz}$, the amplitude of the driving direction of the diamond-shaped ultrasonic motor in both the X direction and the Y direction reaches a maximum. The maximum value in the X direction is 0.161 mm, and the maximum value in the Y direction is 0.187 mm.

4.2 Mechanical characteristics experiment

The diamond-shaped ultrasonic motor driving signal platform consists of a signal generator (HFPA-42) and a power amplifier (Agilent 33210A). Figure 5 shows the diamond-shaped ultrasonic motor test system, which is mainly composed of two parts: the guide rail and the laser displacement sensor (optoNCDT 1302, Germany) to test the performance index of the diamond-shaped ultrasonic motor.
Figure 6. The mechanical characteristic curve of diamond-shaped ultrasonic motor.

In the figure, V is the no-load speed, U is the peak-to-peak value of the driving voltage, and f is the driving frequency. It can be seen from this:

1) When the driving voltage is 220V, input the single-phase sinusoidal excitation to the A-channel forward excitation signal in Figure 2. When the excitation frequency is 18.18KHz, the diamond-shaped ultrasonic motor moves to the positive direction of the Y-axis the fastest, and its no-load speed is 43.76mm/s. Input the single-phase sinusoidal excitation for the B-channel reverse excitation signal in Figure 2. When the excitation frequency is 18.07KHz, the diamond-shaped ultrasonic motor moves to the negative direction in the negative direction of the Y-axis, and its no-load speed is 43.14mm/s.

2) The optimal driving frequency driven in the positive direction of the Y-axis is 18.18KHz, and the error rate is 6.5% compared with the frequency 19.36KHz obtained by harmonic response analysis; the optimal driving frequency driven in the negative direction of the Y-axis is 18.07KHz. Compared with the frequency obtained by the harmonic response analysis, the error rate is 7.1%; it can be seen
that the optimal operating frequency of the motor is about 18.1 KHz, and the driving frequency required for bidirectional driving is equal.

(3) The optimum driving frequency difference between the forward and reverse directions of the diamond-shaped ultrasonic motor is only 110 Hz. At the optimum driving frequency, the difference of the no-load speed is only 0.62 mm/s. It can be obtained that the diamond-shaped ultrasonic motor has the same forward and reverse driving conditions, and the driving effect is the same. The reliability of the diamond structure is also verified.

5. Conclusion
A two-way self-moving linear ultrasonic motor is designed to ensure that the centre of gravity of the ultrasonic motor is always in the Y-Z plane. The motor measures 28 mm × 5 mm × 5 mm and has a mass of 2.5 g. It is made of a metal elastomer and PZT bonded structure, and the manufacturing process is simple. The harmonic response analysis of the motor is carried out to determine the optimal resonant frequency of the motor, and the mechanical properties of the diamond-shaped ultrasonic motor are tested. Experiments show that the ultrasonic motor has the characteristics of fast response. When the diamond-shaped ultrasonic motor moves in the positive direction of the Y-axis, its no-load speed is 43.76 mm/s; in the negative direction of the Y-axis, its no-load speed is 43.14 mm/s, and the motor has good bidirectional characteristics.

Acknowledgments
This work is supported by the National Natural Science Foundation of China (Grant NO.51577112).

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