Dynamic analysis of a standing wave type linear ultrasonic motor with phase control

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Abstract. A hybrid excitation standing wave linear ultrasonic motor is studied. The relationship between phase difference and velocity is analyzed in detail. ANSYS has been used to establish the finite element model. Modal analysis and harmonic response analysis are carried out to obtain the resonant frequency of the stator and the law of the driving foot’s amplitude varying with the phase. A prototype is made and its phase difference-velocity relationship is tested. The results show that the no-load running velocity of the motor decreases with the increase of phase difference. On the premise that the working frequency is 21.9 kHz and the electric field intensity is the same, the maximum no-load running speed of the motor can reach 88.3 mm/s when the phase of the voltage applied to the piezoelectric ceramics on the upper surface is the same as that applied to the piezoelectric ceramics at the end.

1. Introduction

Linear ultrasonic motor [1] (LUSM) is a kind of actuator which converts electric energy into mechanical energy by using the inverse piezoelectric effect of piezoelectric material [2]. LUSM [3] plays an important role in aerospace [4], precision instruments [5] and other fields [6-8] with its small size, fast response and no electromagnetic interference [9].

According to the relative direction of electric field and polarization, the working modes of piezoelectric ceramics can be divided into three types. When the electric field direction is parallel to the polarization direction, the transverse and longitudinal vibration mode of piezoelectric ceramics occur; when the electric field direction is perpendicular to the polarization direction, the torsional vibration mode of piezoelectric ceramics occurs. Linear ultrasonic motors studied at home and abroad mainly use transverse and longitudinal vibration modes of piezoelectric ceramics to work up to now [10-13]. The transverse vibration mode of the piezoelectric ceramic on the upper surface and the torsional vibration mode of piezoelectric ceramics at the end of the stator are used to excite the first-order bending vibration mode in the stator elastomer in this paper.

A hybrid excitation standing wave linear ultrasonic motor is studied in this paper. The relationship between phase difference and velocity of the motor is analyzed theoretically. ANSYS allows to obtain modal analysis of the stator. Harmonic response analysis is also performed to find out the resonance frequency of the stator and thus achieve the relationship between phase difference and amplitude of driving foot. A prototype is made, and its phase difference-velocity relationship is tested.
2. Motor structure and working principle

2.1. Motor structure

The linear ultrasonic motor studied in this paper consists of three piezoelectric ceramics. In this paper, the layout of piezoelectric ceramics is different from that of traditional motor piezoelectric ceramics [14-16]. One piece of the piezoelectric ceramic is pasted on the upper surface of the stator elastomer, and the other two pieces are pasted on two ends of the stator elastomer. The first-order flexural mode (B1) is excited in the stator elastomer by the torsional transverse stretching vibration modes of the piezoelectric ceramic on the upper surface and the torsional vibration modes of the piezoelectric ceramics at two ends. The driving feet which deviate one eighth of the wavelength of the standing wave node of the stator in the same direction are pasted under the lower surface of the stator elastomer.

| parameter parts | Length (mm) | Width (mm) | Height (mm) |
|------------------|-------------|------------|-------------|
| Elastomer ends   | 2           | 10         | 1           |
| middle           | 24          | 10         | 5           |
| Piezoelectric ceramic ends | 2 | 10 | 4 |
| upper            | 20          | 10         | 0.5         |
| Driving foot     | 1           | 10         | 3           |

The elastomer of stator is 28 mm in length, 5 mm in height and 10 mm in width. The size of end piezoelectric ceramic is 2mm×4mm×10mm, and size of piezoelectric ceramic on upper surface is 20mm×0.5mm×10mm. The height of driving foot is 3 mm. Specific parameters are shown in Table 1. The stator elastomer is made of phosphorus bronze and the driving foot is made of stainless steel.

2.2 Working principle

The first-order bending modes are excited together in the stator elastomer by applying voltage signals to the piezoelectric ceramics at the upper end and the end. At this time, the two asymmetrically placed driving feet contact with the slider in turn and the thrust generated in the oblique direction causes the displacement of the slider.

3. Dynamic characteristics of the motor

3.1 Displacement Response of First-order Bending Forced Vibration of Stator

The telescopic vibration of piezoelectric ceramics with piezoelectric constant d31 and torsional vibration of piezoelectric ceramics with piezoelectric constant d15 are used to work. Assuming that the phase value of applied voltage of piezoelectric ceramics on the upper surface is zero, then the applied voltage to the piezoelectric ceramic on the upper surface is expressed as:

\[ U_{up}=Ae^{j0} \]  \hspace{1cm} (1)

When the piezoelectric ceramics on the upper surface are excited by voltage \( U_{up} \), the expression of standing wave generated in the stator is as follows:

\[ y_{up}=Ak_1 \cos \omega t \cos x = B \cos \omega t \cos x \]  \hspace{1cm} (2)
Under the same electric field intensity, the voltage applied to the end piezoelectric ceramics can be expressed as:

\[ U_{\text{end}} = 4Ae^{j\phi} \]  

(3)

The standing wave generated by two end piezoelectric ceramics in the stator is expressed as:

\[ y_{\text{end}} = 4A k_2 \cos(\omega t + \varphi - x) + 4A k_2 \cos(\omega t + \varphi + x) + 4A k_2 \cos(\omega t + \varphi - x) + 4A k_2 \cos(\omega t + \varphi + x) \\
= 8(\alpha + 1) A k_2 \cos(\omega t + \varphi) \cos x \\
= C \cos(\omega t + \varphi) \cos x \]  

(4)

Where \( \alpha \) is the reflection coefficient, and \( 0 \leq \alpha \leq 1 \); \( k_2 \) is the ratio coefficient of stator amplitude to voltage when the piezoelectric ceramics on the upper surface are excited; \( k_2 \) is the ratio coefficient of stator amplitude to voltage when the piezoelectric ceramics at the end are excited; \( B \) is the amplitude of the stator when the piezoelectric ceramic on the upper surface are excited; \( C \) is the amplitude of the stator when the piezoelectric ceramics at the end are excited; \( \varphi \) is the phase difference between two power sources. Combined equation (2) and (4), the standing wave in the stator can be expressed as:

\[ y = y_{\text{up}} + y_{\text{end}} = B \cos \omega t \cos x + C \cos(\omega t + \varphi) \cos x \]

Where,

\[ \sigma = \arctan[C \sin(\omega t + \varphi)/(B + C \cos(\omega t + \varphi))] \]  

(6)

Order,

\[ D = [(B + C \cos \varphi)^2 + (C \sin \varphi)^2]^{0.5} \]

(7)

Then, the equation (5) can be expressed as

\[ y = D \cos(\omega t + \sigma) \cos x \]  

(8)

3.2 Numerical relationship between phase and velocity

The horizontal velocity of the driving foot is caused by the deflection angle [17], [18], it can be expressed as:

\[ V_x = (h + H/2) \dot{y} / x \sin \varphi \]

(9)

The positions of the two driving feet are - 3/4\( \pi \) and 3/4\( \pi \). It can be seen from formula 9 that in order to ensure the same driving direction, the two driving feet must work time-sharing. Assuming that each driving foot drives half a cycle, then the average velocity can be expressed as:

\[ V_{av} = [2(h + H/2)] D \sin(\omega t + \sigma) \sin(x \sin(\omega t + \sigma)) / T \\
(\omega t + \sigma \rightarrow 0, \pi) \]  

(10)
Where, $T$ is a cycle, and:

$$T = \frac{2\pi}{\omega} \quad (11)$$

$$x = \frac{3\pi}{4} \quad (12)$$

Then,

$$V_{av} = \left[ 2(h + H/2) \omega^2 D \sin(3\pi/4) \right] / \pi \quad (13)$$

By combining the above equation (7) and (13), the average velocity can be obtained. Using the standard unitary value, $B=1, C=0.7, W=1, H=1, h=0.6$ the relationship between average velocity and phase is obtained as shown in Fig. 1.

**Fig. 1.** The relationship between average velocity and phase

**4. Finite element analysis of stator**

In order to further study the influence of the phase of the power supply voltage on the running speed of the motor, the finite element model is established by ANSYS, the modal analysis and harmonic response analysis are performed to obtain the phase-speed relationship. The first-order bending vibration mode of the stator is shown in Fig. 2 below. The resonance frequency of the stator is 21.9 kHz. Under the resonant frequency, the phase difference of the voltage between the piezoelectric ceramics on the upper surface and the piezoelectric ceramics at the end is changed. The phase difference-amplitude curve is obtained by harmonic response analysis as shown in Fig. 3.

**Fig. 2.** First-order Bending Vibration of Stator
In Fig. 3, when the phase difference is in the range of 0 to 150, the vibration amplitude of the driving foot decreases with the increase of the phase difference between the two voltages.

5. Experiment

The motor prototype is shown in Fig. 4. Firstly, the impedance-frequency characteristics of the prototype are tested. The test results are shown in Fig. 5 below. The impedance-frequency characteristic curve of the motor is shown in Fig. 5(a) when voltage is applied to the piezoelectric ceramic on the upper surface alone. The resonance frequency of the motor is measured to be 22.05 kHz. When the excitation voltage is applied to the end piezoelectric ceramics alone, the measured curve is shown in Fig. 5(b). The resonance frequency of the motor is measured to be 21.95 kHz.
The experimental platform is shown in Fig.6. The voltage of 62.5V is applied to the piezoelectric ceramics on the upper surface and 250V is applied to the piezoelectric ceramics at the end to ensure that they are in the same electric field strength. The phase difference-velocity curve of the motor is measured at resonance frequency of 21.9 kHz by means of multiple measurements of the average value.

As shown in Fig.7, it can be seen that there is a close relationship between the speed of the motor and the phase difference between two voltages. When the phase difference ranges from 0 to 150, the no-load speed of the motor is tested. The results show that the speed of the motor decreases as the phase difference increases. When the operating frequency is 21.9 kHz and the phase values of the applied two voltages are equal, the maximum speed of the motor without load is 88.3 mm/s. The experimental results are in agreement with those obtained by ANSYS analysis. It further proves the correctness of the above analysis.

(b) electrify piezoelectric ceramics at two ends alone

**Fig.5.** Impedance-frequency characteristics

**Fig.6.** Platform of the experiment

**Fig.7.** Phase difference-velocity curve
6. Conclusion

Taking a hybrid excitation standing wave linear ultrasonic motor as the research object, its dynamic characteristics are analyzed in detail. The relationship between the phase difference of the power supply voltage and the no-load running speed of the motor is studied. The prototype is fabricated, and its impedance-frequency characteristics are tested. At the resonant frequency of 21.9 kHz, the phase difference-velocity relationship is tested. The experimental results show that when the value of phase difference ranges from 0 to 150, the no-load running speed of the motor decreases gradually, and the maximum speed is 88.3 mm/s.

7. Reference

[1] C. S. Zhao 2007 Technology and Application of Ultrasound Motor Beijing: Science Press pp 313–348
[2] CY. L, TY. Z, Y. C, DY. F. 2007 Applications Research of Piezoelectric Ceramic Components with Shear Modes in Ultrasonic Motors Small and Special Electrical Machines vol 35 no 10 pp 14-17
[3] ROH, Yongrae, KWON, et al 2004 Development of a new standing wave type ultrasonic linear motor Sensors & Actuators A: Physical vol 112 no 2 pp 196-202
[4] W. S. Chen, X. Li, T. Xie. 2007 Application of Ultrasonic Motor in Space Detection Small & Special Electrical Machines vol 35 no 1 pp 42-45
[5] Nagira Y Sakayachi T Hikita M 2014 Rotary motion generated by synthesized circular / elliptic drive with straight-move ultrasonic motors Ultrasomics Symposium IEEE
[6] H. Xu, C. S. Zhao. 2003 Development and Application of Linear Ultrasonic Motors China Mechanical Engineering, vol 14 no 8 pp 715-717
[7] G. H. Qing, Q. T. Liu, W. Q. Huang, et. 2003 Recent Advances in Linear Ultrasonic Motor Small & Special Electrical Machines vol 31 no 2 pp 24-26
[8] L. Q. Chen, M. J. Ren, Z. X. Zhang. 2005 Application of Linear Ultrasonic Motor on Precision machine tool Micromotors vol 38 no 4 pp 76-78
[9] H. Xu. 2008 Application of Linear Ultrasonic Motor for Precise Stage Micromotors vol 41 no 10 pp 68-69
[10] Liu Y X, Chen W S, Liu J K, et al. 2008 Design and analysis of a cylindrical standing wave ultrasonic motor using cantilever and sandwich type transducers Symposium Piezoelectricity Acoustic Waves and Device Applications
[11] Kanda T, Makino A, Ono T, et al. 2006 A micro ultrasonic motor using a micro-machined cylindrical bulk PZT transducer Sensors and Actuators A: Physical vol 127 no 1 pp 131-138
[12] Chong Li, Cunyue Lu, Yixin Ma. 2017 Magnetic field tuning characteristics of bimodal ultrasonic motor stator Journal of Shanghai Jiaotong University (Science) vol 22 no 2 pp 129-132
[13] Guangqing Wang, Wentan Xu, Bingqiang Yang. 2017 Operating Mechanism and Characteristics Analysis of a T-Shaped Linear Ultrasonic Motor Transactions of China Electrotechnical Society vol 32 no 15 pp 111-119
[14] Li X, Ci P, Liu G, et al. 2015 A two-layer linear piezoelectric micromotor. IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control vol 62 no 3 pp 405-411
[15] Hou X, Lee H P, Ong C J, et al. 2013 Development and numerical characterization of a new standing wave ultrasonic motor operating in the 30-40kHz frequency range Ultrasomics vol 53 no 5 pp 928-934
[16] Behera B, Nemade H B. 2017 Recent developments of piezoelectric motors with diverse operating principles *ISSS Journal of Micro and Smart Systems* vol 6 no 2 pp 173-185

[17] Singiresu S. Rao. 2004 Mechanical vibrations USA: *Prentice Hall* pp 439-449

[18] XH.Y. 2001 Research on Linear Standing Wave Ultrasound Motor and Its Self-oscillating Driving Circuit

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