

Friction Behavior on Contact Interface of Linear Ultrasonic Motor with Hard Contact Materials

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Abstract: How to improve the efficiency of the linear ultrasonic motor with hard contact materials (HLUSM) or the precision motion stage driven by HLUSM, becomes a hot issue. Analysis and testing of friction behavior on the contact interface of HLUSM is one of the key issues. Under the action of ultrasonic vibration and impact, the friction behavior on contact interface is very complex due to micro-amplitude and high frequency. Moreover, it is difficult to observe and test it. Focusing on the frictional behavior on the interface of HLUSM, a new method, through testing the vibration of the driving tips (scanning vibrometer PSV-400-3D) and the motion of the slider (displacement sensor LK-G30), respectively, is proposed. Then, take the HLUSM as an example, theoretical analyses and experiments are carried out. Theoretical analysis shows that the average speed of the slider should be 600 mm/s when there is no slippage between the stator and slider during the contact process. Experimental results show that the average speed of the slider is about 390 mm/s. At the same time, the tangential vibration speed of the driving tip of HLUSM is larger than 600 mm/s. Therefore, there must be slippage between the stator and slider of HLUSM. Further experimental results show that the maximum efficiency is less than 10%. The slippage on the contact interface should be the main reason for the low efficiency of HLUSM.

Key words: friction behavior; ultrasonic vibration; slippage; efficiency

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0 Introduction

Hard contact materials, such as $\text{Al}_2\text{O}_3/\text{ZrO}$ ceramics, is widely used to reduce the effect on positioning accuracy by the deformation of the contact interface, and improve motion accuracy and lifetime of the linear ultrasonic motor (LUSM). The friction on the contact interface is the main reason of structural energy dissipation. Under the action of micro-amplitude vibration with ultrasonic frequency, the friction behavior on the ceramics contact interface ($\text{Al}_2\text{O}_3\text{-ZrO}$) is very complex. Research on the microscopic friction behavior on the contact interface is a basic work to reveal the mechanisms of the energy

transfer and dissipation of the linear ultrasonic motor with hard contact materials (HLUSM) under ultrasonic vibration. Certainly, the energy transfer and dissipation on the interface are very closely related to the efficiency of HLUSM.

There are two different situations about the friction characteristics under the action of ultrasonic vibration and impact. One is associated with the contact model of the travelling wave rotary ultrasonic motor^[1-3]. The other is about the contact problem of LUSM^[4,5]. Most of the existing studies assume that only the static friction exists on the contact interface. Twiefel et al. established an experimental platform to investigate the normal direction high-frequency impact process, and

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one special circuit was used to measure the contact duration^[6]. Then, for the three contact conditions of linear standing wave ultrasonic motors, stick, slip and separation, an elementary piecewise linear model was proposed and solved with semi-analytical method^[7]. However, these studies are still not sufficient to understand the fundamentals of the friction behavior on the contact interface. The transmitting model of ultrasonic vibration in ultrasonic transducer and capillary were studied in the ultrasonic bonding progress^[8]. The microscopic vibration locus and the relationship between ultrasonic vibration energy density and the section area were studied. Recently, the vibration of stator's center of mass and the friction of stator and slider were studied^[9].

This paper focuses on the study of the interfacial microscopic friction behavior of HLUSM. Furthermore, the energy transfer efficiency issues are also studied.

1 Performance and Friction

1.1 Performance of HLUSM

The butterfly-shape LUSM is a good choice for the precision positioning stage for its high thrust and speed. Shi Yunlai et al.^[10] conducted a lot of optimal design works of butterfly-shaped LUSM. However, the contact state and friction behavior of HLUSM on the contact interface may be very different. Therefore, an experiment is conducted with the help of XL-80 laser interferometer. Mass of the slider is 0.594 kg, and the optical assembly fixed on the slider is 0.371 kg. There is no-load along the direction of movement. The experimental results show that the speed of the slider is a long rising process. It costs about 100 ms before reaching steady state. As shown in Fig. 1, the maximum speed is less than 420 mm/s, although the slider can reach the steady state during the stroke of 60 mm. The results indicate that the wear and tear on the contact interface are serious, and the energy transfer efficiency is very low. Therefore, further research on the interfacial friction behavior of HLUSM is necessary.

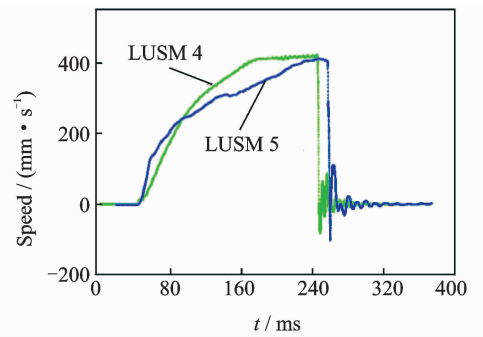


Fig. 1 Experimental curves of slider's speed of HLUSM (Driving frequency: 50 kHz, pre-pressure: 40 N)

1.2 Theoretical analysis of friction behavior on contact interface

According to the research on HLUSM, we take the butterfly-shape HLUSM as only one driving tip to analyze its characteristics in theory. Then, the pressure between the stator and slider is equal to value shown on the pressure monitor.

When HLUSM is working in steady state, the ideal elliptical track of the driving tip is shown in Fig. 2. It can be seen that, moving trajectory of the driving tip is an ellipse which can be divided into two components in tangential (x) and normal (y) direction. The center of the ellipse is defined as the original point O of the coordinate system. The driving tip of stator comes into contact with the slider from t_0 to t_1 and pushes the slider forward in x -direction by friction force. Then, they are separated, the slider moves continuously in an attenuated mode, the stator remain idle until they come into contact again (t'_0).

Taking the slider as the analysis target when HLUSM works in steady state and assuming the friction force between the slider and its lead rail

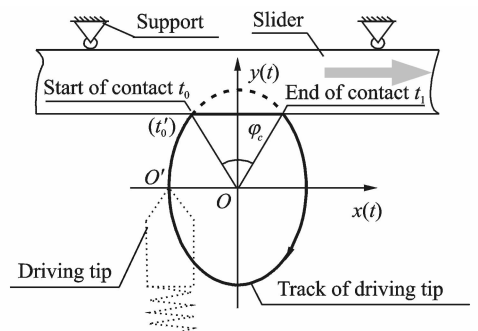


Fig. 2 Ideal elliptical track of driving tip of HLUSM

can be ignored, the schematic is shown in Fig. 3. In the normal direction, the contact force F_c is equal to the structure constraint force F_r . Obviously, F_c is relevant to the pre-pressure F_0 and the amplitude of the driving tip of HLUSM. In the tangential direction, the driving force F_τ should be equal to the sum of the load F_l and the velocity-dependent viscous friction force F_v . At steady state, the speed of slider is higher than that at transient state.

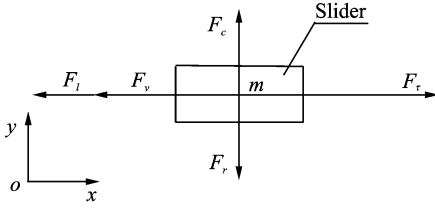


Fig. 3 Dynamic model of slider

Assuming that there is no slippage between the stator and slider during the contact process, we can get the maximum speed or efficiency of HLUSM. Moreover, to simplify the problem, only the pre-pressure F_0 is taken into account. Thus, the driving force is equal to the tangential static friction force. The following two equations can be obtained according to the Coulomb friction law.

$$F_\tau = \mu_s F_c = \mu_s F_0 \quad (1)$$

where μ_s is the static friction coefficient between the driving tip and slider. Moreover

$$F_v = c\dot{x}(t) \quad (2)$$

Then, the following equation can be derived as

$$F_l = F_v = F_\tau \quad (3)$$

According to the practical experience, the values of c , μ_s , F_0 and F_l are set as 0.1 m/s, 0.08, 40 N and 1.96 N. Therefore, $\dot{x}(t)$ is 12.4 m/s. It is much larger than the above experimental results. Then, we recalculate it by using another method.

According to Newton's second law of motion, the slider's movement can be described as^[11]

$$\begin{cases} m \frac{d\dot{x}}{dt} + c\dot{x} = F_\tau - F_l \\ \dot{x}(t_0) = v_m \end{cases} \quad (4)$$

where \dot{x} is the velocity of slider, m the mass of

the slider, c the damping coefficient of slider, and v_m the average speed of the slider.

The slider speed in the moment t_1 can be calculated as^[12]

$$\dot{x}_c(t_1) = v_m e^{-\frac{c}{m}(t_1-t_0)} + e^{-\frac{c}{m}(t_1-t_0)} \cdot \int_{t_0}^{t_1} \frac{F_\tau - F_l}{m} e^{\frac{c}{m}(t_1-t_0)} dt \quad (5)$$

Then, the average speed of slider in separation period $t_1 < t < t'_0$ is

$$\bar{\dot{x}}_f(t) \approx \left[1 - \frac{c(t'_0 - t_1)}{2!} \right] \left[\dot{x}_c(t_1) + \frac{F_l}{c} \right] - \frac{F_l}{c} \quad (6)$$

Eq. (6) indicates that the slider's speed at the separation moment and duration of separation are two vital factors affecting the steady speed of HLUSM. Then, the speed difference after the driving cycle is

$$\Delta\bar{\dot{x}} = \bar{\dot{x}}_f(t) - v_m \quad (7)$$

Eq. (7) shows that how much energy the slider gets from the stator in one driving cycle.

If t_0 is defined as the starting point of one steady state driving cycle, f_d is the frequency of driving signals, t_1 can be expressed as $(2f_d)^{-1}$ when we assume that φ_c is 180° (Fig. 2), and parameter t'_0 is expressed as f_d^{-1} . Finally, $\bar{\dot{x}}_f(t)$ can be calculated with these parameters given in Table 1. It is 200.03 mm/s when these parameters are set as the values of the second column in Table 1 and $\Delta\bar{\dot{x}}$ is 0.03 mm/s. Then, if F_l is changed to 0.22×9.8 N (third column in Table 1), $\Delta\bar{\dot{x}}$ is 200.02 mm/s. Moreover, if v_m is assumed as 400 mm/s, $\Delta\bar{\dot{x}}$ will be 0.025 mm/s. It is obvious that $\Delta\bar{\dot{x}}$ has not changed too much in so

Table 1 Reference values of parameters using prediction speed of slider

Symbol	Value 1	Value 2	Value 3
$v_m / (\text{m} \cdot \text{s}^{-1})$	0.2	0.2	0.4
$c / (\text{m} \cdot \text{s}^{-1})$	0.1	0.1	0.1
m / kg	0.4	0.4	0.4
f_d / kHz	50	50	50
μ_s	0.08	0.08	0.08
F_0 / N	40	40	40
F_l / N	0.2×9.8	0.2×9.8	0.2×9.8

short period time even though v_m or F_l is changed. Therefore, we can deduce the steady speed of slider with $\Delta\bar{x}$ and the movement time (t_s) as

$$\dot{x}_m(t) = \Delta\bar{x} \times t_s \times f_d \quad (8)$$

Then, 0.03 mm/s can be used as the reference value of $\Delta\bar{x}$. Meanwhile, assuming t_s is 0.4 s, then, \dot{x}_m is 600 mm/s. Substantially, it is equal to 650 mm/s when the slider is working in steady state with 0.2 kg load.

In summary, although there are great differences among the above theoretical analysis results, the comparison of theoretical results and primary experimental results indicates that there must be serious slippage existing on the contact interface of HLUSM.

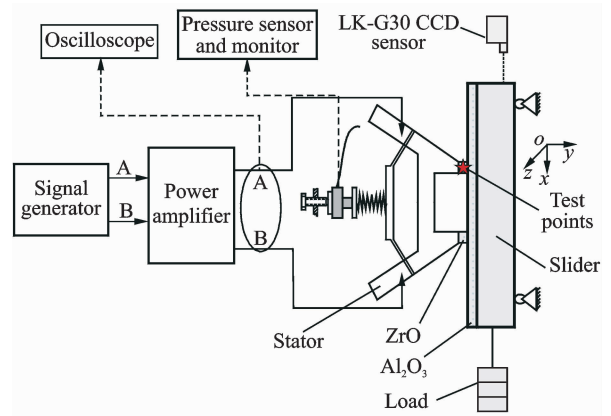
2 Experiment about Friction Behavior on Contact Interface

There are several required assumptions in the above theoretical analysis. As a result, there are large differences among the results of different methods. However, they are no less than 600 mm/s. It is larger than the value in the Fig. 1. Therefore, further experimental study is necessary to understand the friction problem on the contact interface of HLUSM.

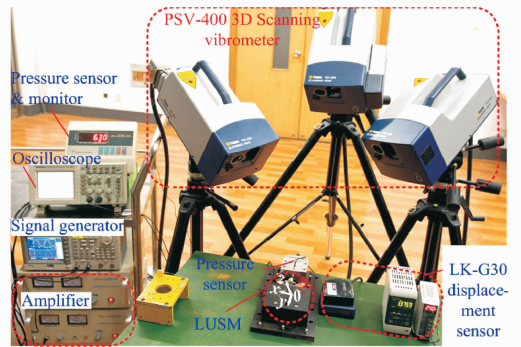
2.1 Experimental system

As shown in Fig. 4, one butterfly-shape HLUSM is used in the experiment. Driving signals are generated by a signal generator (Tektronix, AFG3022) and amplified by a power amplifier (HFVP-83A). Meanwhile, the actual phase difference and amplitudes are monitored by a digital storage oscilloscope (Techtronix, TDS2014). The pre-pressure can be adjusted by means of an adjusting mechanism including adjusting bolt, compression spring, pressure sensor and the monitor. The ceramic blocks made from ZrO and Al₂O₃ are fixed on the stator and the slider, respectively.

A scanning vibrometer (Polytec; PSV-400-3D) is used to measure displacement and velocity



(a) Schematic



(b) Graph

Fig. 4 Experimental system

of the driving tip in three directions under actual working condition. In the single/continuous mode, the testing system can save the speed/displacement data of 80 ms. The reference input signal is separated from the zero phase channel of signal generator. In the motion direction of the slider, a laser displacement sensor (LK-G30 CCD) is used to measure the velocity of the slider. For the short valid measuring range, it is placed at the end of slider's stroke. The testing points are shown in Fig. 4(a). The advantage of the testing system is that the microcosmic vibration speed of the driving tip and the average speed of the slider can be simultaneously measured.

2.2 Experimental results about friction behavior on contact interface

The driving signals of HLUSM are 50 kHz and 300 V (peak-to-peak value) in the experiment. The sampling frequency of the measurement system is 204.8 kHz. A mass of 200 g is hanged on the slider as the load. Pre-pressure is

40 N.

The coordinate system defined in the experiment is shown in Fig. 4(a), where x direction is along the movement, y -direction is vertical to x , and z -direction is defined as along the laser beam of the top laser head. As shown in Fig. 5, experimental results show that the tangential speed of the driving tip is similar to the sine curve, and the amplitude is about 600 mm/s. In Fig. 6, the speed of the slider is 360 mm/s, calculated with the displacement data measured by LK-G30 sensor. It is significantly less than the maximum tangential vibration speed of the driving tip. Therefore, the experimental results prove that there must be slippage on the contact interface. Hence, that should be sliding friction instead of static friction is dominated during the energy transfer process.

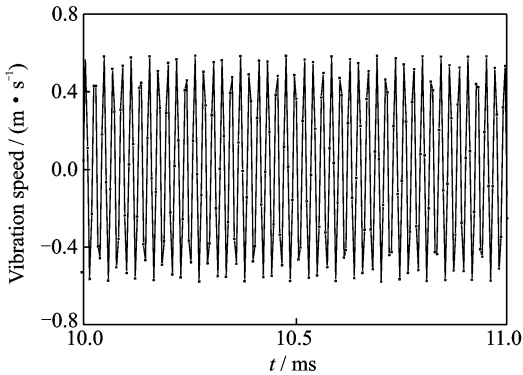


Fig. 5 Measured tangential vibration speed of driving tip of HLUSM

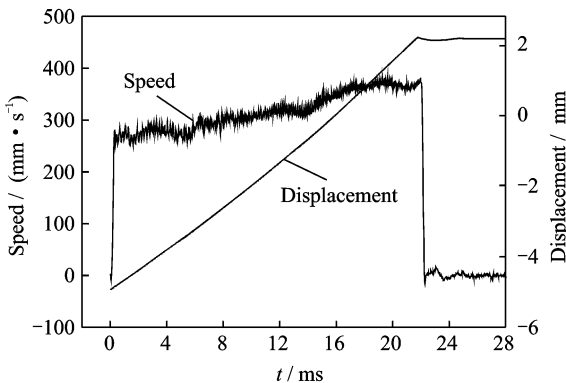


Fig. 6 Experimental results of displacement and speed of slider

3 Influences of Slippage on Efficiency of HLUSM

The velocity of the slider can be used to cal-

culate the efficiency together with the input voltage (300 V) and current ($0.15I_p$).

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{F \times v}{(V_{p-p} \times I_p) / 4} \quad (9)$$

where η is the efficiency of HLUSM, F the load, and v the speed of slider. P_{out} and P_{in} are output and input power, respectively, and V_{p-p} and I_p are input voltage and current, respectively. In the above case, the efficiency of HLUSM is 6.4%.

The energy loss of slippage on the contact interface between the stator and the slider reduces the efficiency of HLUSM.

The reference values of the common parameters of driving frequency, load, pre-pressure and driving voltage are 50 kHz, 1.96 N, 40 N and 300 V, respectively. The phase difference is 90° . According to Eq. (9), we can get the different efficiency curves with the change of the driving voltage, the pre-pressure and the load, etc, as shown in Fig. 7.

In the experiment, only the load of HLUSM is variable. Experimental results show that the highest efficiency occurs at the load is 3 N. The general trends of the efficiency decreases with the further increase of load. That is to say, the slippage on the contact interface is more seriously with the load increase. The efficiency of HLUSM is less than 10%.

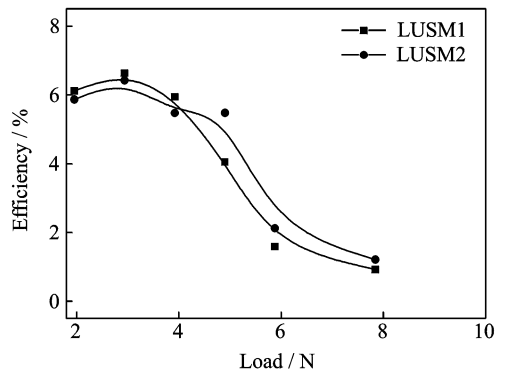


Fig. 7 Efficiency v. s. load

4 Conclusions

Focusing on the frictional behavior on the interface of HLUSM, a new method, through testing the vibration of the driving tips (scanning vibrometer; PSV-400-3D) and the motion of the

slider (displacement sensor LK-G30), respectively, is proposed in the paper. Then, take HLUSM as the example, theoretical analyses and experiments are carried out. Theoretical analysis results show that average speed of the slider is larger than 600 mm/s. It is at least 1.43 times the previous experiments speed 420 mm/s. Meanwhile, the measured maximum tangential speed of the driving tip by vibrometer is close to 600 mm/s. But the measured speed of slider is still less than 360 mm/s. If we take 390 mm/s, the average value of 360 mm/s and 420 mm/s, as the speed of the slider, it is only about 65% of the tangential speed of the driving tip. It can be seen that there is a big difference between the speed of slider and the tangential speed of the driving tip of stator. Therefore, there must be serious slippage on the contact interface. This is very different from many people's previous understanding. Further experimental results show that the maximum efficiency of HLUSM is less than 10%. The slippage on the contact interface should be the main reason for the low efficiency of HLUSM.

Moreover, the working parameters, such as the driving voltage, pre-pressure and load are very important to make HLUSM working in high efficiency.

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