Tribological Approach for Reliability and Durability of Ultrasonic Motor

Koshi Adachi

School of Mechanical Engineering
Tohoku University
Sendai, Japan
koshi@tribo.mech.tohoku.ac.jp

Abstract

The reliability and durability of an ultrasonic motor is usually determined by wear at the contact interface between a drive and a driven element, due to its driving mechanism. Wear control is therefore essential as the key design input to achieve ultimate performance of the ultrasonic motor.

In this paper, a high precision and small precise positioning linear stage with an ultrasonic motor as a promising stage for an electron-beam direct-writing system is introduced. It was realized by the optimum design of the overall system, including tribological materials and operating conditions from the viewpoint of wear control at the contact interface of the ultrasonic motor.

1. Introduction

Ultrasonic motor (USM) is a tribological device, in which the driving force is frictional. Because of its compact size, high torque, superior controllability and responsiveness, it provides a promising actuator for small and precise machines.

In addition, the USM generates no magnetic fields, and can therefore be used in the vacuum chamber in which non-magnetic field is strongly required such as electron beam direct-writing systems that is the key device for high-resolution manufacturing to produce next generation Large Scale Integrated circuits (LSI).

Based on these advantages, a high precision and small precise positioning linear stage driven by an ultrasonic motor was developed as a promising stage for an electron-beam direct-writing system [1]. Figure 1 shows a schematic diagram of the precise positioning stage driven by linear USM. The use of an USM instead of conventional electromagnetic motor resulted in a size reduction to one half of the previous design, and a positioning precision, which was three times higher.

The stage is driven and controlled by the friction force generated in the contact interface between a drive tip and a driven rail. The reliability and durability of the stage are therefore determined by tribological properties such as friction and wear at the contact interface [1-3].

For accurate transmission of the motion, stable and relatively high friction at the contact interface is required. Moreover high wear resistance of both tribological elements is essential to maintain accurate performance of USM, since wear causes a decrease in the mechanical accuracy of the system.

In this paper, the optimum design to realize the precise positioning stage driven by USM is introduced from the viewpoint of wear control by considering of tribological materials [1] and operating conditions such as contact load between a drive tip and a driven rail, PID gains [1] and sampling time for feed back control of positioning.

2. Principle of precise positioning stage driven by an ultrasonic motor

The stage is driven by the friction force generated in the contact interface between a drive tip of USM and a driven rail on the stage as shown in Fig. 1.

Figure 1: A schematic image of precise positioning stage driven by an ultrasonic motor.
The drive tip of the USM is oscillated elliptically with ultrasonic frequency of 40 kHz by a controlled piezoelectric actuator. The amplitude of vibration is controlled by the operating voltage applied to the piezoelectric actuator. The stage speed increases with the applied voltage by the vibration amplitude change.

The positioning of the stage is controlled with a closed loop algorithm of PID controller in the point to point positioning method. The design demands the movement of the stage by 650 μm/1 μm within 200 ms.

The value of the operating voltage applied to the USM is determined from the deviation $e(n)$ between the true and ideal positions of the stage every 1 ms. The position control method is summarized in the block diagram shown in Fig. 2. The operating voltage $E(n)$ applied from the PID controller to the motor driver is determined from the following equation.

$$E(n) = K_P e(n) + K_I \left[ \sum_{i=1}^{n} e(i) \right] + K_D \left( e(n+1) - e(n) \right) \quad (1)$$

Where $K_P$, $K_I$, and $K_D$ are the proportional gain, integral gain and differential gain respectively, and $e(n)$ is the position error at nth position detecting.

3. Tribologically-based design of precise positioning stage driven by USM

3.1. Material selection of tribological elements

Through our previous works on wear of materials in unlubricated sliding condition [4], we found that advanced ceramics had two wear modes that could be classified and named as "mild wear" and "severe wear" [4]. In the mild wear mode, wear surface became relatively smooth like polishing, and low wear rate less than $10^{-6}$ mm$^3$/Nm was obtained even though friction coefficient was not small value. The value of this wear rate means high wear resistance, which, as far as we know, is not obtained in any metals at all.

Then, I believe firmly that transmissibility and durability of the stage are achieved using an advanced ceramics in the mild wear region for the tribo-elements, since initial contact condition between the drive tip and the driven rail are maintained because of small change in surface roughness and geometry of the tip and the rail.

Based on this tribological understanding, alumina ceramics were selected for both the drive tip and the driven rail.

3.2. Design to achieve precise positioning and mild wear

Figures 3 (a) and (b) show surface profiles and SEM images of two representative wear surfaces of the drive tip with spherical shape observed after operation of the stage. They clearly show the results of mild and severe wear mode mentioned above. It is obvious that the optimum design of the whole system, including the operating condition, is the key to maintain low wear in the mild wear regime, even if a so-called wear-resistant material is used.

For ceramics, both of the following criteria must be satisfied to achieve mild wear [4].
**Figure 4**: Distribution of preload and applied weight on the stage for mild wear and severe wear.

\[
S_{cm} = \frac{(1+10\mu)P_{\text{max}}\sqrt{d}}{K_T} \leq 6 \tag{2}
\]

\[
S_{cJ} = \frac{\gamma}{\Delta T_s} \sqrt{\frac{WH}{kpc}} \leq 0.04 \tag{3}
\]

where \( \mu \) is the friction coefficient (tangential coefficient), \( P_{\text{max}} \) the maximum Hertzian contact pressure, \( d \) the grain size, \( K_T \) the fracture toughness, \( \gamma \) the heat partition ratio, \( \Delta T_s \) the thermal shock resistance, \( v \) sliding velocity, \( W \) the normal load, \( H \) the Vickers hardness, \( k \) thermal conductivity, \( p \) density and \( c \) specific heat. \( S_{cm} \) and \( S_{cJ} \) is named as mechanical severity of contact and thermal severity contact, respectively, which describes an index of crack propagation caused by mechanical stress or thermal one.

These necessary conditions for the mild wear of ceramics stress the importance of the design of contact pressure between the drive tip and the driven rail, and control of the amount of slip generated at the contact interface to transmit the force and the motion, related to the tangential coefficient in above criteria.

### 3.2.1 Selection of preload between the drive tip and the driven rail

Figure 4 shows for various combinations of preload and driven stage mass whether precise positioning (i.e. movement by 650 \( \mu \)m \( \mu \) within 200ms) is possible or not under constant PID gains. It can be seen that the optimum preload, at which precise positioning is possible, depends on the mass of the driven stage.

Distribution of mild wear and severe wear are also shown in the same figure.

**Figure 5**: Combination of PID gains for precise positioning possible [1].

It can be seen that severe wear can be generated even under conditions where precise positioning is possible. It clearly shows that selection of preload related to stage mass to achieve mild wear is more important than that needed for precise positioning.

### 3.2.2 Design of PID gains for feedback control

Figure 5 shows various combinations of PID gains whether precise positioning is possible, under constant combination of preload and driven stage mass. It can be seen that setting of the optimum PID gains is required to achieve precise positioning, which are related to the combination of preload and driven stage mass. Further, it was observed that severe wear was generated even under conditions where precise positioning was possible. It clearly shows that design of PID gains to achieve mild wear is more important than that needed for precise positioning.

### 3.2.3 Design of sampling time for feed back control

Positioning of the stage is more rapid and more precise if the position is corrected over a short time interval. Based on the theory of positioning, a shorter sampling time for feedback control is better for positioning. For this drive mechanism, however, too short a sampling time causes a rapid change in drive tip motion, which leads to large slip at the contact interface. Optimum sampling time therefore exists to achieve low wear and also precise positioning. A wear volume reduction of one-third has been realized experimentally by changing from the smallest sampling time derived from positioning theory to the optimum sampling time selected from a tribological viewpoint [5].
3.3. Monitoring of tribological condition for design of the precise positioning stage

Even in the same hard system, wear mode and wear volume were drastically changed by design of soft system such as PID gains and sampling time mentioned above. This is caused by differences in the amount of slip generated in the contact interface to transmit the force and the motion to the driven rail, for different PID gains and sampling time. Selection of PID gains and sampling time to achieve mild wear is therefore more important than that needed for precise positioning.

The PID gains directly affect the operating voltage applied to the USM. The operating voltage controls the amplitude of the drive tip vibration. The difference in operating voltage caused by the different PID gains causes a different motion of drive tip to achieve precise positioning. As a result, the amount of slip at the contact interface between the drive tip and the driven rail is different: the amount of slip is related to the operating voltage applied to the USM.

The extent of fluctuation of the operating voltage $E_f$, which means the average variation of operating voltage during the sampling time, can be used to express the difference in the waveforms of the operating voltage, and it has relation to slip between the drive tip and the driven rail.

$$E_f = \frac{\sum_{n=0}^{N} (E_{n+1} - E_n)}{N} \quad (4)$$

where $n$ is the number of sampling time, $N$ is the number of the sampling time when the required positioning is completed, $E_n$ is the operating voltage applied to the USM at nth sampling.

Figure 6 shows the specific wear amount of the drive tip, which is related to the wear mode, as a function of the $E_f$. It shows a critical value of $E_f$ that determines the transition from mild wear to severe wear. This point would correspond to the critical tangential coefficient in eqns. (2) and (3). The fluctuation of the operating voltage $E_f$ has been shown to be a good indirect parameter for monitoring and controlling the wear mode of tribological elements. Based on this understanding, optimum PID gains can then be designed to achieve minimum value of $E_f$.

3.4. Further tribologically-based design of the precise positioning stage

In practice the contact condition between the drive tip and the driven rail would change ultra microscopically during operation, even if only very little wear in the mild wear mode is achieved by optimum design. This means that the optimum values of the PID gains will change with time. In this case, feedback can be applied to retain the optimum conditions, with the preload and PID gains being varied by using the fluctuation of the operating voltage as the monitoring parameter. By using feedback-controlled PID gains, wear volume of the drive tip was decrease by more 25% compared with the value obtained for constant PID gains [5].

These results show the value and efficiency of using feedback algorithms not only for precise positioning, but also for the active control of wear in very high performance ultrasonic motor.

4. Conclusions

(1) It was clearly shown that optimum design from the viewpoint of wear control at the contact interface of driving element is essential as the key design input to achieve ultimate performance of ultrasonic motor.

(2) A precise positioning stage driven by an ultrasonic motor, which have been realized by the optimum design mentioned above, provides a promising solution for an electron-beam direct writing system for the next generation LSI.

5. References