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Dynamic analysis of an ultrasonic motor using point contact model

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ABSTRACT

We propose the dynamic modeling of a traveling wave ultrasonic motor using a point contact model between the stator and rotor. This model can simply and accurately estimate the transient response of the rotor motion. In this paper, we model the dynamic behavior of the motor torque and angular velocity based on the vibration amplitude of the elliptical motion generated in the ultrasonic motor. The use of a recent high-speed camera with a high-power lens (high-speed microscope) enables the observation of elliptical motion and the measurement of vibration amplitudes. We build a synchronous motor drive system including the high-speed microscope and verify the model experimentally. The proposed model has been in good agreement with the experimental results.

1. Introduction

Ultrasonic motors use a friction drive that transfers driving force from the stators to the rotors through a contact as a driving principle. They have several benefits such as high torque density, high accuracy, good response time, and silent drive. The most well-known ultrasonic motor design is the traveling wave ultrasonic motor [1]. It has been applied to many devices ranging from camera autofocus mechanisms to surgical robots under development [2–4]. Other designs have also been used, such as ultrasonic motors using two Langevin transducers [5,6] and using two vibration modes (L1-F2 mode) [7–10], for precise positioning mechanisms. In all designs, a stator and rotor are pressed by a large preload, and then a large friction force acts at their interface. When voltages are applied, the stator generates an elliptical motion at the interface and transfers driving force to the rotor by friction.

One key issue of modeling the driving force transfer is how to deal with the contact problem between the stator and rotor. Existing studies on modeling the contact have introduced slips and equations of motion for estimating motor output values such as a torque and angular velocity. In steady-state models, the contact is well regarded as a function of slip, the multiplication of a coefficient by the difference between stator and rotor velocities, for associating the angular velocity with the torque [11–15]. By choosing the coefficient appropriately, such models work well and their torque–velocity curves are in accordance with experiments. In transient-state models, the slip is identified by a damping coefficient in the equations of motion [16–19]. The transient response of rotor motion can be predicted in dynamics from an assumed elliptical motion, but both the rotor motion and the elliptical motion have not been verified experimentally.

The verification of dynamic models requires not only evaluating the transient response of the rotor's angular motion but also measuring the displacement of the elliptical motion. However, measurement of the elliptical motion has been difficult due to extremely small vibration amplitude and the ultrasonic range of the vibration frequency. In recent years, the specifications of high-speed cameras have reached a frame rate above the driving frequency of ultrasonic motors. We have succeeded in observing the elliptical motion and measuring its vibration displacement using a high-speed microscope. This high-speed microscope has clarified how the magnitude of elliptical motion relates to steady-state torque and angular velocity [20]; however, the dynamic relationship between the elliptical motion and the rotor motion has not been studied.

In this paper, we model the dynamic behavior of a traveling wave ultrasonic motor from elliptical motion production to rotor motion generation. This series of dynamic modeling are verified using a synchronous motor drive system that simultaneously measures the elliptical motion and angular velocity. Although the proposed model is simple and easy to use, it achieves good agreement with the experimental results. Using this model, we discuss the mechanism in which the contact transfers force and examine how the contact relates to the motor torque and angular velocity during the period from start to steady state.

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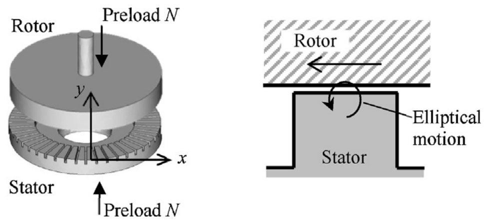

Fig. 1. Friction drive mechanism of a traveling wave ultrasonic motor.

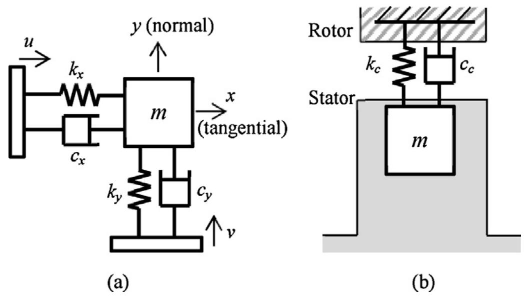

Fig. 2. (a) Mechanical model of the elliptical motion with tangential direction and normal direction. (b) Mechanical model of the rotor.

2. Modeling of ultrasonic motor

2.1. Equation of motion of elliptical motion

A traveling wave ultrasonic motor comprises an annular stator and a disc rotor, as shown in Fig. 1. The stator and rotor are pressed by a preload, and then friction force acts at their interface. When voltages are applied to piezoelectric elements at the bottom of the stator, a traveling wave is produced on the stator surface in contact with the rotor [1]. During this time, a point on the stator contact surface moves in an elliptical orbit. This elliptical motion transfers a driving force to the rotor at the top of the orbit.

For modeling the dynamic behavior of the elliptical motion, we focus on a mass particle that describes the elliptical orbit on the stator surface. This particle's motion is expressed as a mechanical system comprising tangential and normal components with spring, damping, and mass, as shown in Fig. 2(a). In the mechanical system, we denote the mass of the particle by m, tangential and normal damping coefficients by c_x and c_y, respectively, and tangential and normal spring coefficients by k_x and k_y, respectively. When input tangential and normal displacements u and v are applied to the system, the respective output tangential and normal displacements x and y are obtained. The equation of motion of the system is

$$m\begin{bmatrix}\ddot{x}\\ \ddot{y}\end{bmatrix}+\begin{bmatrix}c_x & 0\\ 0 & c_y\end{bmatrix}\begin{bmatrix}\dot{x}\\ \dot{y}\end{bmatrix}+\begin{bmatrix}k_x & 0\\ 0 & k_y\end{bmatrix}\begin{bmatrix}x\\ y\end{bmatrix}=F. \tag{1}$$

The force F generated by the input displacements, on the right side of (1), is given as

$$F=\begin{bmatrix}c_x & 0\\ 0 & c_y\end{bmatrix}\begin{bmatrix}\dot{u}\\ \dot{y}\end{bmatrix}+\begin{bmatrix}k_x & 0\\ 0 & k_y\end{bmatrix}\begin{bmatrix}u\\ v\end{bmatrix}. \tag{2}$$

The input displacements u and v are determined by the output of the piezoelectric element system. They can be simply given as

$$\begin{bmatrix}u\\ v\end{bmatrix}=\begin{bmatrix}A_u\cos(2\pi f_r t)\\ A_v\sin(2\pi f_r t)\end{bmatrix}, \tag{3}$$

where A_u and A_v are the amplitudes of the input displacements, and f_r is the resonant frequency of the ultrasonic motor. By substituting the input displacements and their time derivatives into (2), the output displacements x and y are obtained:

$$\begin{bmatrix}x\\ y\end{bmatrix}=\begin{bmatrix}A_x\left(1-e^{-c_x t/2m}\right)\cos\left(2\pi f_r t+\psi\right)\\ A_y\left(1-e^{-c_y t/2m}\right)\sin\left(2\pi f_r t+\psi\right)\end{bmatrix}, \tag{4}$$

where A_x and A_y are the amplitude of output displacements, and ψ is the phase difference shifted from the input displacements. This relationship between x and y describes the growth in an elliptical orbit on the x–y plane at the start of motion. This elliptical motion of the mass particle transfers a driving force to the rotor.

2.2. Definition of stator velocity and slip

The slip is considered to be a relative velocity between the peak tangential velocity of the elliptical motion (stator velocity) and the angular velocity of the rotor (rotor velocity). The stator velocity is determined from the tangential velocity of the mass particle at the top of the elliptical orbit. When the input displacements are applied in (3), the elliptical motion starts to grow. At a point where the stator top contacts the rotor, the mass particle tangentially moves with a velocity A_{vx}, which is estimated from (4):

$$A_{vx}=2\pi f_r A_x\left(1-e^{-c_x t/2m}\right), \tag{5}$$

where A_{vx} takes its values discretely with time when $2\pi f_r t+\psi=\pi/2$, $5\pi/2$, $9\pi/2,\ldots$, in (4). By transforming this tangential velocity to angular velocity, the stator velocity ω_S (rad/s) is

$$w_S=\frac{A_{vx}}{2\pi r}, \tag{6}$$

where r is the radius of the stator.

As the stator velocity increases, the rotor velocity also increases and converges with the stator velocity. During the period between start and convergence, a slip occurs between the stator and rotor. This slip velocity (rad/s) is expressed as the relative velocity by subtracting the rotor velocity ω_R from the stator velocity ω_S. The slip rate s is obtained by dividing the relative velocity by the stator velocity:

$$S=\frac{w_S-w_R}{w_S}. \tag{7}$$

The slip rate is always positive because the stator velocity ω_S is larger than the rotor velocity ω_R at all times. The slip rate s is close to 1 at the start of rotation and then converges to 0 at large rotor velocities.

2.3. Stator torque model

The torque generated by the stator is estimated by a point contact model based on Coulomb friction law [11,21]. The point contact model is evidently simpler than existing models that consider area contact [14,17], but it works well for a typical traveling wave ultrasonic motor. For a given preload N, the dynamic friction torque τ_d between the stator and rotor is

$$\tau_d=\mu_d N r \tag{8}$$

where μ_d is the coefficient of dynamic friction. When the stator generates the elliptical motion, a resultant normal force F_c acts at the contact points between the stator and rotor. Assuming that the preload N is replaced in (8) with the normal contact force F_c, we obtain the driving torque of the ultrasonic motor τ_{stator}:

$$\tau_{\mathrm{statror}}=\mu_d F_c n r, \tag{9}$$

where n is the number of the contact points at which the top of the elliptical motion contacts the rotor. In our experiments, the stator generates five waves at its resonance, thus the number of