The frictional characteristics of Single-phase-drive type USM

Yosuke Nakagawa
Keio University, 3-14-1 Hiyoshi Kohoku-ku, Yokohama, 223-8522, Japan
Kenjiro Takemura
Tokyo Institute of Technology, 4259 Nagatsuta-cho Midori-ku, Yokohama, 226-8503, Japan
Takashi Maeno
Keio University, 3-14-1 Hiyoshi Kohoku-ku, Yokohama, 223-8522, Japan

Abstract - In this paper we analyze the mechanical characteristics of the single-phase-drive type ultrasonic motors. Though single-phase-drive type ultrasonic motors (USMs) has many merits against the multi-phase-drive type USMs, the research of them are not popular and the design method is not established yet. We simulated the static driving characteristics of the single-phase-drive type USM and cleared up the relationship between design parameters and T-N curve, output power and frictional efficiency. Finally we will show the adequacy of the simulations by conducting the driving tests.

I. INTRODUCTION

Ultrasonic motors have advanced features including low-speed and high-torque, high response and silence. Many researchers utilized those features for precision devices. USMs are divided into two. One is the single-phase-drive type USM and the other is the multi-phase-drive type USM. Single-phase-drive type USM needs single current voltage and drive the rotor/slider by linear vibration of the stator. Multi-phase-drive type USM needs multi current voltages with some phase difference, and drive the rotor (slider) by elliptical vibration. They have merits and demerits. Single-phase-drive type USM is easy to be manufactured because the structure is simple. However, output power is smaller and more difficult to change driving directions than that of multi-phase-drive type USM. On the other hand, multi-phase-drive type USM can output high power and easy to change driving directions. However, multi-phase-drive type USM needs to equalize the two natural frequencies for driving. Hence, we need more time and cost for manufacturing.

As the respect of the practical use, single-phase-drive type USM is more practical than multi-phase-drive type USM. However, the research of the multi-phase-drive type USMs is more popular and the design method of the single-phase-drive type USM is not established.

In this paper, we clear up the relationship between design parameters and driving characteristics numerically and show the adequacy of the result by conducting the driving tests.

II. DESIGNING PARAMETERS OF THE MOTOR

As the USMs are driven by friction force from the stator, the contact conditions between the rotor /slider and stator is very important. In the case of multi-phase-drive type USM, it is shown that stiffness of the contact area (stator's indented length to the rotor/slider) and the trajectory of the contact area of the stator dominantly affect the driving characteristics[1][2]. So we focused on the stiffness of the rotor and the trajectory of the contact area of the stator as the important designing parameters. About the trajectory of the stator, we deal the angle of the linear trajectory of the stator with the parameter.

III. NUMERICAL SIMULATION

Modeling

In the simulation, we used the "discrete arrayed spring model". The model is shown in Fig1. We assumed the deformation at the contact point of the rotor/slider and the stator as the deformation of springs. We arrayed the normal and tangential spring at the surface of the rotor/slider. k_x and k_y is the stiffness of the rotor/slider. If the stator is in contact with the rotor/slider, the springs are compressed. Hence generated the reaction force of the rotor/slider is generated.

Because the contact area of the stator moves back-and-forth, if slip is generated at all the contact area all the time, single-phase-drive type USM can't be driven. For driving single-phase-drive type

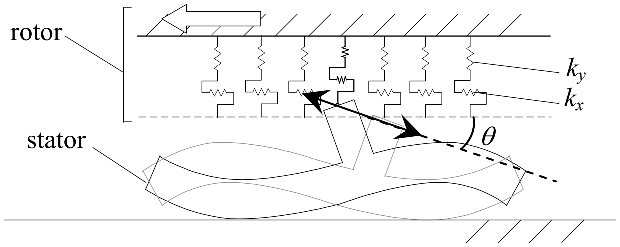


Fig. 1 Discrete-arrayed-spring model

USM, stick-slip at the contact area is important. So we computed the friction force considering the stick-slip. We describe the computing algorism below [3]. We assumed that the height and the driving speed V of the rotor/slider are constant. The trajectory at the top of the stator was given beforehand. When the top of the stator contact with the rotor, we assume the contact condition is stick, compute the normal force F_y and tangential force F_x. Then we check the adequacy of the assumption by the equation (1).

$$F_x < \mu_s \cdot F_y \quad (1)$$

μ_s is the coefficient of static friction. If F_x and F_y meet the equation (1), the assumption before is correct. So the calculated F_x is correct. If F_x and F_y don't meet the equation (1), the assumption is not correct. So we calculate F_x by equation (2).

$$F_x = \frac{\mu_s \cdot F_y}{k_y} \quad (2)$$

Friction loss W_{loss}, mechanical input W_{out} and frictional efficiency are computed by the equation (3), (4) and (5).

$$W_{loss} = \frac{1}{T}\sum \left| F_x \cdot V_{rel} \right| \quad (3)$$

$$W_{out} = \frac{1}{T}\sum \left| F_x \cdot V \right| \quad (4)$$

$$\eta = \frac{W_{out}}{W_{in} + W_{out}} \quad (5)$$

Where, V_{rel} is the relative velocity between horizontal velocity of the stator and the driving velocity of the rotor/slider. T is the cycle of the vibration.

Result of the simulation

(*a*) *Stiffness of the rotor/slider*

We simulated changing the stiffness (stator's indented length to the rotor/slider). When we change the stiffness at the rotor/slider, the indented length of the stator got changes. Fig. 2, 3,

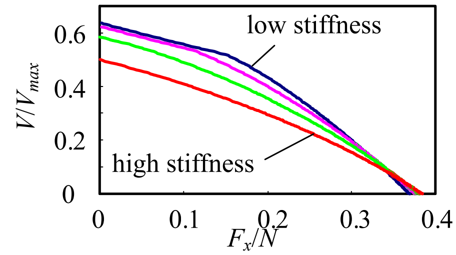


Fig. 2 T-N curve when the stiffness is changed

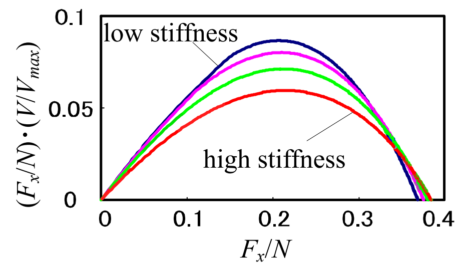


Fig. 3 Output power when the stiffness is changed

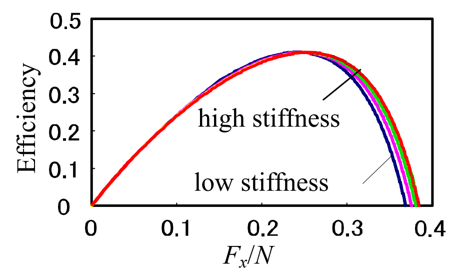


Fig. 4 Efficiency when the stiffness changed

and4 show the T-N curve, output power and frictional efficiency. N is the normal force at the contact area. V_{max} is the maximum of the tangential speed of the stator. Fig. 2 shows that non-dimensional speed increase when the stiffness of the rotor/slider decreases (sinking length increase). Stiffness of the rotor doesn't affect the non-dimensional force and frictional efficiency. The reason is that the linear vibration of the stator is unique. When the stiffness is low, indented length of the stator decrease and rotor/slider contact only when the normal displacement of the stator is high. If the motion of the stator can be assumed as the simple harmonic oscillation, speed of the stator is max at the center of the vibration and the velocity at the edge is zero. If the stiffness of the rotor/slider is high and the indented length is small, the rotor/slider is in contact with the stator only when the velocity of the stator is very small.

(*b*) *Trajectory of the contact area of the stator*

Next, we computed the driving characteristics of the motor when the angle θ is

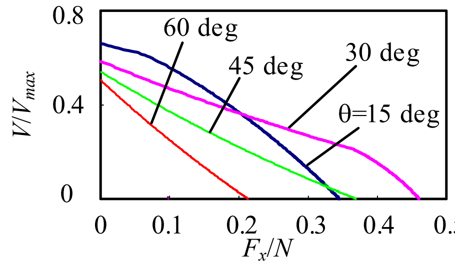


Fig. 5 T-N curve when the trajectory is changed

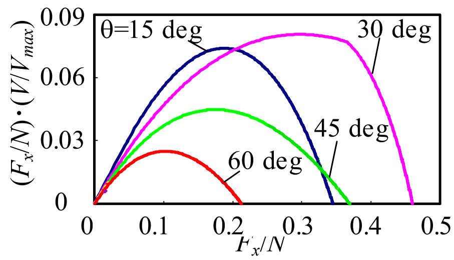


Fig. 6 Output power when the trajectory is changed

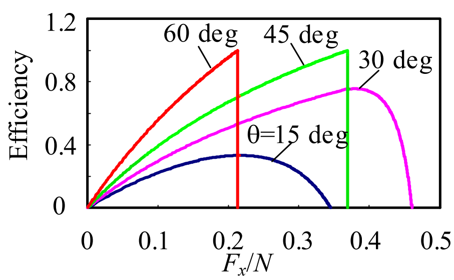
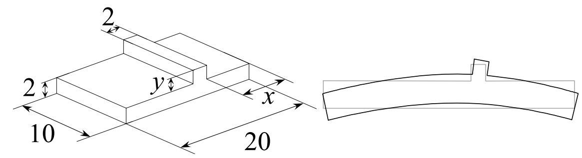


Fig. 7 Efficiency when the trajectory is changed



(a) Size (b)Mode shape

Fig8. Designed stator

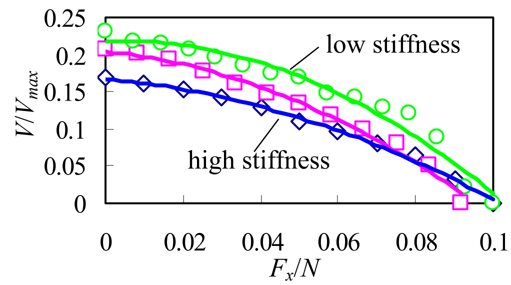


Fig. 9 T-N curve when the stiffness is changed

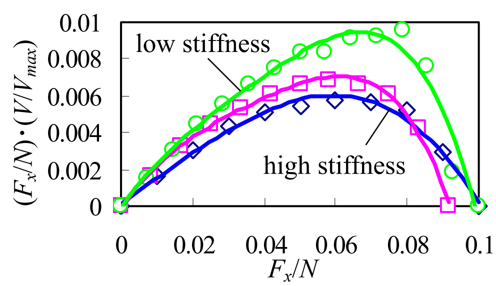


Fig. 10 Output power when the stiffness is changed

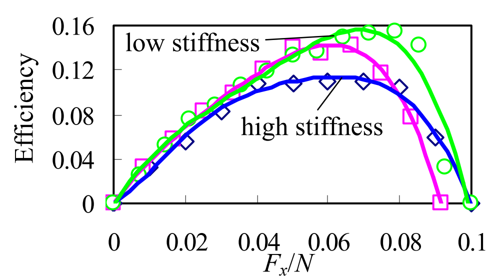


Fig. 11 Efficiency when the stiffness is changed

changed (Fig2). .The total amplitude of the stator didn't change. Fig 5, 6, and 7 show the results. As shown in Fig. 5, the non-dimensional speed increases by decreasing the angle θ. The non-dimensional force has the peak. In connection with the T-N characteristics, we can check a peak of non-dimensional output power in Fig. 6. We can see that the frictional efficiency has the peak at very low speed independently to the angle θ.

If the angle θ increase, the maximum tangential speed of the stator decrease and the speed of the rotor/slider decrease. The reason why the non-dimensional force has the peak is in relation to the stick-slip at the contact area. If the angle θ is small, the tangential amplitude of the stator increases. However the tangential amplitude of the stator is too large; slip is dominant on the contact area and driving force decrease. In relation to the T-N curve, the output power has the peak too. Fig. 7 shows that the frictional efficiency is about 100% at the low speed. When the motor is driven at low speed, the slipping time decrease. This causes the decrease of frictional loss W_{loss} and the increase of the frictional efficiency. So the trajectory of the contact area of the stator has the best one for high output power and frictional efficiency.

IV. DRIVING TESTS

Design of the stator

Fig. 8 shows the stator we manufactured. The shape of the stator is the plain plate with projection. Stator can be in contact with the rotor/slider at the projection. We use the first bending mode for driving. The natural frequency is about 26～28kHz.

We changed the trajectory of the projection by changing the position (x) and the height (y). Piezo-ceramics is bonded at the back of the stator and we set two sheets of electrodes. One is for driving and the other is for sensing the amplitude of the stator. The stator is made of stainless steel.

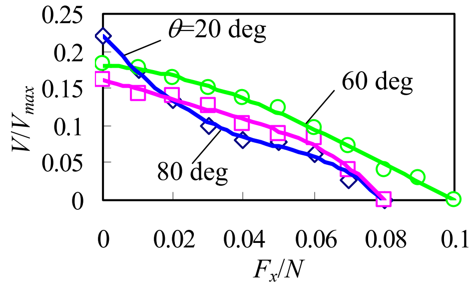


Fig. 12 T-N curve when the trajectory is changed

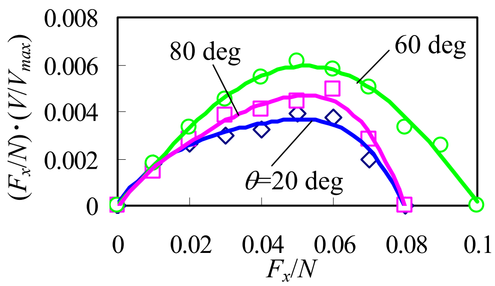


Fig. 13 Output power when the trajectory is changed

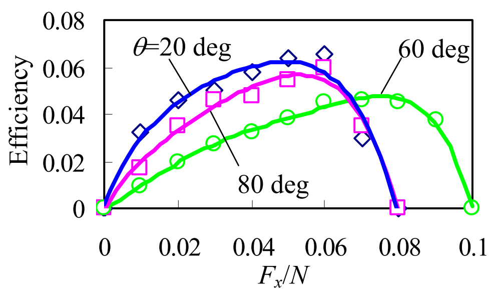


Fig. 14 Efficiency when the trajectory is changed

Experimental setup

To check the adequacy of the simulation, we conducted the driving test with changing the stiffness of the rotor/slider and the trajectory of the projection (angle θ). If we use many rotors/sliders with various values of stiffness, we need many rotors/sliders. So we changed the normal force to the rotor and changed the indented length. Trajectory of the projection can be changed by manufacturing stators the parameter x and y is changed. When we input voltage from the oscillator through the amplifier, stator vibrates and the rotor rotates. The axis of the rotor is fixed and normal force can be controlled by weights. The load of the rotor can be measured by the weight. The rotational speed of the rotor can be measured by encoder. The coefficient of friction was about 0.6.

Result of the experiments

(a)stiffness of the rotor

Fig. 9, 10 and 11 shows the relationship between driving characteristics and the stiffness of the rotor. As shown in Fig. 9 and 10, the non-dimensional speed and output power increase with the increase of the stiffness. Fig.11 shows that the total efficiency has the peak when the non-dimensional speed is small.

(b)Trajectory of the stator

Fig. 12, 13 and 14 are the results of the driving tests when the trajectory is changed. Fig. 12 shows that the non-dimensional speed increases by the increase of angle θ. The non-dimensional force has the peak at about 60 deg. The total efficiency becomes maximum at high driving force at all the angle θ.

Discussion

The results of the driving tests match those of simulations qualitatively. However, the measured total efficiency does not have the same tendency as simulated ones. Total efficiency includes not only frictional loss but also inertial loss and supporting loss, electrical loss. Much precise study on efficiency considering those effects is needed.

V. CONCLUSIONS

The frictional characteristics of Single-phase-drive type USM is calculated by numerical simulation and the relationship among the stiffness, the trajectory of the projection and the driving characteristics in mechanical part are clarified. As a result of the simulation, it was shown that the best performance is obtained by decreasing the stiffness of the contact point and by designing the trajectory of the angle of the projection to be about 30 deg. Finally, the driving tests are conducted to check the adequacy of the simulations in mechanical part.

This study was supported in part by Grant-in-Aid for Encouragement of Young Scientists (B)15760093 of the Ministry of Education, Culture, Sports, Science and Technology of Japan.

VI. REFERENCES

[1] H. Hirata, S. Ueha, "Design of a Traveling Wave Type Ultrasonic Motor", *IEEE Trans. Ultrason. Ferroelect. Freq.Cont.*,vol. 42, no. 2 pp. 225-231, 1995

[2] H.Storck, J.Wallashck, "The effect of tangential elasticity of the contact layer between stator and rotor in traveling wave ultrasonic motors", *Int. J. Non-linearMech*. Vol. 38, pp. 143-159, 2003

[3] T. Maeno, "Contact analysis of traveling wave type ultrasonic motor considering stick/slip condition", *J. Acourst. Soc. Jpn*, vol.54-4, pp.305-311, 1998 (in Japanese)