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Torque control of ultrasonic motor using holding torque reduction by standing wave excitation

定在波励振による保持トルク減少を用いた超音波モータのトルク制御

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1. Introduction

Ultrasonic motor has many unique, useful features such as lightweight, compact structure, less audible noise, high torque without speed reduction gear, fast response, self-locking, and so on. Therefore, many researchers utilized ultrasonic motor for new applications, including an assisted suit system walking activity for elderly[1)], a five-fingered robot hand imitating human for use such as teleoperation[2)], and haptic force-feedback interface[3)].
On the other hand, while these applications require torque control, the torque control of ultrasonic motor is relatively tricky than that of electromagnetic motor because the ultrasonic motor has nonlinear torque characteristics.
In this paper, we focused on the holding torque of ultrasonic motor, which was reported as one of the factors that makes torque control of ultrasonic motor difficult[3)]. Moreover, we proposed a way to eliminate holding torque effect to the torque control system.

2. Principle of holding torque reduction

As mentioned above, the holding torque of the ultrasonic motor makes it difficult to control the output torque of the ultrasonic motor. When the rotation direction is reversed, the holding torque direction changes and makes a large disturbance to the torque control system.[3)] It is reported that the holding torque can be reduced by exciting standing wave on the stator.[4)]
Therefore, we simulated friction force between stator and rotor using an elastic model to reveal the holding torque reduction phenomenon. The normal force $u_n(\varphi)$ and tangential force $u_t(\varphi)$ are proportional to deformation of the rotor in each direction, where φ is the angle of the ring stator surface.

$$f_n(\varphi) = k_n u_n(\varphi), f_t(\varphi) = k_t u_t(\varphi)$$

The deformation in the normal direction is calculated as below.

$$u_n(\varphi) = \begin{cases} w(\varphi) - h, & w(\varphi) - h \geq 0 \\ 0, & w(\varphi) - h < 0 \end{cases}$$

where $w(\varphi)$ is the vibration displacement of the stator, h is the height of free surface of rotor, which is determined by the condition as

$$F_n = \int_0^{2\pi} f_n(\varphi)\, d\varphi.$$

When the contact surface is sticking ($|f_t(\varphi)| < \mu f_n(\varphi)$),

$$\frac{\partial u_t}{\partial t}(\varphi) = v - v_R$$

where v is tangential speed of stator and v_R is the speed of the rotor.
When the contact surface is slipping, $u_t(\varphi)$ is determined by equation $|f_t(\varphi)| = \mu f_n(\varphi)$, where μ is the friction coefficient of the contact surface.
Finally, the torque produced by the motor is calculated as the total torque produced by whole contact surface as

$$T = \int_0^{2\pi} f_t(\varphi)\, r d\varphi.$$

As shown in **Fig. 1**, when no vibration is excited, the entire contact surface produces the maximum frictional force. As vibration amplitude increases, the frictional torque decreases. By exciting vibration to the stator, the elastic rotor surface repeats stick and slip, and this makes the friction torque smaller.

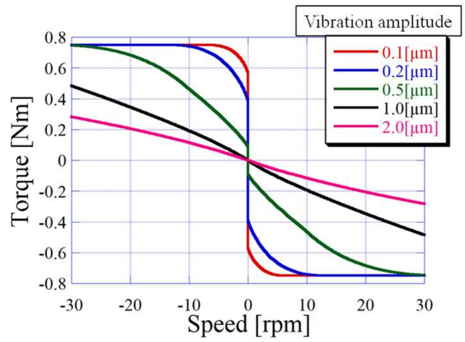

Fig. 1　simulated speed-torque characteristics

3. Experimental setup

To measure the speed-torque characteristics of the motor with the standing wave excitation on the stator, we built experimental setup. The ultrasonic motor USR60(Fukoku) was rotated by an electromagnetic servo motor NX920AA-PS25-3(Oriental motor) connected to the output shaft of USR60. The digital signal processer DSP1104(dSPACE) controlled the experiment system. DSP sent a command of two driving voltage amplitude, frequency, and phase to

sine-wave generator AD9959(Analog Devices). These driving voltages were amplified 500 times by amplifiers HSA4052(NF Corporation). and 1:5 transformers, and then those were applied to two driving electrodes of the motor.
A torque sensor SS-050(Ono Sokki) measured the rotational speed and the torque.
In order to measure the vibration amplitude of the stator, the feedback electrode voltage of the ultrasonic motor was used, which proportional to vibration amplitude. The feedback voltage was attenuated by the active differential probe TA041(Pico Technology), then inputted with an attenuated driving voltage of the ultrasonic motor to a lock-in amplifier LI5640(NF Corporation). to convert its amplitude to an analog signal.

4. Experiment

To excite the standing wave on the stator, two in-phase 100[Vrms] voltages were applied with various driving frequencies 42.5[kHz], 43.0[kHz], and 43.5[kHz]. The electromagnetic servo motor speed was swept from -30[rpm] to 30[rpm] in 120[s] to measure the torque-speed characteristics at low speed.
Since standing wave doesn't make a driving force, the holding torque from the motor was always opposite to the rotating direction (**Fig. 2**). More importantly, the smaller holding torque was obtained with a large vibration amplitude. This tendency implies the holding torque can be removed by maintaining the vibration amplitude to some extent.

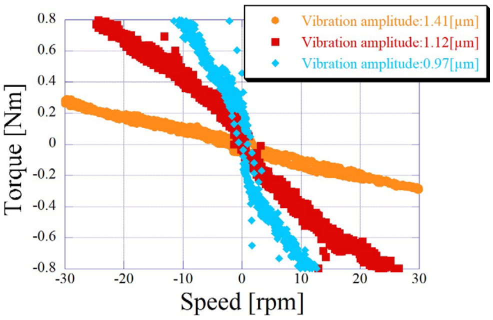

Fig. 2 Measured torque-speed characteristics

5. Torque control

From the result of section 4, we inferred that we could eliminate the large error from the holding torque reported in previous research by keeping large vibration amplitude.
To prove this hypothesis, we compared two control methods using the same experimental setup as section 3. One was a driving frequency control as PI control, and the other was a phase control method.
Since the frequency control method adjusts vibration amplitude based on the resonance characteristics, we expected it to suffer the control error due to the large holding torque with small vibration amplitude. On the other hand, since the phase control method doesn't adjust the vibration amplitude and keeps large vibration amplitude, it was expected small error
In all experiments, the target torque was kept at 0[Nm], and the electromagnetic motor controlled the rotational speed of motor sinusoidally during the experiments.

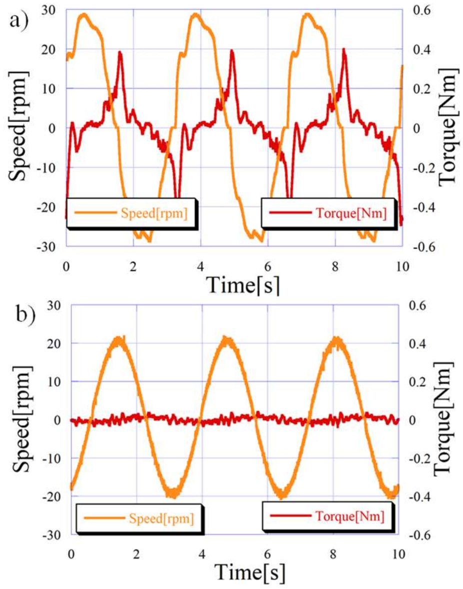

Fig. 3 Torque error of two control methods
(a) frequency control (b) phase control

Fig. 3a shows the result of the frequency control. As we expected, the measured torque suddenly changed at the reverse of rotation. The root mean squared error was 0.15[Nm]. On the other hand, in the case of the phase control, such error was removed, and the torque error was reduced to 0.014[Nm] (**Fig. 3b**).

6. Conclusion

By theoretical analysis using the elastic rotor model, we found that the holding torque can be reduced or eliminated by large vibration amplitude, and we verified this phenomenon by experiment.
In addition, the phase control method resulted in quite small error at the reverse of rotation. This makes it possible to implement the torque control system with high backdrivability, which is indispensable on various applications such as wearable robotics or manipulator.

References

1. T. Kaneko, Y. Orino, S. Hachisuka and T. Morita, LifeTech 2020 - 2020 IEEE 2nd Glob. Conf. Life Sci. Technol. 275 (2020).
2. I. Yamano and T. Maeno, Proc. - IEEE Int. Conf. Robot. Autom. 2005 [April], 2673 (2005).
3. P. Sandulescu, S. Member, M. Amberg, B. Lemaire-semail and F. Ionescu, IEEE Trans. Haptics **4** [4], 327 (2011).4.
4. S. W. Chung and K. T. Chau, IEEE Trans. Ind. Electron. **55** [1], 302 (2008).