SPEED CONTROL FOR ULTRASONIC MOTORS USING FUZZY ON-LINE TUNING SYSTEM

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ABSTRACT – This paper presents a speed control for ultrasonic motors using a PI controller and disturbance torque observer. Since the PI gains and the observer's poles are generally fixed, the control performance deteriorates when the driving conditions vary much. Therefore, we propose the speed control scheme that the PI gains and the observer's poles are adjusted on-line in accordance with the speed ripple using fuzzy reasoning.

1 . INTRODUCTION

Ultrasonic motors(USMs) are a newly developed motor and it has excellent performance and many useful features, e.g., high torque density, low speed, compactness in size, no electromagnetic interferences and so on[1]. The features that USM can operate in low speed range is useful for utilizing as gearless actuators or direct servo drives. Recently they have been utilized as actuators for driving joints of articulated robots. The proposed speed control scheme would be applied to these applications because they require quick and precise speed control for various load conditions. However, the drive principle of USM is different from that of general electromagnetic type motors, furthermore, USM has highly non-linear speed characteristics and these characteristics are sensitive to the change of driving conditions such as driving frequency and applied load torque. Therefore, it is difficult to control USM with high performance at all times.

In recent years, there have been reported some precise mathematical models of USM based on equivalent circuit[2] or Minddlin and Reissner theories[3], however, these models are too complex to apply for motor control. Therefore, most speed/position controllers for USM have been designed using a proportional and integral (PI) controller[4], [5] which might not use the mathematical model of the motor. The control algorithm of this controller is simple, and has the advantageous features — wide stability margin and high reliability — when the PI gains are well tuned. However, the speed characteristics of USM vary with driving conditions, therefore, adjusting the PI gains is necessary to obtain fine speed control performance at all times.

The authors have been proposed speed control of USM using fuzzy neural network(FNN) in a previous work[6]. In the speed control, the controller is effective for the characteristic variations because the PI gains are adjusted on-line using FNN. However, in that work, it is difficult to improve the speed tracking performance and the disturbance suppression ability at the same time.

In order to solve the problems and control USM with high performance, we employ a PI controller and disturbance torque observer. The control system is robust with respect to plant parameter variations and disturbance torque. Since the PI gains and the observer's poles are generally fixed, the control performance deteriorates when the driving conditions vary much. Therefore, we propose the speed control scheme for USM, the PI gains and the observer's poles are adjusted on-line in accordance with the speed ripple using fuzzy reasoning.

In general, the speed of USM can be controlled by driving frequency and phase difference of applied voltages. This paper adopts the driving frequency control input in order to simplify the drive system and improve the efficiency of USM. Firstly, a brief description of drive principle of USM and the drive system used in this paper is shown in Section 2. The characteristics of speed ripple of USM are indicated in Section 3. Then, a speed control system using the proposed control scheme is constructed in Section 4. The effectiveness of the proposed control scheme is compared with that of a PI controller in Section 5. Finally, conclusions

Table 1. *Design specifications of tested USM.*

Driving frequency	40 kHz
Driving voltage	100 Vrms
Rated current	53 mA × 2
Rated torque	0.314 Nm
Rated output power	3 W
Rated speed	9.0 rad/s
Weight	0.240 kg

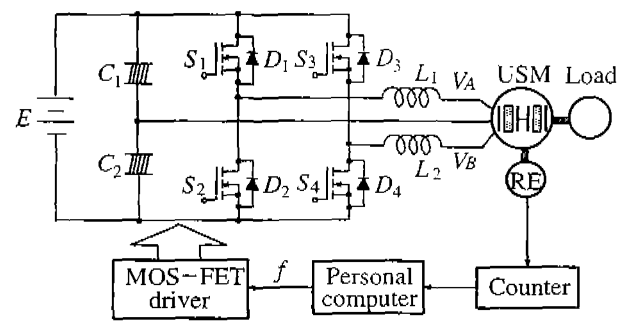
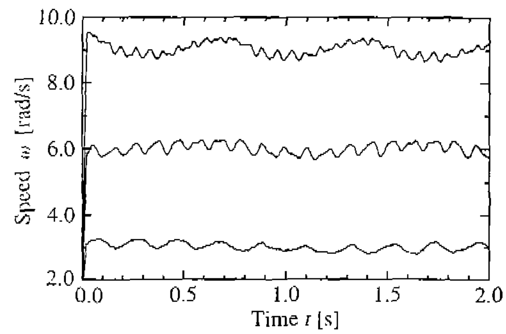
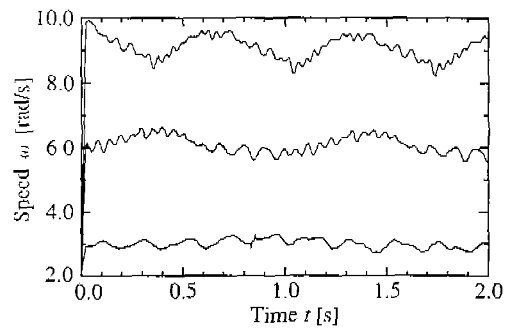


Fig. 1. Drive system for USM.



(a) No load.



(b) Load torque T_L=0.30Nm.

Fig. 2. Revolving speed vs. driving conditions.

of this paper are summarized in Section 6.

2. DRIVE SYSTEM

The drive system of speed control for USM is shown in Fig. 1, and the design specifications of tested USM are shown in Table 1. A typical traveling-wave type USM consists of a rotor, stator made by elastic body, and piezoelectric elements [1]. When two-phase voltages whose frequency is near the resonant frequency of the motor are applied to the piezoelectric elements, traveling wave is produced on the surface of the stator. The traveling wave generates vibration force with an elliptic locus on the stator surface, then the rotor in contact with stator is rotated by the vibration force. Drive control system of USM are generally considered to be driving frequency control and phase difference control of two-phase voltages V_A and V_B. As the efficiency of USM using the phase difference control to speed control is low, we adopt the driving frequency control only.

In Fig. 1, load and rotary encoder are connected with the USM via coupling, and the motor speed is measured using the rotary encoder which has 10,000 pulses per revolution. The microcomputer calculates the control input, and the control signal is transmitted to the drive circuit using programmable frequency oscillator which generates the switching signals for the drive circuit. Then the drive circuit generates the two-phase alternating voltages V_A and V_B, and they are applied to the USM.

3. CHARACTERISTICS OF SPEED RIPPLE

Fig. 2 illustrates the characteristics of speed ripple for driving conditions at a fixed driving frequency. The driving frequency is determined so that the revolving speed becomes almost 3.0rad/s, 6.0rad/s, and 9.0rad/s, respectively. As shown in Fig. 2, in the case of open-loop drive, there are large speed ripple, and the speed ripple becomes large as the revolving speed increases. Furthermore, it becomes large as applied load torque increases as shown in Fig. 2(b). Therefore, the suitable PI gains and observer's pole are different with driving conditions such as revolving speed and applied load torque.

In case of that the PI gains and the observer's pole are fixed, the control performance deteriorates when the driving conditions vary much. For the purpose of solving this problem, this paper proposes a speed con-

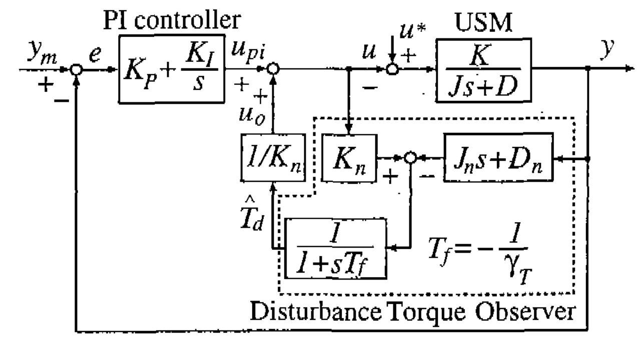


Fig. 3. Block diagram of speed control.

trol scheme which can compensate change of the speed ripple by adjusting the PI gains and the observer's pole.

4. SPEED CONTROL SCHEME

Fig. 3 shows a speed control system by using a PI controller with disturbance torque observer, where y_m is the commanded speed, y is the actual revolving speed, e is the speed error, u is the control input(driving frequency), and u^*(=41.6kHz constant) is the biased frequency, respectively.

The control input u is determined as

$$u = u_{pi} + u_o \tag{1}$$

where u_{pi} is the control input of the PI controller and u_o is the control input which compensates disturbance torque. These control inputs are determined as follows

$$u_{pi} = \left(K_P + \frac{K_I}{s}\right)e \tag{2}$$

$$u_o = \frac{\hat{T}_d}{K_n} \tag{3}$$

where K_P, K_I are the proportional gain and integral gain of PI controller, $\hat{T}_d$ is the estimated equivalent disturbance torque which can be estimated by the disturbance torque observer.

If the PI gains and observer's pole are tuned suitable value, fine control performance is obtained by the control input u. However, as the speed characteristics of USM vary with driving conditions, the control system may be unstable when the PI gains and the observer's pole are fixed. Therefore, we propose the speed control scheme of USM, the PI gains and the observer's poles are adjusted on-line in accordance with the speed ripple using fuzzy reasoning.

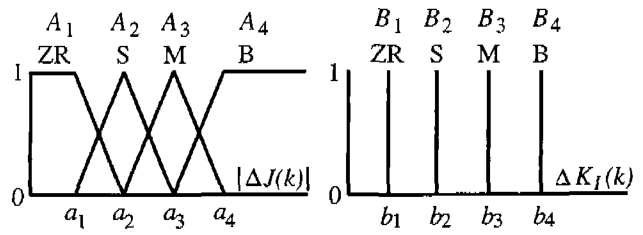


Fig. 4. Membership functions for $|\Delta J(k)|$, $\Delta K_I(k)$.

On-line Tuning of PI controller

In the speed control, it is important to improve the speed tracking performance and the disturbance suppression ability. As the disturbance suppression ability can be determined by pole assignment of disturbance torque observer, the proportional gain of the PI controller is tuned in order to improve the speed tracking performance, and then, it is fixed. Therefore, only the integral gain is adjusted on-line in accordance with the speed ripple using a fuzzy reasoning.

The steady state error can be reduced by the integral controller. Therefore, in order to adjust the integral gain, we adopt the mean absolute value of the speed control error as a cost function. The cost function is described as

$$J(k) = \frac{T_S}{m} \sum_{n=k-m}^{k} |e(n)| \tag{4}$$

where T_S is the sampling period, m is a number of data for calculating the cost function $J(k)$.

At the steady state, $\Delta K_I(k)$ indicated in (5) is determined using fuzzy reasoning in order to reduce the cost function $J(k)$

$$K_I(k) = K_I(k-1) \pm \Delta K_I(k). \tag{5}$$

The integral gain adjustment procedure is explained as follows. For instance, either of an increase/decrease of the integral gain is decided, and then, integral gain is updated every m sampling period. If the cost function is decreases compared with the preceding one, the direction of increment and decrement of the integral gain is the same. In case the cost function is increased, the direction of increment and decrement is turned over.

In order to determine the $\Delta K_I(k)$, we adopt the fuzzy reasoning. The difference of the cost function is adopted as the input variable of the fuzzy reasoning. The membership functions of the fuzzy sets are shown in Fig. 4. The singleton values for output fuzzy set is selected to reduce the computational burden for defuzzification. The abbreviations used in these fuzzy sets are as follows

ZR : Zero, S : Small, M : Medium, B : Big.

The i-th fuzzy rule is given as

$$\text{Rule } i : \text{if } |\Delta J(k)| \text{ is } A_j \text{ then } \Delta K_I(k) \text{ is } B_j \quad (6)$$

$$j=1,\ 2,\ 3,\ 4$$

where A_j is the fuzzy set of the antecedent functions, while B_j is the fuzzy set of the consequent functions. Finally, the defuzzification is performed as

$$\Delta K_I(k) = \sum_{i=1}^{4} w_i B_i \Big/ \sum_{i=1}^{4} w_i. \quad (7)$$

To avoid the sudden change of the integral gain, $\Delta K_I(k)$ determined by (7) is filtered out through low-pass filter(LPF).

Design of Disturbance Torque Observer

To obtain the estimated equivalent disturbance torque $\hat{T}_d$, we design the disturbance torque observer. The motion equation with respect to parameter variations for the USM is represented by

$$J_n \frac{d\omega}{dt} + D_n\omega + T_d = K_n u \quad (8)$$

where, $T_d = \Delta J \frac{d\omega}{dt} + \Delta D\omega - \Delta K u + T_L$ is the equivalent disturbance torque, ΔJ, ΔD, ΔK are the parameter variations from nominal values, n implies nominal value, T_L is the applied load torque.

To construct the disturbance torque observer, the dynamic model for the disturbance torque is defined by $\dot{T}_d$=0. From (8) and $\dot{T}_d$=0, the state equation and the output equation are represented as

$$\begin{bmatrix} \dot{\omega} \\ \dot{T}_d \end{bmatrix} = \begin{bmatrix} -\frac{D_n}{J_n} & -\frac{1}{J_n} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \omega \\ T_d \end{bmatrix} + \begin{bmatrix} \frac{K_n}{J_n} \\ 0 \end{bmatrix} u \quad (9)$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \omega \\ T_d \end{bmatrix} \quad (10)$$

From (9) and (10), the disturbance torque observer is constructed using Gopinath's observer design algorithm as

$$\hat{T}_d = \xi_T + G_T\omega \quad (11)$$

$$\dot{\xi}_T = \hat{A}_T\xi_T + \hat{B}_T u + \hat{C}_T\omega \quad (12)$$

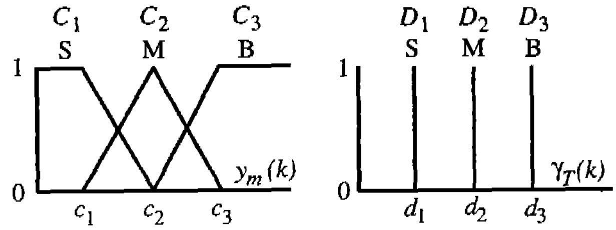


Fig. 5. Membership functions for $y_m(k)$, $\gamma_T(k)$.

where ξ_T is the intermediate variable, G_T is the observer gain, $\hat{A}_T$=G_T/J_n, $\hat{B}_T$=$-G_T K_n/J_n$, $\hat{C}_T$=$G_T(G_T+D_n)/J_n$, $G_T = J_n\gamma_T$ and, γ_T is the observer's pole. Notice that the estimation rate of $\hat{T}_d$ is determined by pole assignment of observer.

In general, the observer's pole is determined in order to obtain a good disturbance suppression ability. Since the characteristics of speed ripple vary with revolving speed, suitable observer's pole is different in accordance with the revolving speed. Therefore, we apply fuzzy reasoning to adjust the observer's pole online in accordance with the revolving speed.

The membership functions of the fuzzy sets are shown in Fig. 5. The commanded speed is adopted as the input variable of the fuzzy reasoning. The i-th fuzzy rule is given as

$$\text{Rule } i : \text{if } y_m(k) \text{ is } C_k \text{ then } \gamma_T(k) \text{ is } D_k \quad (13)$$

$$k=1,\ 2,\ 3.$$

The defuzzification is performed as

$$\gamma_T(k) = \sum_{i=1}^{3} w_i D_i \Big/ \sum_{i=1}^{3} w_i. \quad (14)$$

To avoid the sudden change of the observer's pole, $\gamma_T(k)$ determined by (14) is filtered out through LPF.

5. EXPERIMENTAL RESULTS

In order to evaluate the control performance of the proposed controller, the experimental results of speed control using the proposed control scheme are compared with that of a conventional PI control.

Speed control by using PI control

The experimental results of speed control using a PI control are illustrated first. The control parameters used in the experiments are shown in Table 2.

Fig. 6 shows the experimental result for adjustable-speed control when the commanded speed is changed

Table 2. Control parameters.

Sampling period	$T_S = 2.0$ ms
Proportional gain	$K_P = 0.10$
Number of data	$m = 500$
Inertia constant	$J_n = 1.438 \times 10^{-4}$ kgm^2
Damping coefficient	$D_n = 1.041 \times 10^{-1}$ Nms/rad
Torque constant	$K_n = 6.247 \times 10^{-4}$ Nm/Hz

Table 3. Parameters of membership functions.

a_1=0.5, a_2=1.0, a_3=2.0, a_4=6.0 ($\times 10^{-3}$)
b_1=0.0, b_2=0.2, b_3=0.5, b_4=1.0 ($\times 10^{-2}$)
c_1=3.0, c_2=6.0, c_3=9.0
$d_1 = -1750$, $d_2 = -1150$, $d_3 = -850$

in a wide speed range, where the integral gain is determined to minimize the cost function at the commanded speed 6.0rad/s. The control performance deteriorates when the commanded speed is 9.0rad/s, because the suitable integral gain vary with revolving speed.

Fig. 7 shows the experimental result for a constant speed and step-wise applied load torque(0.30Nm, 96% rated torque). In Fig. 7, the speed ripple is large when the applied load torque is changed. Accordingly, it is difficult to control the USM with high performance using a PI controller with fixed gain.

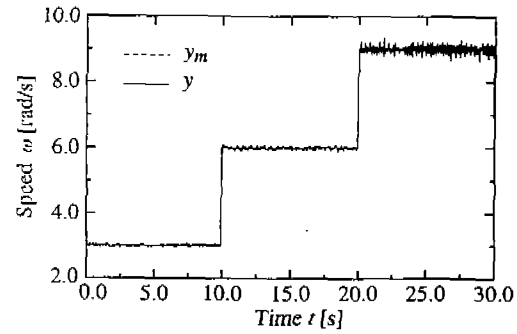
Speed control using proposed control scheme

The control parameters and the parameters of membership functions used in the experiments are shown in Table 2 and Table 3, respectively.

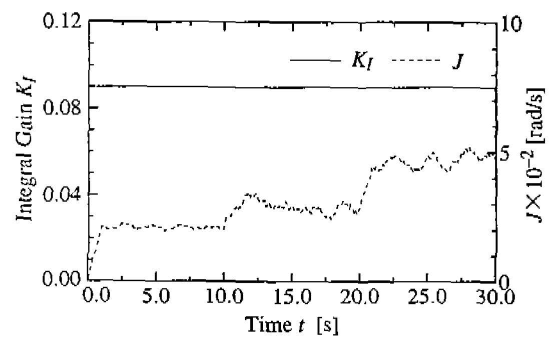
Fig. 8 shows the experimental result for adjustable-speed control when the commanded speed is changed in a wide speed range, but the disturbance torque observer is not used in order to evaluate the on-line tuning scheme of the integral gain. In Fig. 8(b), the integral gain is adjusted on-line in order to minimize the cost function. Therefore, the high-performance speed drive is achieved as shown in Fig. 8(a).

Fig. 9 shows the experimental result for a constant speed and step-wise applied load torque. In Fig. 9(a), the speed ripple is suppressed well even if the applied load torque is changed, because the control input u_o compensates the disturbance torque.

Fig. 10 shows the experimental result for adjustable-speed control and step-wise applied load torque. As shown in Fig. 10(b), the observer's pole is adjusted on-line in accordance with the revolving speed. As the result, the fine disturbance suppression ability is obtained at each commanded speed.



(a) Revolving speed.



(b) Integral gain K_I, cost function J

Fig. 6. Speed control using PI control (K_I=0.09).

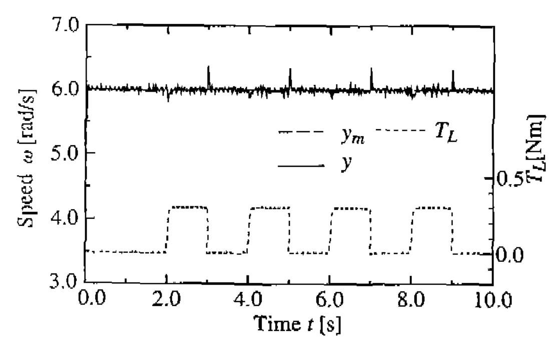
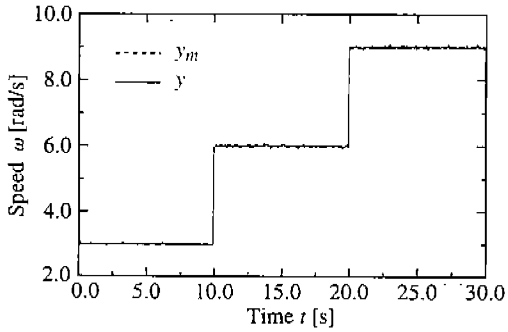


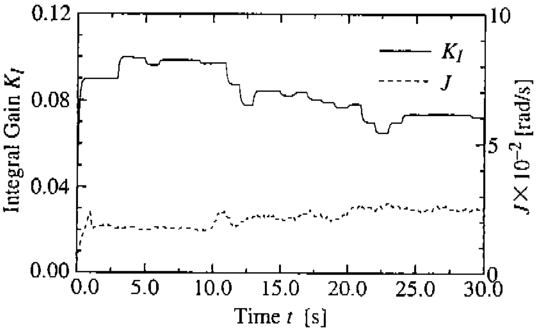
Fig. 7. Speed control using PI control (K_I=0.09).

6. CONCLUSIONS

As the speed characteristics of USM vary with driving conditions, it is difficult to control USM with high performance at all times. For the purpose of solving the problem, this paper proposed a speed control scheme that the integral gain of the PI controller and the observer's pole are adjusted on-line in accordance with the speed ripple using fuzzy reasoning. The experimental results demonstrated the effectiveness of the proposed control scheme.

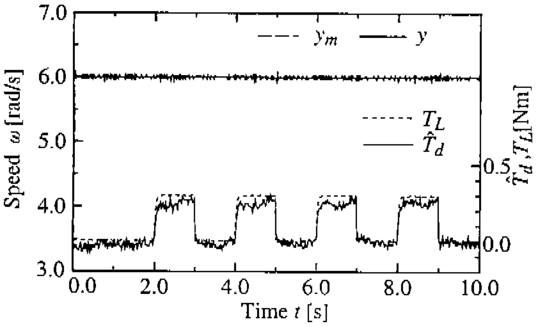


(a) Revolving speed.

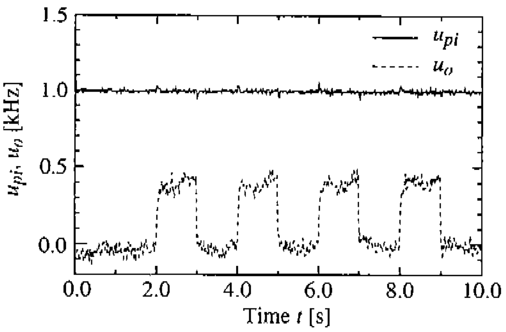


(b) Integral gain K_I, cost function J

Fig. 8. Speed control using proposed control scheme (without disturbance torque observer).

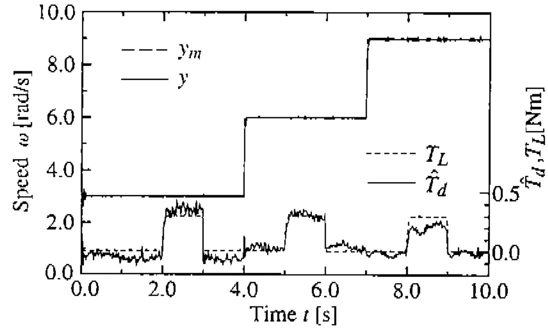


(a) Revolving speed.

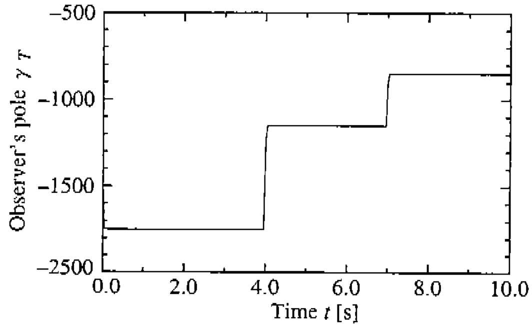


(b) Control inputs u_{pi}, u_o

Fig. 9. Speed control using proposed control scheme (with disturbance torque observer).



(a) Revolving speed.



(b) Observer's pole γ_T.

Fig. 10. Speed control using proposed control scheme (with disturbance torque observer).

7. REFERENCES

[1] T. Kenjyo and T. Sashida, An Introduction of Ultrasonic Motor, Oxford Science Publications, 1993.

[2] Nogarede B. and Piecourt E., "Modelisation of a Travelling Wave Piezoelectric Motor by Equivalent Electromechanical Circuit", *Proceedings of the International Conference on Electrical Machines*, pp. 128-133, 1994.

[3] P. Hagedorn and J. Wallaschek, "Travelling Wave Ultrasonic Motors, Part I: Working Principle and Mathematical Modelling of the Stator", *Journal of Sound and Vibration*, Vol. 155, No. 1, pp. 31-46, 1992.

[4] H. Takeishi and R. Mitarai, "Dual Mode Position Control of Ultrasonic Motor", *Proceedings of the 31th Society of Instrument and Control Engineers Annual Conference*, pp. 401-402, 1992 (in Japanese).

[5] T. Izumi, H. Yasutsune, Y. J. Kim, M. Nakaoka, S. Furuya, and T. Maruhashi, "New Inverter-Fed Power Ultrasonic Motor for Speed Tracking Servo Application and Its Feasible Evaluations", *Proceedings of 1995 International Conference on Power Electronics and Drive Systems*, pp. 766-773, 1995.

[6] T. Senjyu, S. Yokoda, and K. Uezato, "Speed Control of Ultrasonic Motors Using Fuzzy Neural Network", *IEEE International Power Electronics Congress Technical Proceedings*, pp. 29-34, 1996.