Robust Position Control of Ultrasonic Motor using VSS Observer

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Abstract— **Intrinsic properties of ultrasonic motor (high torque for low speed, high static torque, compact in size, etc.) offer great advantages for industrial applications. However, when load torque is applied, dead-zone occurs in control input. Therefore, sliding mode controller, which is a nonlinear controller, is adopted for ultrasonic motor. The state quantities, such as acceleration, speed, and position are needed to apply the sliding mode controller for position control. However, rotary encoder causes quantization errors in the speed information. This paper presents a robust position control method for ultrasonic motor by using Variable Structure System(VSS) observer. The state variables for sliding mode controller are estimated by the VSS observer. Besides, a small, low cost, and good response sliding mode controller is designed in this paper by using a micro computer that is essential in embedded system for the developments of industrial equipments. The effectiveness of the proposed method is verified by experimental results.**

I. INTRODUCTION

In recent years, ultrasonic motor(USM) is gaining attention as it has good characteristics and is small in size. The drive source of ultrasonic motor is ultrasonic vibration of piezoelectric element. USM is expected to be applied to robot actuator, high precision positioning and medical equipments[1]. The operating principle of an USM has complicated speeds characteristics compared to conventional electromagnetic motor which makes it a special kind of motor.

However, an USM has dead-zone in its control input with applied load torque[3]. Since H_∞ controller is a linear controller[2], it cannot control the USM with unknown dead-zone. Therefore, sliding mode controller[4]-[6], which is a nonlinear controller, is used for robust position control of USM with unknown dead-zone. To apply sliding mode controller for position control of USM, state variables such as acceleration, speed and position of the USM are needed. Speed information detected by a rotary encoder have quantization errors, especially in low speed region. Therefore, to estimate actual rotor speed accurately by a using VSS observer[7] is proposed with the possibility of decreasing quantization error.

Essential industrial equipments are developed in small size, lightweight and power-saving technology, by using embedded system. Use of micro computer in embedded system, has advantages(such as it can discretize all processing, can design stable and small size circuit in comparison to analog circuit, can construct control system at low cost, can upgrade response, and can make the system easily design easy and change).

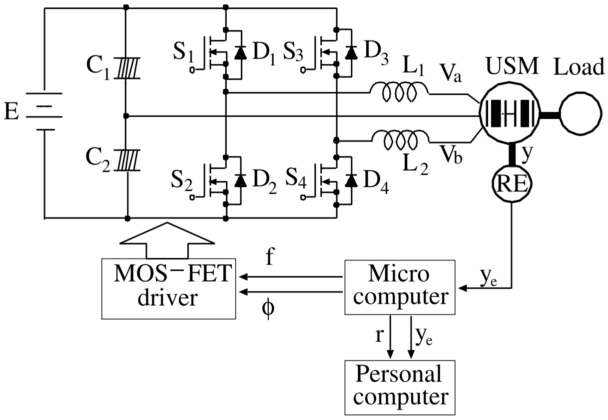

Fig. 1 Drive system of USM.

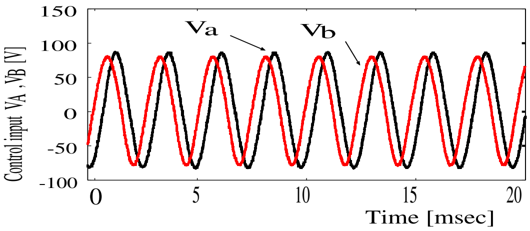

Fig. 2 Output voltages of two-phase inverter.

This paper presents a digital implementation[8]-[9] of a sliding mode controller and a VSS observer by using a micro computer for efficient position control of the USM with unknown dead-zone. The state variables are estimated by the VSS observer and are used in sliding mode controller. The proposed sliding mode controller is found satisfactory.

II. SYSTEM CONFIGURATION

A. Driving system of USM

All configuration of the USM control system used in this study is shown in Fig. 1. The USM used in the experiment is a traveling wave USM(SHINSEI CORPORATION : USR-60). Output voltages of the two-phase inverter are shown in Fig. 2. A traveling wave is formed on the stator surface when impress

Table 1. Design specifications of USM.

Drive frequency	40 kHz
Drive voltage	100 V_{rms}
Rated current	53 mA/phase
Rated torque	0.314 Nm
Rated output power	3 W
Rated speed	9.0 rad/s
Mass	0.240 kg

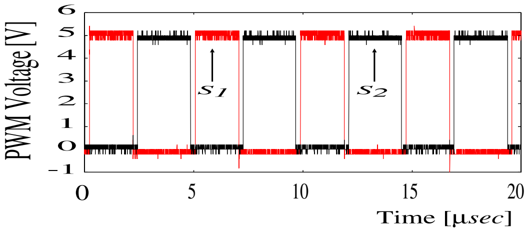

Fig. 3 PWM signal.

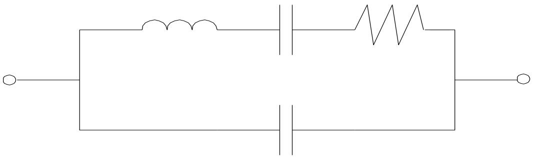

Fig. 4 Equivalent circuit of USM.

this voltage to stator, a rotor moves, and USM turns to the opposite direction of the traveling wave.

Specification of the USM is shown in Table 1. Electromagnetic brake of the load and the rotary encoder are connected by a coupling. Electromagnetic brake is used to apply the load torque when applied voltage. The rotary encoder is used for detecting the produced pulse in proportion to angle of the rotation of the motor shaft. Micro controller detects the rotor position for pulse number by rotary encoder(10,000 pulse/rev.). Reference position r and measured position y_e of the USM are recorded. There are two control methods of USM[10]: driving frequency control and applied voltage phase difference control. In position control of the USM, applied voltage phase difference control has higher efficiency than driving frequency control. In this study, we use applied voltage phase difference control, and the driving frequency f is constant at 41 kHz.

B. Driving circuit configuration

Power MOS-FET are used an switching device. The USM is a large capacitive load by looked from the inverter side. For improved efficiency to decrease capacitive load, intercalate inductances are set in series.

In PWM signal to generate micro computer input to inverter circuit, short to switch on both arm of tops and bottoms, brake switching devices by over current, we should input PWM signal with off time of both arm(dead time). Generated PWM signals with dead time are shown in Fig. 3. In Fig. 3, to generate dead time in input signal to switching device S1 and S2 can check. The inverter produces rectangular wave forms with these PWM signals. However, we can get sinusoidal voltage by making resonance with the equivalent circuit of the USM of Fig. 2 as shown in Fig. 4.

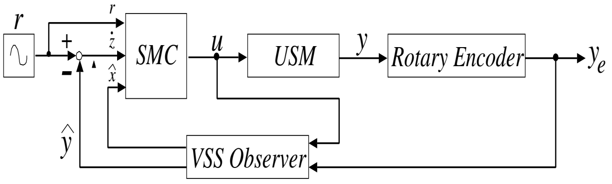

Fig. 5 System configuration.

III. CONTROL ALGORITHM

System configuration in this study is shown in Fig. 5. This section is designed sliding mode controller and VSS observer.

A. Sliding mode controller design

In this paper, we assume that the USM is a linear system. USM state equation of second order is given as follows.

$$\dot{x}(t) = Ax(t) + Bu(t), \tag{1}$$

where,

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -\omega_n^2 & -2\zeta\omega_n \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ K_f\omega_n^2 \end{bmatrix}. \tag{2}$$

K_f is the variable in changeable by the drive frequency.

Sliding mode controller applied to the servo system, is shown in Eq. (3). To configure, servo system state equation is shown in Eq. (4).

$$z(t) = \int_0^t (r(t) - y(t))dt, \tag{3}$$

$$\begin{bmatrix} \dot{z} \\ \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -\omega_n^2 & -2\zeta\omega_n \end{bmatrix} \begin{bmatrix} z \\ x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \omega_n^2 \end{bmatrix} u + \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} r \tag{4}$$

where r is the reference position, y is the rotor position. This equation is rewritten as

$$\dot{x}_z = A_z x_z + B_z u + E_z r. \tag{5}$$

where, switching function is defined as

$$\sigma = Sx_z. \tag{6}$$

where, S is a constant of switching hyperplane variable. Switching function on sliding mode is

$$\sigma = 0. \tag{7}$$

By $\dot{\sigma} = S\dot{x}_z$, $\dot{\sigma}$ is 0 when sliding mode is

$$0 = SA_z x_z + SB_z u_{eq} + SE_z r. \tag{8}$$

and it obtains the following equivalent input.

$$u_{eq} = -(SB_z)^{-1}(SA_z x_z + SE_z r). \tag{9}$$

Control input u is configured as linear control term u_l and nonlinear control term u_{nl}, if $u_l = u_{eq}$, $u_{nl} = -k\ \mathrm{sgn}(\sigma)$, control input u is presented by the following equation.

$$\begin{aligned} u &= u_l + u_{nl} \\ &= -(SB_z)^{-1}(SA_z x_z + SE_z r) - k\ \mathrm{sgn}(\sigma). \end{aligned} \tag{10}$$

where, k is a constant.

Next, Lyapunov function is selected as following equation.

$$V_c = \sigma^T (SB_z)^{-1} \frac{\sigma}{2}. \tag{11}$$

Differentiating the equation, we have

$$\begin{aligned} \dot{V}_c &= \sigma^T (SB_z)^{-1} \dot{\sigma} \\ &= \sigma^T (SB_z)^{-1} [SA_z x_z + SB_z u + SE_z r] \\ &= \sigma^T \{(SB_z)^{-1} [SA_z x_z + SE_z r] + u\}, \end{aligned} \tag{12}$$

and

$$\dot{V}_c = -\sigma^T k\ \mathrm{sgn}(\sigma) = -\mathrm{k}\frac{\sigma^2}{\|\sigma\|}. \tag{13}$$

Therefore if $k > 0$ and Lyapunov function is negative, can stable sliding mode controller.

B. Design of VSS observer

This section discusses the design of the VSS observer. The continuous time system presented as

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bh(t) + Bu(t), \\ y(t) &= Cx(t). \end{aligned} \tag{14}$$

where, h is a nonlinear term or uncertainty parameter. Since (C, A) is observable, constant matrix L exists, and configuring to complex plane half, left side of the following equation, A_o can stable eigenvalue,

$$A_o = A - LC. \tag{15}$$

Therefore, there is

$$PA_0 + A_0^T P = -Q, \tag{16}$$

satisfying $P > 0$ for A_o and positive matrix $Q > 0$, and F can be defined as

$$FC = B^T P. \tag{17}$$

State estimate error e is defined by

$$e(t) = \hat{x}(t) - x(t). \tag{18}$$

and F estimate error α is defined by

$$\alpha = F\{\hat{y}(t) - y(t)\}. \tag{19}$$

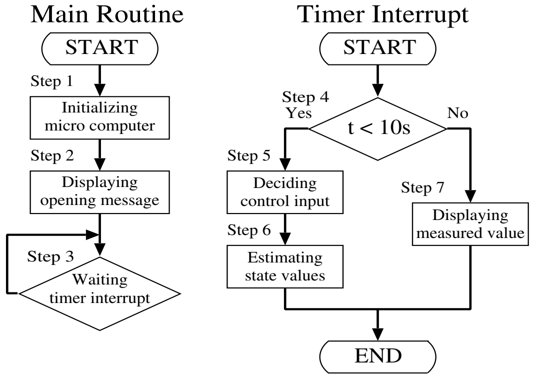

Fig. 6 Control algorithm.

where, $\hat{x}(t)$ and $\hat{y}(t)$ are the estimated value of $x(t)$ and $y(t)$. Using these, the design of the VSS observer can as follows.

$$\begin{aligned} \dot{\hat{x}}(t) &= A_0\hat{x} + Ly + Bu + B\delta, \\ \delta(t) &= \begin{cases} -\frac{\alpha}{\|\alpha\|}\rho & for \quad \alpha \neq 0, \\ 0 & for \quad \alpha = 0. \end{cases} \end{aligned} \tag{20}$$

where, ρ is a constant. The following error equation can be obtained by differentiating Eq. (18).

$$\begin{aligned} \dot{e} &= \dot{\hat{x}} - \dot{x} \\ &= A_0\hat{x} + Ly + Bu + B\delta - Ax - Bh - Bu \\ &= A_0 e + B\delta - Bh \\ &= \begin{cases} A_0 e - B\frac{\alpha}{\|\alpha\|}\rho - Bh & for \quad \alpha \neq 0, \\ A_0 e - Bh & for \quad \alpha = 0. \end{cases} \end{aligned} \tag{21}$$

It selects to Lyapunov function as following equation.

$$V_o = \frac{1}{2} e^T P e. \tag{22}$$

By differentiating V_o with respect to t, we have

$$\dot{V}_o = \frac{1}{2}\dot{e}^T P e + \frac{1}{2} e^T P \dot{e}, \tag{23}$$

where, by substituting Eq. (19), $FC = B^T P$, $e^T C^T F^T = \alpha^T$, and $|\alpha^T h| \leq \|\alpha\|\rho$,

$$\begin{aligned} &\alpha \neq 0 \\ &\dot{V}_o(t) = \tfrac{1}{2} e^T (PA_0 + A_0^T P) e \\ &\qquad\quad - e^T PB\tfrac{\alpha}{\|\alpha\|}\rho - e^T PBh \\ &\qquad = -e^T Q e - e^T C^T F^T \tfrac{\alpha}{\|\alpha\|}\rho - e^T C^T F^T h \\ &\qquad = -e^T Q e - \|\alpha\|\rho - \alpha^T h \\ &\qquad \leq -e^T Q e - \|\alpha\|\rho + \|\alpha\|\rho = -e^T Q e, \end{aligned} \tag{24}$$

$$\begin{aligned} &\alpha = 0 \\ &\dot{V}_o(t) = \tfrac{1}{2} e^T (PA_0 + A_0^T P) e - e^T PBh \\ &\qquad = -e^T Q e - \alpha^T h \\ &\qquad \leq -e^T Q e, \end{aligned} \tag{25}$$

which obtains $e(t) \to 0 (t \to \infty)$ for $\dot{V}_o$.

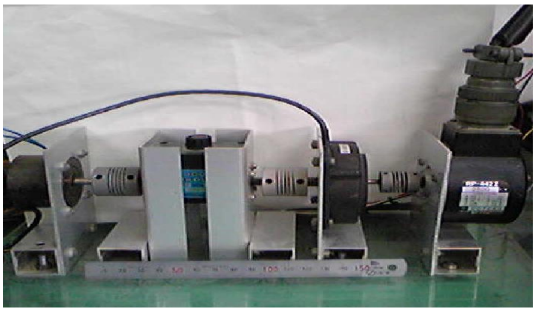

Fig. 7 Configuration of USM.

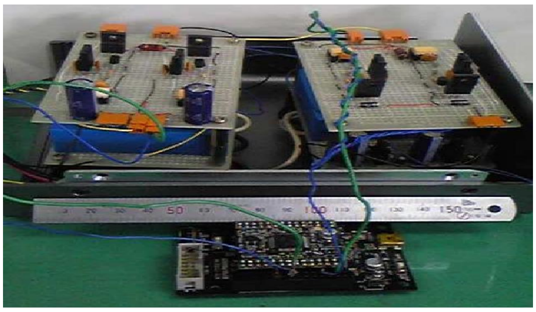

Fig. 8 Micro computer and drive circuit.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. *Micro computer algorithm*

Micro computer used in this research is SH7125 of SH/Tiny series. It uses development environment tool HEW(High-performance Embedded Workshop) of Renesas Technology Corp, and is written in C. Features of SH7125 are PWM mode, timer interrupt, and phase number count mode of MTU2. Using these features, we implemented sliding mode controller for the USM.

The control algorithm is shown in Fig. 6, and the steps are given as following.

STEP1 Initialize micro computer.
STEP2 Display opening message.
STEP3 Wait for timer interrupt.
STEP4 Determine the setting time.
STEP5 Decide the control input.
STEP6 Estimate the state values.
STEP7 Display the measured value.

B. *Experimental results*

USM experimental set up is show in Fig. 7, and the micro computer and the drive circuit are shown in Fig. 8. Here, control cycle is 1 ms, data sampling time is 20 ms, reference position of USM is sinusoidal wave, reference position frequency is 0.2 Hz, drive frequency f is 41 kHz, initial position is $y = 0.0\ \mathrm{rad}$ and they are implemented digitally. Control parameters are shown in Table. 2.

Experimental results by using the proposed sliding mode controller are shown in Figs. 9, and 10. Figs. 9(a), and 10(a), provide good control both for no load and applied load. Figs. 9(d), and 10(d), provide good position estimation. Figs. 9(f), and 10(f) provide that estimated speed is reduced in quantization error.

Table 2. Control parameters.

S	$[-1.1 \times 10^4 \quad 8.8{\times}10^3 \quad 147.7 \quad 3.2]$
K_f	3.3
k	0.1
F	1
ρ	0.1
L	$[0.3 \quad 1.4{\times}10^{-9} \quad -7.1 \times 10^{-5}]^T$
ζ	0.2
ω_n	2200.8

Therefore, it can be said from the discussion of the experimental result that the proposed sliding mode controller has robustness, provide effective to control the USM with unknown dead-zone.

V. CONCLUSIONS

The USM has an excellent performance and many other useful features. However, dead-zone occurs in control input with applied torque. In this paper, we proposed robust position control of the USM using the VSS observer. The VSS observer is nonlinear observer, achieved to reduce quantization error and to provide good position estimation. The sliding mode controller is nonlinear controller, achieved to robust position control for USM. Then, the dead-zone effect is reduced by the sliding mode controller using the VSS observer. Experimental results demonstrated good tracking performance and robustness of the proposed control and estimate scheme.

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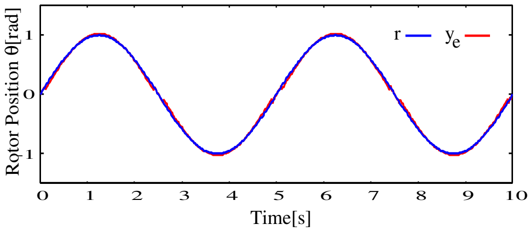
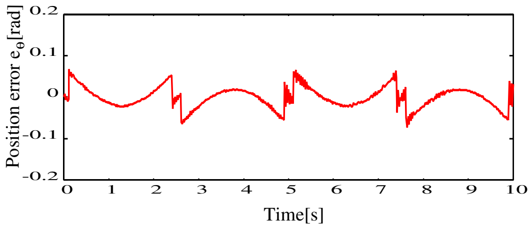
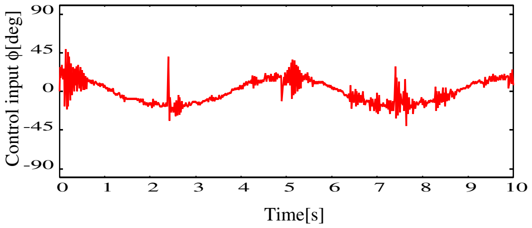


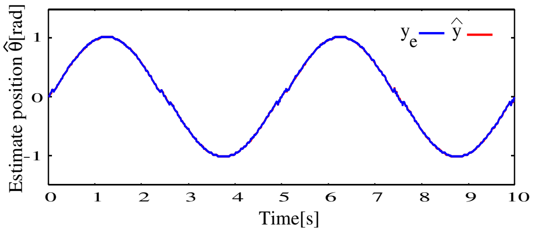
(a) Reference position and measured position.



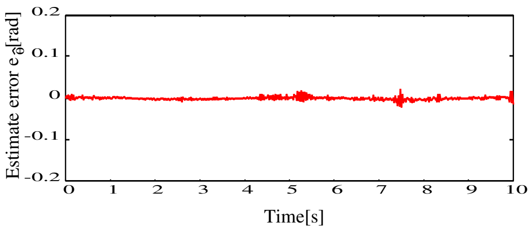
(b) Position error.



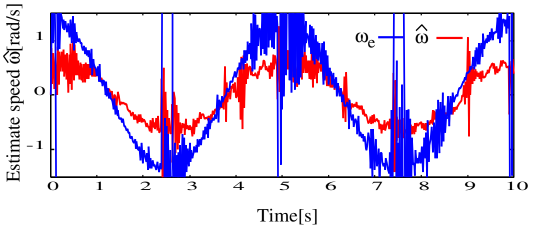
(c) Control input.



(d) Measured position and estimate position.

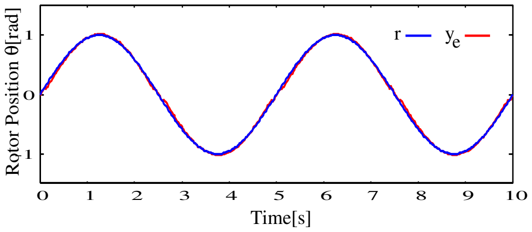


(e) Estimate position error.

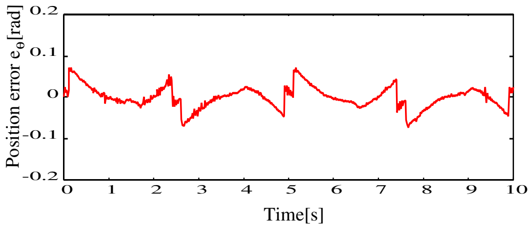


(f) Measured speed and estimate speed.

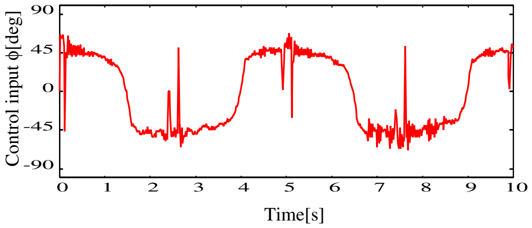
Fig. 9 Experimental result with sliding mode controller(τ_L=0.0Nm).



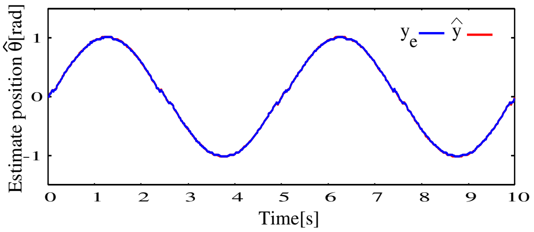
(a) Reference position and measured position.



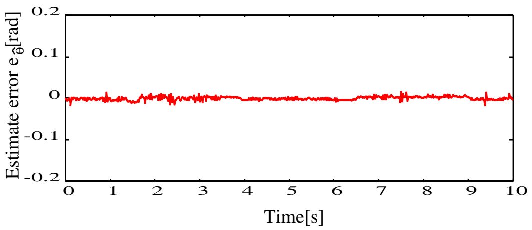
(b) Position error.



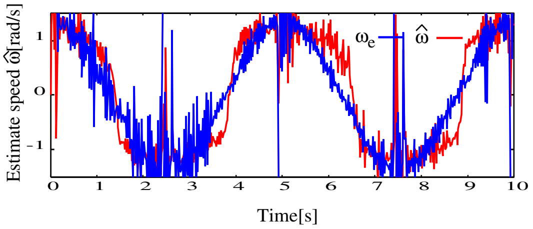
(c) Control input.



(d) Measured position and estimate position.



(e) Estimate position error.



(f) Measured speed and estimate speed.

Fig. 10 Experimental result with sliding mode controller(τ_L=0.2Nm).