Thin-disc piezoceramic ultrasonic motor. Part II: system construction and control

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Abstract

Design and performance evaluation of an ultrasonic motor was discussed in [Wen et al., Thin-disc piezoelectric ultrasonic motor. Part I: design and performance evaluation, Ultrasonics]. Higher precision position control of piezoceramic ultrasonic motor depends on mechanical design and servo control of a very precise and adequate metrology. This paper proposes the design of a driving circuit and controller to deal with non-linearities behavior in the model of piezoceramic-driving ultrasonic motor. The performance of the driver and the effectiveness of the proposed controller are demonstrated by command inputs of sinusoidal and step signals. For comparison purpose, the ultrasonic motor is controlled using two methods; i.e., proportional-integral-derivative (PID) and sliding-mode control (SMC). It was proven that SMC would compensate automatically for unmodeled behaviors such as piezoceramic non-linearities and mechanical stick-slip phenomena. Furthermore, SMC scheme has been successfully applied to position tracking to demonstrate the excellent robust performance in noise rejection.

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1. Introduction

The novel configuration of a thin-disc piezoceramic-driving ultrasonic actuator is developed as a stator in this study, which is a piezoceramic (PZT) membrane bonded on a metal sheet structure. By applying the constraints on the specific geometry positions on the metal sheet, the various behaviors of flexural waves have been formed at the different directions. This simple and inexpensive structure of actuator demonstrates that the mechanical design of actuator and rotor could be done separately and flexibly according to the requirements for various applications. Following the driving frequency of a single-phase AC power, the rotor is rotated by the actuator with rotational speeds of 600 rpm under rated operation using a friction-contact mechanism. Based on the unique feature of ultrasonic motor in quick response and high braking ability, the multi-frequency driving circuit (MFDC) was designed to multi-resonant-mode operation. A closed-loop servo control, sliding-mode control (SMC), is used as a positioning compensator. SMC scheme only needs an approximate mathematic model and has been successfully applied to position tracking to prove the excellent robust performance in noise rejection.

In order to demonstrate the excellent controllability of multi-frequency driving feature at the specific operating frequency, an approximate mathematic model could be obtained by system identification and next the traditional proportional-integral-derivative (PID) controller was applied to positioning function for such ultrasonic motor. The performance of PID controller is evaluated as reference to other different controller for thin-disc USM because of PID variety in applications and convenience in implementation. In this paper, the actuating principle of flexural waves for thin-disc USM is the mechanical vibration resulting from extension-shrinkage motion of a metal sheet due to the converse
piezoelectric effect of PZT membrane and via a friction-contact mechanism to transfer dynamic energy for turning preload between stator and rotor was occurred, or if the temperature sensitivity of piezoelectric effect for PZT materials was happened, there were the serious dead-zone [1] phenomena for rotational operation. Some mechanical phenomena were also directly influenced by the deflection amount of metal sheet and external loading, such as stick-slip friction, hysteresis, and so on. Unfortunately, at this moment, the system always displayed the non-linear features. In previous papers, there is lack of helpful and exactly dynamic mathematic model for control design. To solve the above mentioned parameter variation and uncertain status, many researchers adopted intelligent control strategies to avoid heavy difficulty in acquisition of mathematic model for a USM plant [1–4]. The rule database of fuzzy control is listed in much experience and decision tables are obtained through expert concept. It will be toughness and unreality for a novel thin-disc PZT ultrasonic motor because of too many unknown existence. Otherwise, the efficiency and convergence in intelligent control are still needed to evaluate. The control rules of neural network are difficult to figure out, especially in neural cell weighting numbers of on-line tuning network. Other drawback of neural control includes enormous calculation and complicated procedure in control system design. Therefore, in this paper, SMC strategy was easily chosen as the major control rule in which had excellent noise rejection and robust features. Only if approximate mathematic model were gained, the control concept of SMC was simple and direct related the physical meaning with convergence guarantee and overcome some non-linearity in mechanical configuration of USM for precisely positioning control.

In the past decades, SMC scheme has been successfully applied to various systems such as robot manipulators [5,6], servo motors [7–9], magnetic bearings [10,11] and UPS inverters [12,13]. The most distinct feature of the SMC scheme is the existence of a sliding mode that occurs on a predefined sliding function. Once the sliding mode operates, the system will be forced to slide along the switching hyperplane. The closed-loop poles can be located precisely at fixed positions in the complex plane, and the closed-loop dynamics is the same as in the sliding regime. If system perturbations (such as parameter uncertainties, external disturbances, and model error) and unmodeled model are of matching types, system response in the sliding mode would be completely insensitive to those perturbations. A robust performance can then be guaranteed.

This paper introduces some aspects relating to the development of a positioning controller for the thin-disc ultrasonic motor. The first section describes the driving circuit of the ultrasonic actuator so to give an understanding of the purpose of frequency switching in order to develop the various rotary directions by frequency control in a single-phase AC power input. With operating frequency via system identification, an approximated mathematic model was obtained for the design of PID or SMC. Since the non-linearities of thin-disc piezoceramic and complexity equations were involved, while studying the position tracking function of an ultrasonic motor, it was decided to define the non-linearities of system such equivalent disturbance torque as dynamically compensated by a more global approach for the SMC. The last section of this paper, which is based on the analysis of experimental results, discusses improvements and limitations of the structure proposed for the controller.

2. Driving circuit

According to ultrasonic actuating characteristics from Part I and experimental results of speed vs. frequency relation curve, angle displacement per input signal period was directly determined by the sinusoidal amplitude of the input voltage onto the piezoceramic of ultrasonic motor. And, rotary direction was controlled by specific frequency of sinusoidal input voltage.

In order to satisfy such characteristics of frequency control for ultrasonic motor, one set of effective driving circuits was implemented as shown in Fig. 1 [14,15]. The major components include a two-quadrant chopper and a single-phase half-bridge series-resonance inverter. Higher DC voltage level is transformed to lower DC voltage level by a two-quadrant chopper. Its adjustment of duty cycle follows the command from controller transferring through D/A servo control card. After level shifter, the adjusted signal \( u_p \) generates \( s^+ \) and \( s^- \) signals via PWM circuit as control inputs of buck converter. The variant DC voltage source \( V_{dc} \) comes from buck converter as the input of a single-phase half-bridge series-resonance inverter. Hence, output voltage \( V_{ac} \) onto ultrasonic piezoceramics could be controlled. Otherwise, the specific frequencies are predefined in VCO(1) and VCO(2) for rotation in clockwise and counterclockwise, respectively. Through a voltage control oscillator, the driving frequency of inverter is chosen by signal \( u_p \) via a frequency selector.

When \( u_p \) great than zero (voltage setting high), frequency \( f_1 \) is chosen and ultrasonic motor rotates clockwise. In contrast, when \( u_p \) equal to zero (voltage setting low), frequency \( f_2 \) is selected and ultrasonic motor also rotates counterclockwise. The detail circuits of power converter displayed as Fig. 2. Since the piezoceramic could be looked as a capacitor in an electric circuit, the series resonant inductors of \( L_a \) and \( L_b \) are expected to match the blocking capacitance \( C_d \) of piezoceramic occurred the circuit resonant phenomena.
Therefore, output signal of an inverter in square wave containing harmonic component is transformed to a basis sinusoidal signal. Due to different frequencies in rotary direction, various resonant inductors are switched by $u_p$ signal. Experimental resonant inductance in clockwise and
counterclockwise directions are 108 and 46 $\mu$H, respectively. Fig. 3 illustrated the PC-based USM driving circuit and control system. The servo control card slotted in PC computer includes multi-channel of A/D, D/A, PIO and optical encoder interface circuit. The output signal of the optic encoder of model MES-30-2000PE is a square signal with A and B phase in 2000 pulse per revolution. The configuration and implementation are set up at real-time workshop (RTW) toolbox of MATLAB/SIMULINK software, with 1 ms sampling interval.

### 3. System identification

The non-linearities and time-variant is inherent characteristics of an ultrasonic motor. These factors include temperature effect, structure hysteresis phenomenon from loading, and preload added to the actuator, etc. It is difficult to obtain the exact mathematical model pertaining to the system dynamic characteristic. Therefore, in this study, open-loop off-line system identification method was employed to obtain the approximate mathematical model. This relative transfer function was calculated in arithmetical mean value of rotor speed divided by input voltage under free and 1 kg weight loading conditions at specific operating frequency. For experimental configuration of modeling as shown in Fig. 4, the existing icons of white noise mixed sign function in Simulink/Matlab software was applied to construct pseudorandom binary sequence (PRBS). And, PRBS was transformed into exciting voltage ($V$) via D/A converter. The voltage signal ($V$) through driving circuit is an exciting energy to get the response signal of angular speed ($\omega$) by mean of the treatment of optic encoder and CPLD module. Ultrasonic motor on the other hand was operated at specific frequency $f_1$ and $f_2$, respectively. After PIO bus transferred data into computer through AD/DA servo control card, total 50,000 data in 1 ms sampling interval were collected as modeling database. Then, the first 30,000 data were modeled in different noise model structures of ARX, ARMAX, OE, and BJ, individually, to implement the first order parameter identification. The model was verified by the last 20,000 data. The experimental results reveal the OE estimating model ($mn = [1 1 1]$) with the least error. After the discrete model was transformed to continuous form by Tathlein method, the approximated transfer function of rotor angular speed to actuator input voltage is $\omega(s)/V(s) = b/(s + a)$. As such, time integral equation represents approximated transfer function of rotor position to stator input voltage as $\theta(s)/V(s) = b/[s(s + a)]$.

### 4. Controller design

According to system identification, the second order transfer function of rotor position to input voltage for the ultrasonic motor is represented in the following mathematical model,

$$\frac{\theta(s)}{u(s)} = \frac{k_m}{s(1 + \tau s)}$$ (1)

Assuming the non-linearity behavior of ultrasonic system as the equivalent disturbance torque, the differential equation (1) becomes [16],

$$\ddot{\theta}(t) = -a_0\dot{\theta}(t) + b_0u(t) - \frac{1}{J_0}T_d(t)$$

$$T_d(t) = T_L + \Delta J\dot{\theta}(t) + J_0\Delta a\dot{\theta}(t) - J_0\Delta b u(t)$$ (2)

where $T_d(t)$ is an equivalent disturbance torque; $a_0 = 1/\tau$, $b_0 = k_m/\tau$, $J_0$ and $T_L$ are an equivalent constant for moment of inertia and loading torque, respectively. $\Delta a$, $\Delta b$, and $\Delta J$ are corresponding to the varying amount of system parameters $a_0$, $b_0$, and $J_0$, respectively. All system uncertainty amount, $d(t) = T_d(t)/J_0b_0$, is also assumed to be bounded as follow,

$$|d(t)| \leq D$$ (3)

Fig. 5 shows the position control system of ultrasonic motor, where $\theta_d(t)$ is defined as position command and $\theta(t)$ as real position of rotor. And based on the state variables of system as follows,
The system state equation then becomes,

\[
x(t) = Ax(t) + B(u(t) + d(t))
\]
\[
y(t) = Dx(t)
\]

where

\[
A = \begin{bmatrix} 0 & 1 \\ 0 & -a \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ b \end{bmatrix}, \quad D = \begin{bmatrix} 1 & 0 \end{bmatrix}
\]

\(a = a_0 \pm \Delta a, 3.94 \leq a \leq 10.99; \ b = b_0 \pm \Delta b, 1.932 \leq b \leq 13.52; \ a_0 = 7.465, \ b_0 = 7.726; \ \Delta a = 3.525, \ \Delta b = 5.794.
\]

These variations are caused from the modification of external loading, the imprecision of parameters, and external disturbance. According to the realistic model, the design detail SMC controller is as stated in the follows.

In the approach of SMC, two or more substructures were created from controlled plant, and some appropriated switching condition on purpose was added to generate sliding mode action for reaching controllable goals. It is necessary to design a sliding surface and next

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**Fig. 5.** Block diagram of USM position control system.

**Fig. 6.** The simulations with sinusoidal command (nominal parameter): (a), (b), and (c) are rotor position, tracking error, and control effort of PID; (d), (e), and (f) are rotor position, tracking error, and control effort of SMC \([u = \text{command}; X = \text{rotor position}].\)
force system’s trajectory into the sliding surface immediately via control manner. Once system trajectory slips into the sliding surface, that is confined and difficultly run away under external interference. Even though the position tracking error was occurred due to variation of external loading or internal parameter, the system stability was guaranteed if that uncertain amount was allowed in the design specification. Since system trajectory was only restricted in \( s(t) = 0 \) tiny space near sliding surface to do extra frequency crash motion until the control target is reached, that is, system trajectory has excellent robust ability in noise rejection. In order to guarantee the existence of approaching mode and sliding mode in the system, design stages are described in Section 4.1.

4.1. Sliding function design

In order to stabilize system tracking path approaching the control target in sliding mode, it is necessary to choose the appropriate switching surface \( s(t) = 0 \) and select an integral form of switching function as follows,

\[
s(t) = c_1 e(t) + c_2 \int_0^t e(\tau) \, d\tau
\]  

(7)

where \( c_1, c_2 \in R^{1 \times 2} \) is positive constant matrices and \( c_1B \neq 0 \).

If the controlled plant was located at sliding mode, then \( \dot{s}(t) = s(t) = 0 \), system could reach the control target \( x = 0 \).

4.2. SMC position controller design

To assure that the system approaches the sliding surface in limited time and that the sliding mode behavior exists, the position controller is designed as the follows,

\[
 u(t) = u_{eq}(t) + u_{sw}(t)
\]

\[
 u_{eq}(t) = (c_1B)^{-1} \left( -c_1Ax - c_2x_2 + c_1 \dot{x}_3 \right)
\]

\[
 u_{sw}(t) = -k \text{sgn}(s(t))
\]
where $u_{eq}(t)$ is the input term of equivalent control, $u_{sw}(t)$ is the input term of discontinuous switching control; and, $\text{sgn}(\bullet)$ is a sign function that is an ideal switching function. Definition as follow,

$$\text{sgn}(s(t)) = \begin{cases} +1, & \text{if } s(t) \geq 0 \\ -1, & \text{if } s(t) \leq 0 \end{cases}$$

where $k$ is defined as $|d(t)| \leq k$, and both of $c_1B$ and $k$ are positive values.

**Lemma.** If the sliding function $s(t)$ of control system satisfied the following conditions, then the existing condition of guaranteed approaching and sliding mode behavior would be sustained [17].

$$\lim_{s \to 0} s \dot{s} \leq 0$$

**Proof.** According to lemma, then

$$s(t)\ddot{s}(t) = s(t)\{c_1\dot{s}(t) + c_2\dot{e}(t)\}$$

$$= s(t)\{c_1[\dot{x}(t) - \dot{x}_a(t)] + c_2[x(t) - x_a(t)]\}$$

$$= s(t)\{c_1[A\dot{x}(t) + B(u(t) + d(t))] - c_1\dot{x}_a(t) + c_2x(t) - c_2x_a(t)\}$$

$$= s(t)\{c_1Ax(t) + c_1B[-(c_1B)^{-1}(c_1Ax(t) + c_2x(t) - c_2x_a(t)) - c_1\dot{x}_a(t) + c_2x(t) - c_2x_a(t)]\}$$

$$= s(t)\{-c_1Bk\text{sgn}(s(t)) + c_1Bd(t)\}$$

$$= -c_1Bk|s(t)| + c_1Bs(t)d(t)$$

$$\leq -c_1Bk|s(t)| + c_1B|s(t)| |d(t)|$$

$$= -c_1B|s(t)| [k - |d(t)|] \leq 0$$

Therefore, only if $k \geq d(t)$ existing in Eq. (11), the existing condition of approaching and sliding mode behaviors in lemma would be satisfied by SMC position controller using Eq. (8). System state $x(t)$ shall steadily slide to control target along sliding surface. In order to
prevent the non-interrupt chattering phenomena in tiny space near sliding mode $s(t) = 0$ of system tracking path and unexpected high frequency noise, sliding layer concept promoted by Slotine [6,18] was employed instead of sliding surface. That is, $\text{sign}(s)$ was alternative to $\text{sat}(s,e)$. The function of $\text{sat}(s,e)$ is defined as follows:

$$\text{sat}(s,e) = \begin{cases} 1; & s > e \\ s/e; & |s| \leq e \\ -1; & s < -e \end{cases}$$

where $e$ is infinitesimal positive. For system reaching the sliding surface in quickly, the corrective term $\alpha \cdot s(t)$ was subjoined into the control rule. Hence, the modified control rule is:

$$u(t) = (c_1b)^{-1}(c_1Ax - c_2x + c_2x_d + c_1x_d) - (k \cdot \text{sat}(s(t),e) + \alpha \cdot s(t))$$  \hspace{1cm} (13)

where $\alpha$ is a positive constant.

### 4.3. Chattering phenomena improvement

In order to avoid the chattering phenomena of system track within infinitesimal space during sliding mode at $S(t) = 0$, which exciting the occurrences of high frequency noise, the function of $S_0(t)$ was developed instead of discontinuous function of $S(t)$ [19].

$$S_0(t) = \frac{s(t)}{|s(t)| + \delta(t)}$$

$$\delta(t) = \delta_0 + \delta_1|e(t)|$$  \hspace{1cm} (14)

where $\delta_0$, $\delta_1$ are positive numbers. The appropriate design of $S_0(t)$ would constrain the chattering phenomena in the desired small zone.

### 4.4. PID controller design

For performance evaluation in positioning compared to SMC, the conventional PID controller was designed. The transfer function of PID is listed as the following:

$$\frac{1}{\tau s + 1}$$

Fig. 9. The experimental results with sinusoidal command (1 kg weight loading): (a), (b), and (c) are rotor position, tracking error, and control effort of PID; (d), (e), and (f) are rotor position, tracking error, and control effort of SMC [$u = \text{command}; X = \text{rotor position}$].
The control target will be gradually reached. If the placement of dual characteristic roots in the design of a PD controller should refer to exactly dynamic mathematical model of plants and the system specifications of transient and steady responses. Three coefficients of $k_p$, $k_i$, and $k_D$ must be selected carefully to fit the system specification, but they are the lack of robust ability in system parameter variation and uncertain status for thin-disc ultrasonic motors.

The characteristic roots of system shall be placed in LHP during sliding mode, and system trajectory being along sliding surface. The control target will be gradually reached. If the placement of dual characteristic roots in the design of close loop system is located in $(-20,0)$ of complex plane, $C_1$ and $C_2$ of switching function $s(t)$ in Eq. (7) are equal to $(1,1)$ and $(400,39)$, respectively. The parameter $(k, x, c)$ of controller $u(t)$ in
Eq. (13) is \((25, 25, 0.001)\), and the designed control input shall be
\[
u(t) = 0.1294(-4000 - 32.535\omega + 4000\theta_d + 40\omega_d + \dot\omega_d) \\
- (25 \text{sat}(s(t), 0.001) + 25s(t))
\] (16)

Usually PID controller, a standard design of the industrial control for the improvement of transient and steady response, was employed and the controller transfer function is given by Eq. (1). For the PID controller designed in this study, the transfer function of the system has the same dual characteristic roots \((-20, 0)\) and an additional pole \((-30, 0)\). The calculated values of 207.09, 8.09 and 1553 would be obtained as the parameters of \(k_P\), \(k_D\), and \(k_I\) of PID controller in Eq. (15), respectively. For performance evaluation of controllers, the sinusoidal and periodical step signals are as an input through the command shaping. That is, the position tracking commands are produced by a second order transfer function in both of simulation and experiment. When the control command was sinusoidal signal, command shaping was set to 1. If next command was set as periodical step signal, command shaping would be the transfer function of \(\zeta = 1, \omega_n = 10\) as the following,

\[
\frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \rightarrow \frac{100}{s^2 + 20s + 100}
\] (17)

The simulating results shown in Figs. 6–9, respectively, based on sinusoidal and periodical step commands, are addressed in the PID and SMC. Their simulation conditions were nominal parameter \((a = a_0 = 7.465; b = b_0 = 7.726)\) and parameter variation \((a = a_{\text{max}} = 10.99, b = b_{\text{min}} = 1.932)\) into the system state equation of ultrasonic motor using PID and SMC method, separately, for position command tracking. The variation in consideration of the response of the system, shown in above figures, was then compared with the controlled performance of the PID and SMC with different reference command.

The experimental conditions are the same as above mentioned with free and 1 kg loading onto carrier platform of ultrasonic motor testing bench using both of PID and SMC methods. The control algorithm was performed using a Pentium computer with 1 ms sampling interval. The response of the rotor position, tracking error, and control effort using the PID and SMC controller are shown in Figs. 10–13.
6. Discussion

According to the simulations shown in Figs. 6 and 7, known in sinusoidal command with both conditions of nominal parameter and parameter variation, the steady error of rotor trajectory was quiet tiny when PID and SMC method were employed respectively. Their position tracking capability is sufficient for the novel USM. However, by using PID method, the position tracking capability was affected by external 1 kg weight loading. On the other hand, the tracking ability was still excellent under SMC method, as shown in Figs. 8 and 9. The simulation and experimental results demonstrate the fact that the rotor positioning completely follows the command in SMC controller. Furthermore, the tracking error amount of SMC method is much less than that of PID method. The comparison of simulations indicates the tracking error of PID in sinusoidal command case is about 5–20 times greater than that in SMC case. However, SMC method has obvious tendency to larger control effort and little high frequency chattering phenomena.

In the cases of periodical step command as shown in Figs. 11 and 13, the rotor trajectory of PID method has the apparently delay in transient response under either parameter variation or external 1 kg loading. The position tracking performance of PID method is obviously poor. The robust characteristics of SMC are directly proven in both of external disturbance and internal nonlinearity of USM. However, SMC method needs more voltage input to overcome the high frequency disturbance in the tracking behavior of periodic step command. During the transient status, the obvious tendency in high frequency chattering phenomena was generated by the higher gain operations, as shown in Figs. 10–13. But, the system has the ability of noise rejection. According to experimental results, the average tracking error of SMC only is one fifteenth times that of PID. The fact implies that the simulation of USM tracking performance is quiet close to the real status.

Based on the simulations and experimental results, loading analysis of steady error in sinusoidal command, the error amount of PID controller is quite larger than that of SMC controller in which only has less 0.01 radius error. From periodic step response of both cases, transient tracking error is kept within 0.02 radius using SMC control. Especially, dynamic loading tracking error of SMC control is less than 0.02 radius, that is 4% dynamic
loading error of PID control had as shown in Fig. 13(b) and (e). However, the control effort of SMC control is still greater than that of PID control. Unfortunately, high frequency chattering phenomena always is existed in SMC system, as shown in Fig. 13(f).

Both cases of parameter variation and external disturbance demonstrate that SMC control has inherently robust feature and little tracking error with comparison to that of PID control. The evaluated effectiveness for PID and SMC control is listed in Table 1. According to the simulating and experimental analysis of tracking capability and known control effort, SMC control has better performance than PID control has, while sinusoidal and periodic step are individually tracking commands. In other words, system uncertainties and external disturbance in SMC could be overall insensitive. As such, the robust performance in noise rejection can be guaranteed.

### 7. Conclusion

Since the direction of rotary motion is controlled by input voltage in specific frequency, the design of driving circuit and controller has been implemented for the novel piezoceramic-driving thin-disc ultrasonic motor. In order to gain the approximate transfer function, system identification method was employed with voltage of actuator as the input signal and position of rotor as the output signal. Based on the approximate mathematical model of transfer function, the performance characteristic of PID and SMC control was compared in

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Table 1

<table>
<thead>
<tr>
<th>Controller</th>
<th>Robust</th>
<th>Tracking error</th>
<th>Mathematical model</th>
<th>Control effort</th>
<th>Chattering phenomena</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>Poor</td>
<td>Little/Nominal</td>
<td>Necessary/Large</td>
<td>Little/Large</td>
<td>None</td>
</tr>
<tr>
<td>SMC</td>
<td>Excellent</td>
<td>Little/Variation</td>
<td>Approximate/Large</td>
<td>Little/Large</td>
<td>Large/Existed</td>
</tr>
</tbody>
</table>

Fig. 13. The experimental results with periodic step command (1 kg weight loading): (a), (b), and (c) are rotor position, tracking error, and control effort of PID; (d), (e), and (f) are rotor position, tracking error, and control effort of SMC \[ u = \text{command}; X = \text{rotor position}. \]
terms of position tracking command in sinusoidal and periodical step function. The experimental results demonstrated that the robust control and low tracking error could be obtained via the SMC control for the ultrasonic motor. Therefore, the SMC is more suitable to control of the novel ultrasonic servomechanism in noise rejection.

References


