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QUICK AND PRECISE POSITION CONTROL OF ULTRASONIC MOTORS USING ADAPTIVE CONTROLLER WITH DEAD–ZONE COMPENSATION

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A position control scheme for an ultrasonic motor using an adaptive controller with dead-zone compensation is presented in this paper. In the proposed controller, the adaptive control scheme compensates the time-varying characteristic of the motor with online parameter identification. In order to overcome the effect of a dead-zone, a P controller is adopted. The effectiveness of the proposed control scheme is demonstrated by experiments. Furthermore, the influence of model orders and control delay on the control performance is determined experimentally. Results show that quick and precise position control performance can be achieved.

K e y w o r d s: ultrasonic motors, position control, adaptive controller

1 INTRODUCTION

The features that ultrasonic motors (USMs) can operate in a low speed range, possess a high holding torque and no need for a brake, are useful for utilizing them as gearless actuators or direct servo drives. The motors have recently been applied as direct drive actuators for articulated robots, actuators for control valves and a positioning table of machine tools because they require a quick response and precise position control of actuators [1, 2].

The drive principle of USM has a complex mechanism such that the rotor is moved by an ultrasonic vibration force of piezoelectric elements on the stator. For this reason, it is difficult to design the position controller based on minute mathematical models. Accordingly, the controllers have been mostly designed using PI controllers or fuzzy controllers [3, 4], which may not use the mathematical model of the motor. These controllers have the features of simple structure, stability and reliability when the controllers are tuned well. However, they have limitations in complex system control and cannot maintain these virtues under the characteristic variations of the plant. Accordingly, it is necessary to develop a mathematical model that is simple and convenient for control and construct the controller to control the ultrasonic motor with high performance.

In addition, the existence of dead-zone effect of ultrasonic motor is a problem as an accurate positioning actuator for industrial application and it is important to eliminate the dead-zone in order to improve the control performance. T. Senjyu proposed a position control scheme of USM with adaptive dead-zone compensation to solve the problem [5]. In this controller, a NN was adopted to determine the dead-zone compensation input. Though good control performance can be achieved, it is too complex to apply.

For the purpose of solving the problems, this paper proposes a position control scheme of USM using adaptive controller with dead-zone compensation. In the proposed controller, the adaptive control scheme compensates the time-varying characteristic variations with online parameter identification, and a P controller is used to overcome the dead-zone effect.

This paper suggests a simplified mathematical model of ultrasonic motor which is represented by a simple difference equation, and both the model orders and control delay are determined experimentally. Phase difference is adopted as the control input in this paper to achieve quick and precise position control.

2 BASIC CHARACTERISTICS OF USM

A typical travelling-wave type USM consists of a rotor, a stator made by an elastic body and piezoelectric elements. When two-phase voltages whose frequency is near the resonant frequency of the motor are applied to the piezoelectric elements, a travelling wave is produced on the surface of the stator. The travelling wave generates vibration with an elliptic locus on the stator surface, and then the rotor in contact with the stator is rotated by the vibration force. The two-phase voltages V_A and V_B are shown in Fig. 1. Figure 2 illustrates the speed characteristics for phase difference of the applied voltage. The motor can revolve to positive/negative direction by the phase difference control. The dead-zone around $\phi = 0$ exists. When the phase difference falls into the dead-zone, the USM stops, and will not reach the command position. Therefore, the dead-zone is a problem for the precise posi-

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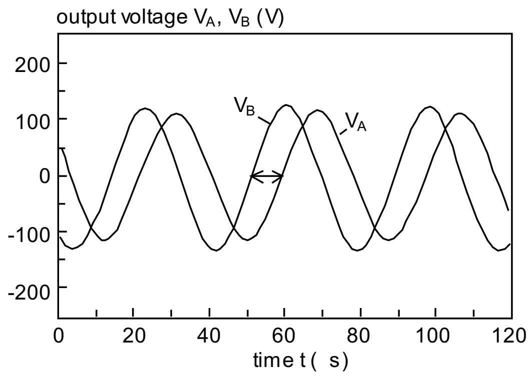

Fig. 1. Output voltages of two-phase inverter

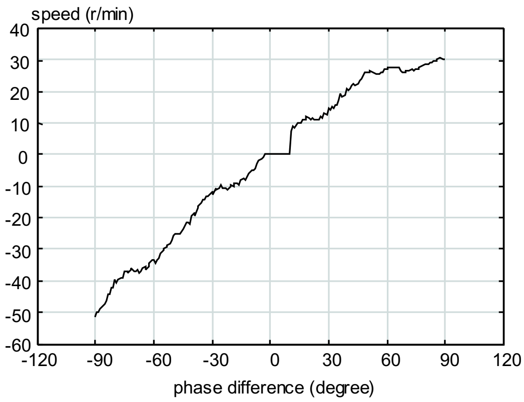

Fig. 2. Speed *vs* phase difference of applied voltage

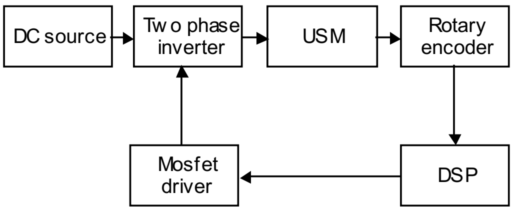

Fig. 3. Block diagram of drive system

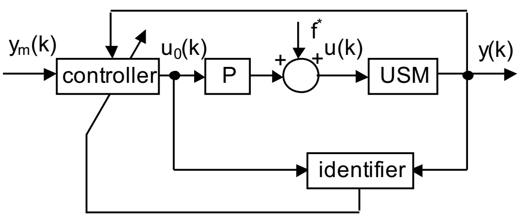

Fig. 4. Block diagram of position control system

Table 1. Design specifications of tested USM

Rated output power	1.3 W
Rated sped	250 r/min
Drive frequency	50 kHz
Drive voltage	110 V
Rated torque	0.05 N.m

tion control actuator. It is necessary to take the dead-zone compensation into account.

3 DRIVE SYSTEM

In this research, an ultrasonic motor USR 30 by SHINSEI is studied. Its main specifications are shown in Tab. 1. The block diagram of the drive system for the ultrasonic motor used in this paper is shown in Fig. 3. The control input is calculated with a Digital Signal Processor (DSP). The DSP used in this work is a TMS320F240 by Texas Instruments. The rotor position is measured by a rotary encoder which has 2500 pulses per revolution. The pulses are multiplied by 4 in DSP to achieve angular revolution of 0.036°. The switching signals with a certain phase difference for two-phase inverters are also generated by the Event Manager of this DSP. Then we get the two-phase alternating voltages with the desired phase difference. The control strategy in the DSP is realized using an assembly language.

4 CONTROL SYSTEM

As stated above, high performance position control of the USM is usually difficult because of the time-varying characteristics of the motor, and the existence of the dead-zone effect. In order to overcome these problems and to control the motor position with high performance, we design a position controller using self-tuning controller (STC) methods. The STC is suitable for controlling the time varying plants. Then, a P controller is designed to eliminate the dead-zone effect.

4.1 Position controller design

The block diagram of the position control system using STC methods is shown in Fig. 4 [6], where $y_m(k)$ is the command position, $y(k)$ is the actual rotor position, $u(k)$ is the control input (phase difference) and $\phi^*(=0°)$ denotes the biased phase difference.

We propose a simplified mathematical model for the ultrasonic motor in the form of eqn. 1 and then construct the position controller assuming that the plant parameters are known.

$$\begin{aligned} Ay(k) &= q^{-d}Bu_0(k) + w(k) \\ A &= 1 + a_1q^{-1} + \cdots + a_nq^{-n} \\ B &= b_0 + b_1q^{-1} + \cdots + b_mq^{-m} \end{aligned} \tag{1}$$

where d is the control delay, q^{-1} is the backward shift operator, $w(k)$ denotes the white noise and n and m are the model orders, respectively.

The adaptive position controller based on STC is designed to minimize the following cost function J_1 [7]:

$$J = E\{[y(k+d) - y_m]^2 + \lambda[u_0(k)]^2\} \tag{2}$$

where $E[\cdot]$ is the expectation operator, and λ denotes the control weight which restricts the variation of control input and make the non-inverse stable system to be stable.

The control input $u_0(k)$ which minimizes the cost function J_1 is obtained by $\partial J_1/\partial u_0(k) = 0$:

$$u_0(k) = \frac{y_m(k) - Gy(k)}{BF + \lambda}\,. \tag{3}$$

In eqn. 3, polynomials F and G are determined by the following Diophantine equation:

$$\begin{aligned} 1 &= FA + q^{-d}G \\ F &= 1 + f_1 q^{-1} + \cdots + f_{nf} q^{-nf} \\ G &= g_0 + g_1 q^{-1} + \cdots + g_{ng} q^{-ng} \\ \deg F &= d - 1 \\ \deg G &= n - 1 \end{aligned} \tag{4}$$

4.2 Parameter identification

The controller must know the motor parameter in order to calculate the control input $u_0(k)$. There are many parameter identification algorithms and, for simplicity, this paper adopts the conventional recursive least squares method. The objective of this method is to find the parameter vector ? which minimizes the following cost function J_2:

$$J_2 = \sum_{k=0}^{N} \rho^{N-k}\big(y(k) - \phi^\top(k)\Theta\big)$$

where

$$\begin{aligned} \phi(k) = \big[&y(k-1) \;\; y(k-2) \;\cdots\; y(k-n) \\ &u_0(k-d) \;\; u_0(k-d-1) \;\cdots\; u_0(k-d-m)\big]^\top \\ \theta = [&-a_1 \;\; -a_2 \;\; -a_n \;\; b_0 \;\; b_1 \;\cdots\; b_m]^\top \end{aligned}$$

and ρ ($\in [0.9, 0.99]$) denotes the forgetting factor. The convergence of the parameter identification becomes fast with small ρ and the parameter identification algorithm is effective for the time varying system. However, when ρ is too small, the identification becomes sensitive to system noise. Since the USM is a slow time-varying system, $\rho = 0.99$ is adopted in this research.

The identification algorithm is finally obtained as follows by solving $\partial J_2/\partial\Theta = 0$:

$$\begin{aligned} \hat\theta(k) &= \hat\theta(k-1) + K(k)[y(k) - \phi^\top(k)\hat\theta(k-1)] \\ K(k) &= \frac{P(k-1)\phi(k)}{\rho + \phi^\top(k)P(k-1)\phi(k)} \\ P(k) &= \frac{1}{\rho}[P(k-1) - K(k)\phi^\top(k)P(k-1)] \end{aligned} \tag{5}$$

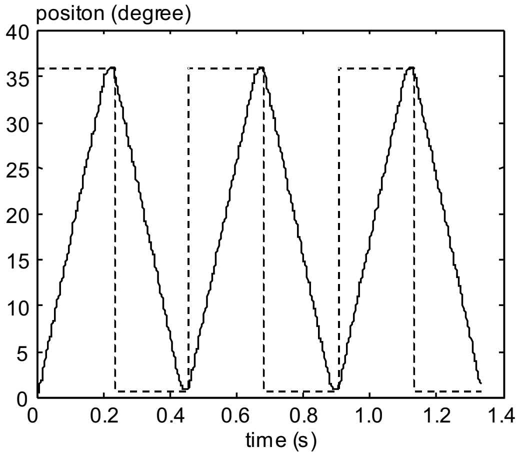

Fig. 5. Position control, rotor position

Table 2. Response time for variable model orders and control delay

n	m	d	response time (s)
2	2	2	0.2273
3	3	2	0.2273
3	3	3	0.2304
2	1	2	0.2273
2	2	1	0.2253
1	1	1	0.3400
1	2	1	0.3379
1	2	2	0.4004
2	2	3	0.2304
1	1	2	0.4024
2	1	1	0.2253

4.3 Dead-zone compensation

As stated above, USM has a dead-zone around $\phi = 0$, which makes the system difficult to achieve precise position control. Therefore, a P controller is used to solve this problem. The control algorithm is:

$$u(k) = \phi^* + K_p u_0(k) \tag{6}$$

where K_p is the proportional gain. The control input calculated by eqn. 6 is restricted from $-90°$ to $90°$.

5 EXPERIMENTAL RESULTS

In order to indicate the validity of the proposed control scheme, experimental results for the position control system are shown in this section. The driving frequency is fixed to 51.5 kHz. The influences of the control delay and the model orders on position control performance are also examined.

Figures 5–8 show the experimental results of position control for $n = 2$ and $m = d = 1$, where Fig. 5 is the rotor position, Fig. 6 is the phase difference, and Figs. 7 and 8 show the parameters a_i and b_i respectively. The experimental results of the response time for variable model orders and control delay are show in Tab. 2. The sampling period $T_s = 1.024$ ms, proportional gain $K_p = 3$,

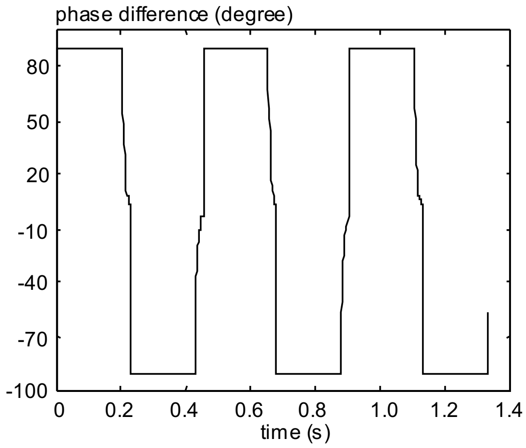

Fig. 6. Position control, phase difference

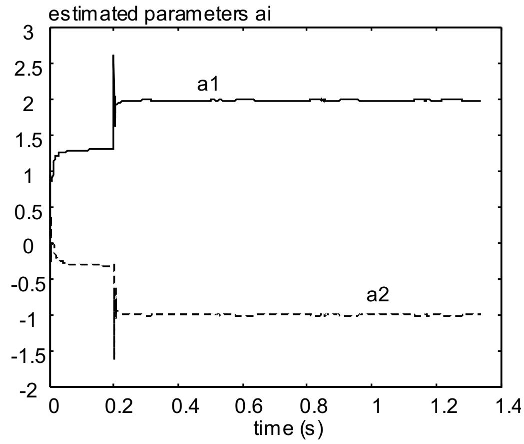

Fig. 7. Position control, parameter a_i

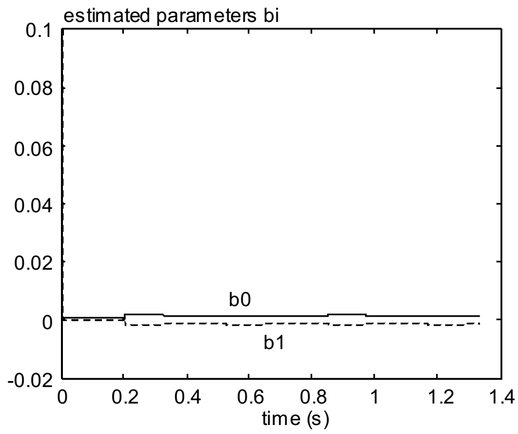

Fig. 8. Position control, parameter b_i

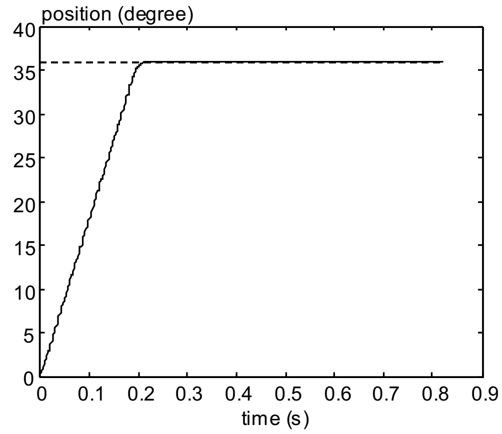

Fig. 9. Rotor position with $K_p = 2$

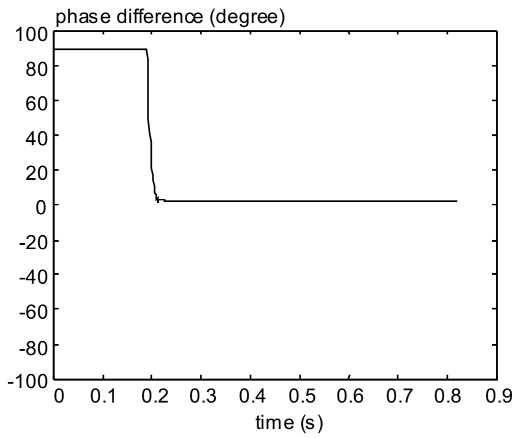

Fig. 10. Phase difference with $K_p = 2$

and control weight $\lambda = 1$. The command position is $0.72^\circ \sim 36^\circ$.

In Fig. 5, good control performance was obtained and the rotor position tracked the command position well with zero tracking error without overshoot. In Fig. 7, plant parameters were identified quickly.

The influence of model orders and control delay on position control was examined experimentally. It can be seen from Tab. 2, that n should not be less than 2. Otherwise, the response time will approximately double when other conditions keep the same. In addition, the influence of m on the control performance is different from that of n. Higher order of m makes less contribution to the reduction of response time, so $m = 1$ is suitable. Otherwise, bigger control delay makes the response time a little longer sometimes.

Therefore, we can draw a conclusion that higher orders of mathematical model and bigger control delay are not better for the position control. However, the computation of the motor parameters and calculation of the control input become more complicated. Hence, the simplified mathematical model, $n = 2$, $m = 1$, and the control delay $d = 1$, are preferable for quick and precise position control.

As to the dead-zone compensation, Figs. 9–10 show the experimental results of position control with $K_p = 2$ when the command position is $0.72^\circ \sim 36^\circ$. The motor cannot track the command position successfully. When the position error approximates zero, as shown in Fig. 9, the control input $\phi \approx 0$, and drops in the dead-zone, shown in Fig. 10. Then the motor stops, and cannot reach the command position. But when K_p is bigger than 2 in this work, the control input will be out of the dead-zone, as shown in Fig. 5, and the motor will track the command successfully and the position error is very small. Therefore, in order to overcome the dead-zone effect and gain precise position control, the proportional gain must be big enough.

6 CONCLUSIONS

The speed characteristics of the ultrasonic motor show that such motors are highly nonlinear and vary with the driving conditions such as temperature rise. Moreover, the existence of the dead-zone effect makes it difficult to track the command successfully without any compensation. In order to overcome these problems and to control the motor position quickly and precisely, this paper proposes a position control scheme using adaptive controller with P controller to overcome the dead-zone effect. The effectiveness of the proposed control scheme was confirmed by experiments. The proposed control scheme can track the command with zero error. Plant parameters in the proposed mathematical model were identified by the recursive squares method. The influences of model orders and control delay on the control performance are also presented. Experimental results show that $n = 2$, $m = 1$, and $d = 1$ are preferable for position control, but the proportional gain should be big enough to overcome the dead-zone effect.

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