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COMMUNICATIONS

PRECISE POSITION CONTROL OF ULTRASONIC MOTOR USING FUZZY CONTROL WITH DEAD–ZONE COMPENSATION

Li Huafeng * — Zhao Chunsheng * — Gu Chenglin **

The ultrasonic motor has a heavy non-linearity and time-varying characteristics which vary with driving conditions. Besides, it possesses a variable dead-zone in the control input. These are problems for accurate actuator positioning in industrial applications. Therefore, it is important to compensate the non-linearity and time-varying characteristic and eliminate the dead-zone in order to improve the control performance. A precise position control scheme for ultrasonic motor using fuzzy controller with dead-zone compensation to control the phase difference of the driving voltages is presented in this paper. The principle and construction of the fuzzy-controller is analyzed and the design method is proposed.

K e y w o r d s: ultrasonic motors, position control, fuzzy control, dead-zone compensation

1 INTRODUCTION

As novel motors with a new principle, new mechanism and new material, ultrasonic motors (USM) have many useful features that traditional electromagnetic ones do not possess, such as a large torque in the low speed range and lacking a brake. The motors have recently been applied as direct drive actuators for articulated robots, 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. The rotor is moved by ultrasonic vibration force of piezoelectric elements on the stator, the resonant frequency and mechanical characteristics of the motor vary with the driving conditions. That is, the USMs have time-varying and non-linear characteristics.

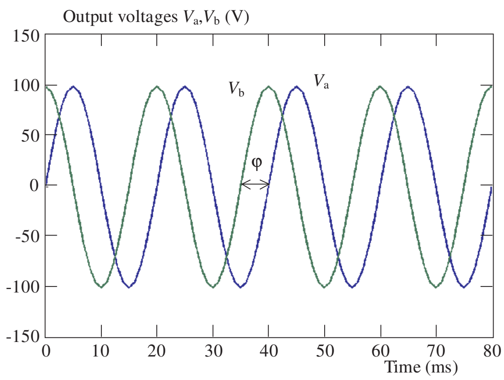

Fig. 1. Output voltages for the USM.

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 which may not use the mathematical model of the motor. These controllers have the features of a 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 [3]. Moreover, it is difficult to implement the adaptive controllers because of the complex arithmetic [4-6]. For the purpose of solving the above problems, this paper proposes a position control scheme of USM using a fuzzy controller with dead-zone compensation. The proposed controller does not use the mathematical model of the motor and is easy to realize.

2 BASIC CHARACTERISTICS OF USM

A typical traveling-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 traveling wave is created on the surface of the stator, which 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 driving voltages V_A and V_B are shown in Fig. 1. As we know there are three variables we can use to control the USM: the amplitude, frequency and phase difference φ of the applied voltage since they all can influence the track and speed of particles on the stator. Among them, frequency is suitable for speed control and phase difference for position control since it can revolve the USM to positive/negative direction smoothly. Therefore, the phase difference is adopted as an input in the proposed precise positioning system. Figure 2 illustrates the speed characteristics for phase difference of applied voltage.

The dead-zone around $\varphi = 0$ exists. When the phase difference falls into the dead-zone, the USM stops, and

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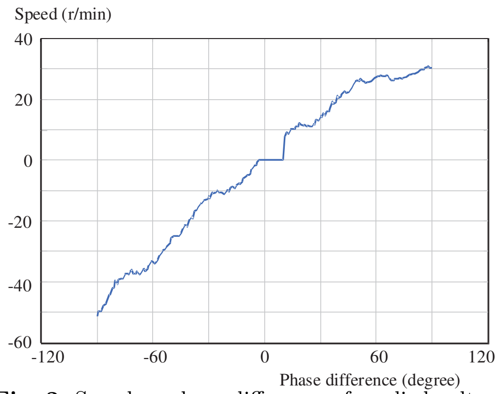

Fig. 2. Speed *vs* phase difference of applied voltage.

will not reach the command position. Therefore, the dead-zone is a problem for the precise position 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 Table 1. The block diagram of the drive system for 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 Instrument. The rotor position is measured by a rotary encoder that has 2500 pulses per revolution. The pulses are improved by 4 times its original in DSP to achieve an 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 desired phase difference. The control strategy in the DSP is realizing using assembly language.

Table 1. Main specifications of the tested USM.

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

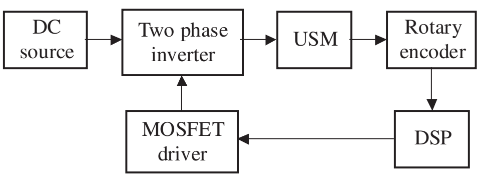

Fig. 3. Block diagram of drive system.

4 CONTROL SYSTEM

As stated above, high performance position control of the USM is usually difficult to be achieved because of the time-varying and strongly non-linear characteristics of the motor, and the existence of a dead-zone effect. In order to overcome these problems and to control the motor position with high performance, we design a position controller using fuzzy controller methods with dead-zone compensation.

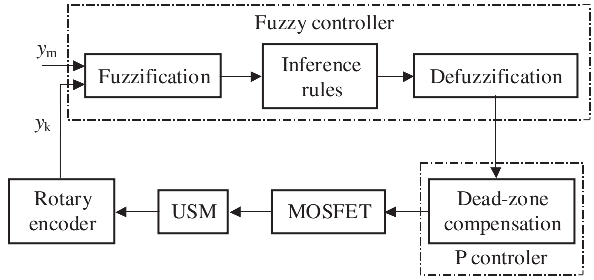

Fig. 4. Block diagram of fuzzy control system.

As we know, the fuzzy control system for USM is a numerical controller utilizing the fuzzy set theory and fuzzy reasoning, and may not use the mathematical model of the motor. But the determination of inference rules relies on the operator's experience [7].

Figure 4 is a diagram of the fuzzy control system. It has two inputs: one is the error e_k, which is obtained by comparing the difference from the position command and the actual position obtained by a rotary encoder which has a resolution of 2500 P/R, and the other the change of the error Δe_k, and the voltages with certain phase difference φ as the output to drive the motor.
That is, $e(k) = y_m - y_k$, $\Delta e_k = e_k - e_{k-1}$.

The core of the system is a fuzzy controller (in the dashed-line frame) that consists of three parts [8]:

1) Converting the actual input to fuzzy quantity (fuzzification);
2) Making fuzzy decision by inference rules according to the input;
3) Converting the gained fuzzy decision to accurate controlled quantity (defuzzification).

The value of e_k is divided into 14 classes:
$U = \{-6, -5, -4, -3, -2, -1, -0, +0, +1, +2, +3, +4, +5, +6\}$
and the corresponding variable A is divided into 8 grades: NL, NM, NS, NO, PO, PS, PM, PL. There are two fuzzy subsets around 0: ZO and PO, which can distinguish the change tendency of the error. The corresponding membership functions of the fuzzy set are selected as Fig. 5. The values of Δe_k and φ are divided into 13 classes. The variable for Δe_k is represented as B and φ as C. They are all divided into 7 grades: NL, NM, NS, O, PS, PM, PL, and the membership functions are shown in Fig. 6 and Fig. 7 respectively.

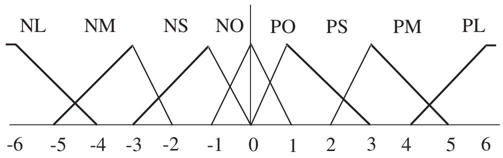

Fig. 5. The membership functions of fuzzy set A.

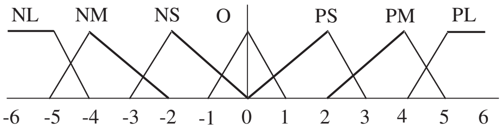

Fig. 6. The membership functions of fuzzy set B.

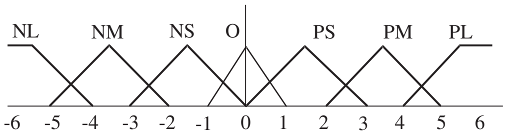

Fig. 7. The membership functions of fuzzy set C.

The control process can be described as "if … and …, then … ", such as "if A is PO and B is PM, then C is PS." Table 2 is the gathering of the fuzzy control rules, and the proposed control system is digitally implemented by a DSP (TMS320F240) based micro-controller.

Table 2. Fuzzy control rules.

C A B	NL	NM	NS	NO	PO	PS	PM	PL
PL	NL	NM	NS	NS	PS	PS	PM	PL
PM	NL	NM	NS	NS	PS	PS	PM	PM
PS	NS	NS	NS	O	O	PS	PS	PS
O	NL	NM	NS	O	O	PS	PM	PL
NS	PM	PM	PS	PS	NS	NS	NM	NL
NM	PM	PM	PS	PS	NS	NM	NM	NM
NL	PL	PM	PS	PS	NS	NS	NM	NL

The output of the fuzzy controller is obtained by the defuzzification of fuzzy subset C:

$$u^* = \frac{\sum_{i=1}^{n} k_i u_i}{\sum_{i=1}^{n} k_i}$$

where u_i is the element of fuzzy subset C, k_i the corresponding weight.

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

$$u(k) = K_p u^*$$

where K_p is the proportional gain.

The output to the MOSFET driver calculated by this equation is restricted between $-90°$ and $90°$.

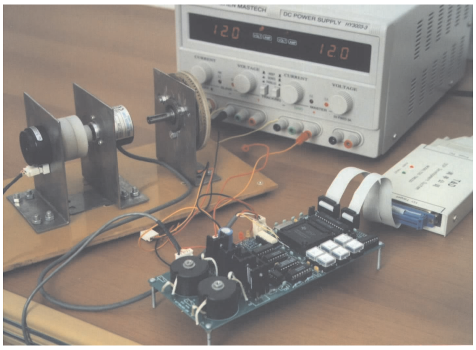

Fig. 8. Precise position control system.

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. Figures 9 and 10 show the experimental results of position control, where Fig. 9 is the rotor position and Fig. 10 is the phase difference. The sampling period $T_s = 1.024$ ms, proportional gain $K_p = 3$ and the command position is $0.72° \sim 36°$. In Fig. 9, good control performance was obtained and the rotor position tracked the command position well with zero tracking error without overshoot.

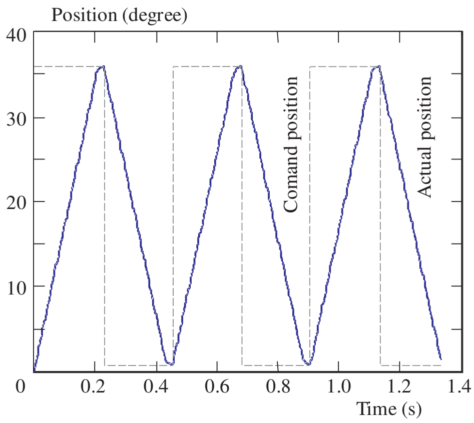

Fig. 9. Position control, rotor position.

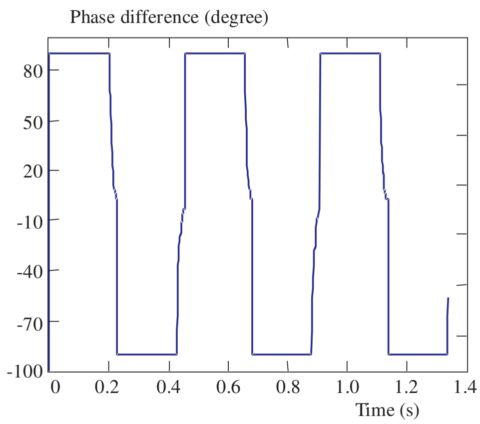

Fig. 10. Position control, phase difference.

As to the dead-zone compensation, Figures 11 and 12 show the experimental results of position control with $K_p = 2$ when the command position is $0.72° \sim 36°$. The motor cannot track the command position successfully. When the position error approximates zero, as shown in Fig. 11, the control input $\varphi \approx 0$, and drop in the dead-zone, shown in Fig. 12. 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. 9, and the motor will track the command successfully even the position error is very small. Therefore, in order to overcome the dead-zone effect and gain the precise position control performance, the proportional gain must be big enough.

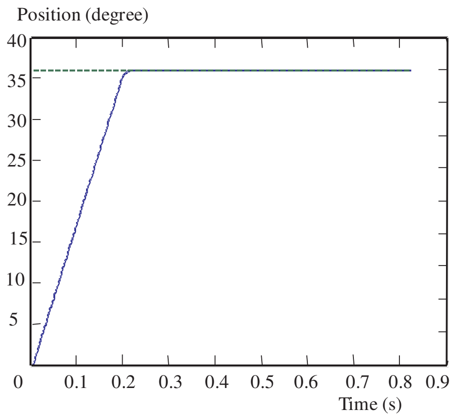

Fig. 11. Rotor position with $K_p = 2$.

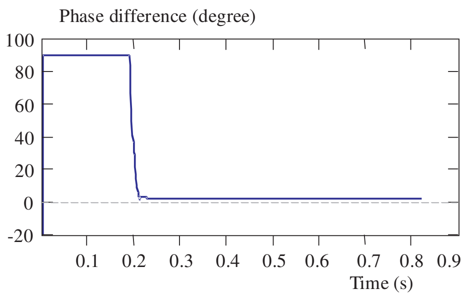

Fig. 12. Phase difference with $K_p = 2$.

6 CONCLUSION

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, a precise position control scheme for ultrasonic motor using fuzzy controller with P controller to overcome the dead-zone effect is presented in this paper. The principle and construct of the fuzzy-controller is analyzed, and the design method is proposed. The effectiveness of the proposed control scheme was confirmed by experiments. The proposed control scheme can track the command with near zero error when the proportional gain is big enough to overcome the dead-zone effect.

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