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Novel intelligent PID control of traveling wave ultrasonic motor

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ABSTRACT

A simple control strategy with acceptable control performance can be a good choice for the mass production of ultrasonic motor control system. In this paper, through the theoretic and experimental analyses of typical control process, a simpler intelligent PID speed control strategy of TWUM is proposed, involving only two expert rules to adjust the PID control parameters based on the current status. Compared with the traditional PID controller, this design requires less calculation and more cheap chips which can be easily involved in online performance. Experiments with different load torques and voltage amplitudes show that the proposed controller can deal with the nonlinearity and load disturbance to maintain good control performance of TWUM.

1. Introduction

Ultrasonic motor uses the converse piezoelectric effect of piezoelectric materials for electromechanical energy conversion, the mechanical energy is transmitted with the help of friction to drive the rotor to rotate [1–4]. Such special operational mechanism causes the obvious nonlinear and time-varying characteristics of the ultrasonic motor for its operating characteristics, which is hard to get ideal motion control performance [5–7].

The conventional PID controller with fixed parameters has more applications in low-cost motor motion control occasions because the simple structure is easier for engineering design [8–10]. But the fixed parameters PID controller is hard to deal with the ultrasonic motor with the obvious nonlinear and time-varying characteristics. Thus the integral control performance is not good. Moreover, with time and with the change of external disturbances, the control performance gets worse, that is it is not robust. Therefore control strategies such as using adaptive control, sliding mode variable structure control and neural network intelligent control algorithms are put forward successively, which have obviously improved ultrasonic motor control performances, especially dynamical ones [11–18]. But the complexity of these algorithms is far beyond the fixed parameters PID control in requiring higher online calculation ability and the resulting increase of the cost of hardware as well as software of the system. So those strategies are more suitable for high-end motion control occasions. For example, the neural network control strategy [13–15] requires a lot of online training and a relatively large amount of calculation, which increases the cost of hardware and software. And the fuzzy neural network [16,17] combines the advantages of fuzzy logic and neural network, which can greatly increase control accuracy. However, the expensive and sophisticated controller confines the usage of this network only to high-precision occasions. In this paper, expert control strategy involving only two rules can realize the control, the calculation is decreased greatly, the controller is simple and the control precision can reach the requirement; thus it can be used in situations that do not require greatly high precision and thus the cost is decreased. Hence, those complex and expensive control strategies are less appealing to manufacturers in the low-cost industrialization of ultrasonic motor.

To realize high performance and low cost with less calculation and complexity, this paper focuses on the improvement of the fixed parameters PID controller with less computation and higher control performance of the ultrasonic motor's speed control. A novel expert PID control strategy with only two expert rules is proposed in this paper. Experiments show that the motor control performance gets better obviously, and real-time calculation is only slightly increased.

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2. Model identification of ultrasonic motor system

To get better performance of ultrasonic motor control, the mathematical model of ultrasonic motor must be consistent with the motor control application, in which the nonlinearity of the motor should be presented.

In this paper, the open-loop step response of speed is used to identify the motor's model. The model can be identified from the data of step response using some methods, such as area method, characteristic point method, and so on. In this paper, the characteristic point method is used to identify the model according to the overshoot and steady state error of the measured step response curves.

The simplified transfer function of the ultrasonic motor can be described as

$$G(s) = K\frac{\omega_0^2}{s^2 + 2\xi\omega_0 s + \omega_0^2} \tag{1}$$

where $K = h_1/f, h_1$ refers to the value of rotating speed on steady state and f is the value of driving frequency which is used as the input variable. The value of K can be obtained directly by measuring. ξ refers to the damping coefficient, ω_0 is the natural frequency. ξ and ω_0 are the model parameters to be identified.

According to the measured data of step responses, the model parameters can be obtained using the characteristic point method. Table 1 shows the identified model parameters with different frequency and rotating speed. It is clear that the same motor model's parameters vary with different input frequencies.

3. Speed control performance of ultrasonic motor with the traditional PID controller

The time-domain expression of the traditional PID controller is

$$u(t) = K_P e(t) + \frac{1}{T_I}\int e(t)dt + T_D\frac{de(t)}{dt} \tag{2}$$

where $u(t)$ refers to the control quantity of the controller's output. For an ultrasonic motor, there are three control quantities: amplitude, frequency and phase difference of driving voltage. In this paper, the frequency is used as the control quantity, namely the $u(t)$ is controlled as the frequency value. $e(t)$ is the control error of the system. In this paper, the speed control of the motor is considered, so $e(t)$ is the speed error. Controller parameters K_P, T_I and T_D are, respectively, the controller's proportional coefficient, integral coefficient and differential coefficient.

Incremental PID controller is widely used in current digital control manners. That is, the control quantity of the present moment (k) is

$$\begin{aligned} u(k) = {} & u(k-1) + K_P[e(k) - e(k-1)] + K_I e(k) \\ & + K_D[e(k) - 2e(k-1) + e(k-2)] \end{aligned} \tag{3}$$

where the controller parameters K_I and K_D are integral coefficient and differential coefficient, respectively. And

$$K_I = \frac{T_S}{T_I}, \quad K_D = \frac{T_D}{T_S} \tag{4}$$

where T_S is the sampling time of the digital control system.

The traditional PID controller is designed to determine appropriate control parameters K_P, K_I and K_D to obtain the expected control performance. Till now, many simple methods have been used to design PID control parameters. For convenience of engineering application, the design methods are usually similar and the results still need to be adjusted slightly in the experiment.

Based on the ultrasonic motor's step response control model in Section 2, the PID control parameters are designed off-line by the engineering method. Note that the expressions of ultrasonic motor's characteristics are discrepant with different speeds, which is also one of the main aspects of its nonlinearity. For this phenomenon, the model in Section 2 is also different at different speeds. For a full inspection of the speed control characteristics of ultrasonic motor under conventional PID controllers, three different models are selected under three typical speeds 30 rpm, 90 rpm and 120 rpm. And then three groups of PID parameters are designed, respectively. The obvious differences between the three groups of parameters just reflect the differences of the three models.

Experiments are implemented to study the speed control effect of the traditional PID controller. The widely used 2-phase traveling wave ultrasonic motor, Shinsei USR60, is used in this experiment as the experimental motor. As shown in Table 2, some important parameters of the adopted motor are listed. The power electronic part of the driving circuit is two-phase H bridges. Speed feedback signal is provided by the optical encoder which is coupling with the motor. The working speed range of the experimental motor is 0–120 rpm.

The sample interval of the rotating speed is an important parameter of the control process. If the value of the sample interval is too large, the sampling value cannot reflect the actual dynamic characteristics of the motor's speed. On the other hand, if the value of the sample interval is too small, more expensive DSP chip should be adopted to meet the requirement of a large calculation amount. In this paper, the value of the sample interval is 0.01 s. This value is smaller than the response time of the experimental motor and can ensure the bandwidth of the control system.

3.1. Experimental adjustment of PID control parameters

According to the three step-response processes with different given values 30 rpm, 90 rpm and 120 rpm of speed, the three groups of PID parameters are adopted as the initial control parameters corresponding to different speeds, respectively. Then the experimental adjustment of PID control parameters is processed to make the three groups of step response processes meet the expected one, then three groups of PID control parameters can be obtained as shown in Table 3. The parameters shown in Table 3 are the set values of tuning parameters of the fixed PID controller. From Table 3,

Table 1
Identified model parameters.

No.	Frequency (kHz)	Speed (rpm)	ξ	ω_0 (rad/s)	K
1	43.1	22.4	0.3373	887.533	0.5200
2	43.2	20.3	0.3753	842.917	0.4707
5	43.3	18.5	0.3241	837.550	0.4275
13	42.7	37.1	0.3912	825.563	0.8678
14	42.8	32.6	0.3744	865.378	0.7610
15	42.9	30.3	0.4238	867.111	0.7064
17	42.4	53.6	0.1999	738.785	1.2636
18	42.5	46.9	0.2873	783.711	1.1021
19	42.6	43.2	0.3156	824.616	1.0137
21	42.3	62.8	0.2935	752.881	1.4855

Table 2
Key parameters of USR60 traveling wave ultrasonic motor.

Parameter	**Quantitative value**
Driving voltage	130 V (RMS)
Driving frequency	40 kHz
Nominal torque	0.5 N m
Rated output power	5.0 W
Rated speed	100 rpm
Peak torque	1.0 N m
Temperature range	From -10° to $+50^{\circ}$
Quality	260 g

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