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Position control of ultrasonic motor using fuzzy PID controller

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Abstract. Time-varying nonlinearity of ultrasonic motor makes it harder to control. In this paper, a double closed-loop position control strategy is designed to achieve high performance of ultrasonic motor's position control. The controller takes driving voltage's frequency as the control variable, and the speed inside loop control with traditional PID controller, position outside loop with three separate fuzzy adjusting devices to adjust the parameters of PID controller. Compared the simulation results of fuzzy PID control to double closed loop PID control, it indicates that the fuzzy PID position controller has stronger anti-interference ability and better robustness.

Key words. Ultrasonic motor, Position control, Fuzzy PID control, PID control.

1. Introduction

The ultrasonic motor is a new-type small and special electric machine that is noted for the inverse piezoelectric effect of piezoelectric materials. Owing to its special working principle, ultrasonic motors possess more advantages than traditional electromagnetic motors, such as small size, small mass, low speed, high torque and so on. Because of its advantages, ultrasonic motors have found an increasingly wide utilization. However, when ultrasonic motors use friction between stators and rotors to transmit the energy, the law of transmission can't be shown in a precise and accurate way due to the complicacy of its slide contact. Moreover, with the change of external conditions, such as temperature, output torque, static pressure between stators and rotors and so on, the resonant frequency of piezoelectric ceramics will vary. What's more, the system is characterized by uncertainty of the parameters, complicacy of the variables, the strong coupling, the varying time and inherent high nonlinearity [1,2]. Therefore, with respect to the performance of ultrasonic motors,

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it not only depends on the motor itself, but also to a great extent depends on the quality of their drive circuit and control strategy.

Recently, many domestic and international scholars have carried on a great deal of research on drive control technique of ultrasonic motors, which are a combination of control strategies and also bring their advantages into full play. For instance, "Fuzzy-PI Dual-Mode Adaptive Speed Control for Ultrasonic Motors" by Shi Tingna [3], "A Neuron Adaptive PID Speed and Position Control" by Fu Ping[4], "Position Control of Ultrasonic Motors Based on H_∞ Mixed-Sensitivity Design Method" by Nguyen [5], "Control of Multiple Ultrasonic Motors with Robust Parameter Design" by Sun Z [6], "Position Control of Ultrasonic Motor Using PID-IMC Combined with Neural Network Based on Probability" by Mu shenglin [7].

PID control is rather a common and mature way of control during the industrial processes. However, traditional PID controller can't meet the need of time-varying and nonlinear controlled member. Fuzzy control can deal with nonlinear controlled member under the circumstances that has loose input, which can not depend on USM mathematical model. Furthermore, fuzzy control can not reach the higher effectiveness of the control scheme, thus, the design of controllers is adopted for a combination of the fuzzy control and other control methods, such as fuzzy PID control, fuzzy neutral net.

Aiming at Shinsei USR60- type ultrasonic motors as the object of study, subject to the characteristics of the varying time and inherent high nonlinearity, the double closed-loop position control strategy is proposed in this paper. In order to achieve the high-performance of position control for ultrasonic motors, for one thing traditional PID controller is adopted for the speed inside loop, for another three separate fuzzy adjusting devices is used for outside loop to adjust the parameters of PID controller.

2. Design of the control system

During the design of the control system, we choose the 2nd order transfer function with pure time delay as the mathematical model of USM, which shown as formula (1):

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

As shown in formula (1), K is open-loop gain, τ is delay time, ξ is damped coefficient, ω_0 is natural frequency. The parameters of models chosen as follows: $\xi = 0.3912$, $\omega_0 = 825.563(\text{rad/s})$, $K = 0.8678$, $\tau = 0.013$.

The ultrasonic motor model that we take as an example is a model of motor's speed and frequency, whose position is the integration of motor's speed. Moreover, double closed-loop position control strategy is adopted for the model during the design of controllers. Owing to the pure delay of the controlled members, PID controller and Smith predictor is adopted for the speed inside loop, and fuzzy PID controller is used for position outside loop. Fig.1 is structure flow chart of speed loop control system, and Fig.2 is structure flow chart of position outside loop control system.

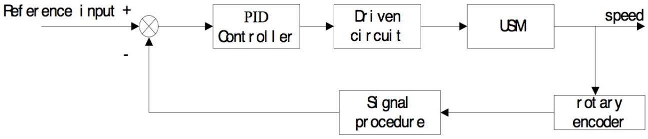

Fig. 1. Structure flow chart of speed PID control system for ultrasonic motors

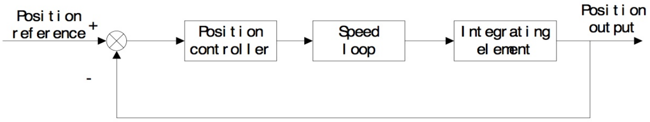

Fig. 2. Structure flow chart of position control system for ultrasonic motors

2.1. Design of the speed inside loop controller

PID controller is adopted for the speed inside loop controller, which makes use of the proportional-plusintegral-plusderivative system error to calculate the controlled variables. The relation between output and error in the time domain is as follows:

$$u(t) = K_P \left[e(t) + \frac{1}{T_1} \int e(t)dt + T_D \frac{de(t)}{dt} \right], \tag{2}$$

$$U(s) = \left[K_P + \frac{K_1}{s} + K_D s \right]. \tag{3}$$

As shown in formula (2), KP is proportional control parameter, TI is integration time parameter, TD is derivative time parameter. We can get formula (3) by Laplace transformation of formula (2). In the formula (3), K_P, K_I, K_D will be proportional control parameter, plusintegral control parameter, and plusderivative control parameter for PID controllers. ($K_1 = \frac{K_P}{T_1}$, $K_D = K_P T_D$).

The module of Simulink in MATLAB is used to undertake research in simulation in this paper. Refer to Fig.3. Simulation diagram of the speed inside loop control system. Due to the pure delay of second-order, we can use Smith predictor method to make the level of noise zero in the process of adjusting PID initial value and PID parameters. The die-away curve method is adopted for PID initial value by a ratio of 4:1.(the overshoot of step response curve is on a ratio of 4:1) After that, we can give the contrast analysis of dynamic performance parameters and smoothness of response curve during the step response of control system. Based on the above, we can arrive at the conclusion : $K_P = 4.8$, $K_I = 1100$, $K_D = 0.004$. When the given speed equals 37r/min, we can get the simulated results. Refer to Fig.3.

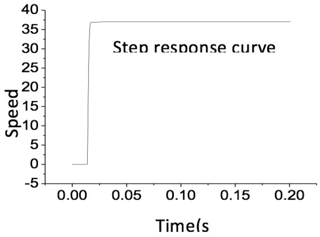

Fig. 3. Simulated curve of PID speed control step response

2.2. Design of the outside loop fuzzy PID controller

In order to deal with nonlinear and time-varying characteristics of ultrasonic motors, three separate fuzzy adjusting devices are used to adjust three control parameters of PID controllers with respect to the design of position outside loop. See Fig.4. Logic diagram of position outside loop control.

Subject to the design of fuzzy PID controllers, "two input one output" is adopted for each of fuzzy adjusting devices, that is to say, "input" refers to error(e) and change of error(ec), and "output" refers to control parameters variables of PID controllers(ΔK_P, ΔK_i, ΔK_d). Thus, we can adjust parameters of PID controllers by the analysis of fuzzy output. Each of fuzzy controllers has 25 control disciplines. Triquetrous subjection function are adopted for language variables of input and output. We also use the Mamdani fuzzy inference method, that is, use the traditional Max-min compositional operation method to be the compositional algorithm of fuzzy relation and fuzzy set, and use the centroid method to solve the fuzzy method.

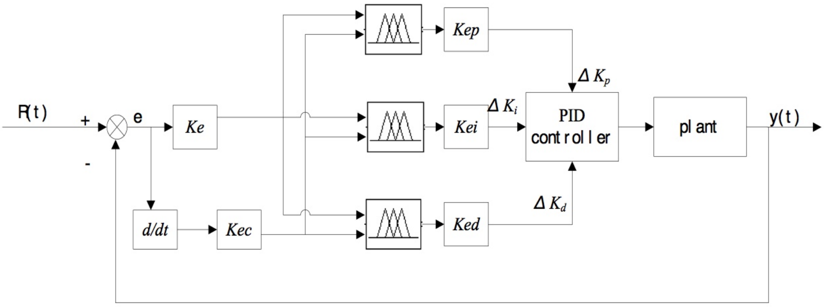

Fig. 4. Logic diagram of position outside loop control

For the parameters of PID controllers(K_p, K_i, K_d) , the adjustment is associated with the change of "e" and "ec", and the requirements of adjustment are as follows:

(1) In order to increase the response speed of the system, we need to increase the parameter K_p with respect to the bigger absolute value of error(e). However, in order to avoid the differential supersaturation caused by the immediate expansion of absolute value for error(e), we need get a smaller parameter K_d to control the

allowed band. Meanwhile, if the overshoot of system response is too big, the system may be reduced to integral saturation. To avoid this, we need limit the integration of controllers($K_i = 0$).

(2) When absolute value of error(e) is medium, we need make K_p smaller and Ki proper. The differential coefficient K_d has a great influence on the system, thus, the evaluation of K_d should be medium in order to ensure the quick response of the system.

(3) When absolute value of error(e) is small, that is, error tends to be zero and system tends to be the set point, we should increase K_p and K_i in a proper way. Meanwhile, we need enhance the anti-interference performance of the system in order to avoid the phenomenon of vibration. Based on the above, we can arrive at the conclusion that the absolute value of "ec" is small while K_d is big and vice versa.

According to the above analysis, the fuzzy subset of input and output variables tends to be {negative big, negative small, zero, positive small, positive big}(hereinafter after known as {NB, NS, ZO, PS, PB}). The method of normalization is adopted for the quantization of input and output variables for fuzzy controllers, that is, the domain tends to be [-1,1] after the process of quantization. What's more, we can make the appropriate control rule list in accordance with the experience of PID parameters' adjustment. Refer to chart 1 and chart 2. Owing to the design of proper fuzzy controllers, we can adjust the PID parameters on line immediately. The formulas of control parameters for PID controllers are as follows:

$$K_p = K_{p0} + \Delta K_p, \tag{4}$$

$$K_i = K_{i0} + \Delta K_i, \tag{5}$$

$$K_d = K_{d0} + \Delta K_d. \tag{6}$$

As shown in these formulas, K_{p0}, K_{i0}, K_{d0} refer to the initial value of control parameters for PID controllers after the adjustment.

Table 1. Rule list of K_p, K_d fuzzy control

ec	E				
	NB	NS	ZO	PS	PB
NB	PB	PB	PS	PS	ZO
NS	PB	PS	PS	ZO	NS
ZO	PS	PS	ZO	NS	NS
PS	PS	ZO	NS	NS	NB
PB	ZO	ZS	NS	NB	NB

Table 2. Rule list of K_i fuzzy control

ec	E				
	NB	NS	ZO	PS	PB
NB	NB	NB	NS	NS	ZO
NS	NB	NS	NS	ZO	PS
ZO	NS	NS	ZO	PS	PS
PS	NS	ZO	PS	PS	PB
PB	ZO	PS	PS	PB	PB

3. Simulation and analysis of control system

With respect to the design of controllers, the frequency-speed model for ultrasonic motors is proposed in this paper. Due to the position that is the integration of speed, we need get the position from the position outside loop and integration element. There is the unit conversion between position and speed, therefore, subject to the design of position outside loop, we not only need the integration element, but also the transmission gain. Since the maximum of the speed for ultrasonic motors is 120r/min, we need limit the amplitude of output for position loop controllers. Additionally, ultrasonic motors can rotate in positive and negative way, thus, the amplitude limit of the speed can range from -120r/min to 120r/min. The simulation diagram of double closed-loop position control is adopted for fuzzy PID control strategy. Refer to fig.5.

Since the precision of the optical-electricity encoder that is connected with the ultrasonic motor tends to be 500 P/R, we can not only make use of the phase detection of DSP56F801 installed timer in the experiment, but also can get the position response precision (0.18°) from the four multiple frequency of quadrate pulse signals. During the simulation, the number of pulse is adopted for the given position input, that is, a pulse equals to 0.18° [8].

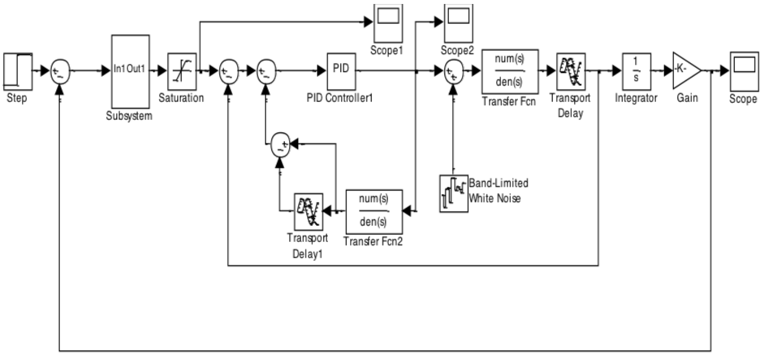

Fig. 5. Simulation diagram of fuzzy PID position control for ultrasonic motors

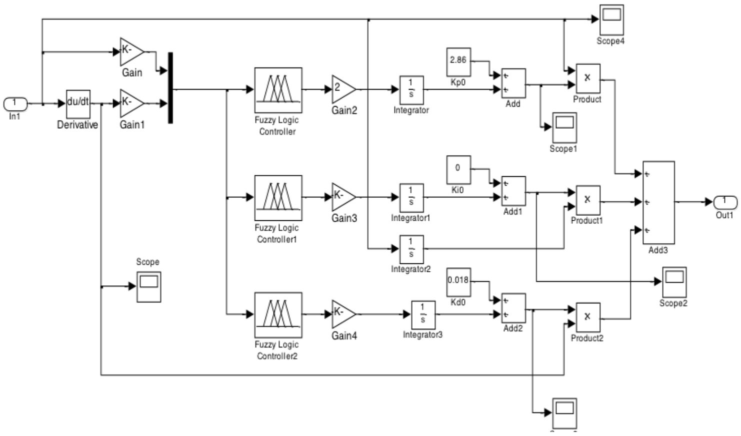

Fig. 6. Simulation diagram of subsystem for fuzzy PID controllers

The module of Simulink in MATLAB is used to undertake research in simulation in this paper. Refer to fig.6. simulation diagram of the fuzzy PID control subsystem. According to the die-away curve method, we can get the initial value of PID control parameters for position loop, that is $K_{p0} = 2.86$, $K_{i0} = 1$, $K_{d0} = 0.018$. By means of adjustment and comparison, we can get the quantification factor of input variables, that is, $K_e = 0.001$, $K_{ec} = 0.00025$. When the quantification factors of output variables(ΔK_p, ΔK_i, ΔK_d) tend to be 2, 10 and 0.001, we can undertake research in simulation for ultrasonic motors' position. Refer to Fig.7. simulated curve of position control system step response. As shown in fig.7, accommodation time of position response curve equals to 0.5s, overshoot equals to 69 pulse, and steady-state error tends to be 6 pulse in the allowed deviation area. By means of adjusting the output scale factor, we can make the overshoot lower, however, the steady-state wave motion tends to be higher with the increase of integral scale factors. As indicated in Fig.8, when the given position is 360° and integral scale factors tend to be 10 and 15, we can get the contrast between the above factors for position step response curve. Based on the same adjustment time, the integral scale factor equals to 15 ($K_{ei} = 15$), thus, the overshoot tends to decrease from 69 pulse to 15.5 pulse, meanwhile, the steady-state wave motion tends to increase from 6 pulse to 15.5 pulse. As indicated in Fig.9 and Fig.10, the number of pulse for the given position equals to 2000, we can also get the same PID controller parameters, that is, $K_{p0} = 2.86$, $K_{i0} = 1$, $K_{d0} = 0.018$. What's more, we can see the contrast between fuzzy PID and PID position step response curve that output scale factor K_{ei} equals to 10 and 15 in the Fig.9 and Fig.10. As indicated in the simulated curve, the fuzzy PID controllers have the edge on various aspects, such as high control performance, good control effect, small overshoot, high respond speed, short adjusting time. However, the position respond curve of fuzzy PID control exists the fluctuation within a narrow range near the steady-state value.

Refer to Fig.11 and Fig.12 speed position step response curve that the number

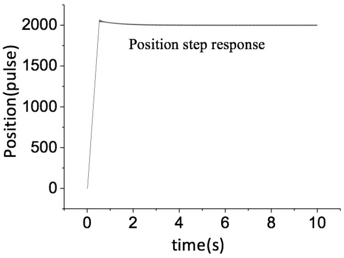

Fig. 7. simulated curve of position control system step response ($y_r = 360°$ that is 2000 pulse)

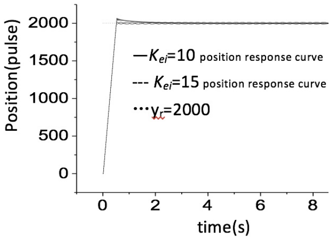

Fig. 8. $y_r = 360°$ position step response curve(different output scale factors)

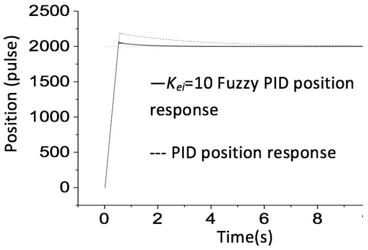

Fig. 9. $y_r = 360°$ contrast of position step response ($K_{ei} = 10$)

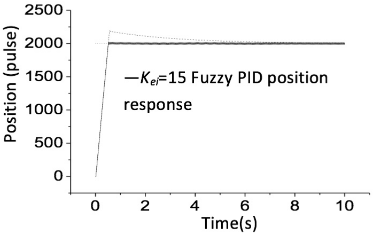

Fig. 10. $y_r = 360°$ contrast of position step response($K_{ei} = 15$)

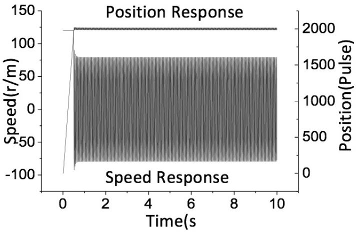

Fig. 11. $y_r = 360°$ speed position step response curve($K_{ei} = 10$)

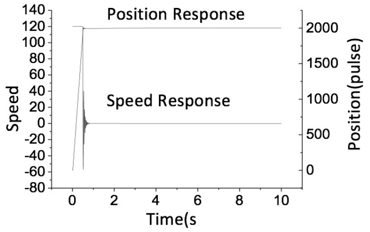

Fig. 12. $y_r = 360°$ speed position step response curve($K_{ei} = 15$)

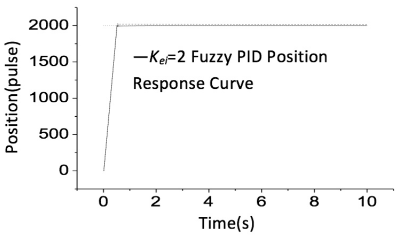

Fig. 13. $y_r = 360°$ speed position step response curve after the adjustment($K_{i0} = 0.1, K_{ei} = 2$)

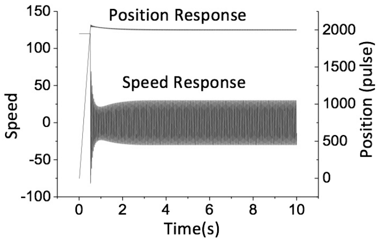

Fig. 14. $y_r = 360°$contrast of position step response($K_{i0} = 0.1, K_{ei} = 2$)

of pulse for given position is 2000 and output scale factor K_{ei} equals to 10 and 15. As shown in the figure, the fluctuation range between position and speed increases in direct proportion, and the fluctuation of speed will be harmful to the work of motors, that is, the frequent change in a positive and negative way is bad for motors. By means of adjusting controller parameters, we can draw the conclusion that decreasing the integral initial value and output scale factor makes the steady-state value smaller. Refer to Fig.13 speed position step response curve for control system. $(K_{i0} = 2, K_{ei} = 2)$ As shown in Fig.14, from the position step response datum, fuzzy PID control has no fluctuation whose steady-state error equals to zero, meanwhile, PID control exists the smaller overshoot that equals to 27 pulse. Moreover, the system needs a long time to remove the static error while fuzzy PID controllers have the edge on removing the static error and respond. As indicated in Fig.15, we can have the comparison for white noise position step response that makes noise variance equal to 0, 0.1 and 1. From the figure, we may reach the conclusion that position controllers have the edge on reducing the noises and robustness of control system. As shown in Fig.16, we can have the contrast for step response curve among the different given position under the conditions that noise variance equals to zero. Furthermore, we can see that position response curve has the same rise speed. As shown in chart 3, we can have the contrast for position control under the different white noises, given position variables and the same PID parameters used by fuzzy PID and PID position controllers. As indicated in chart 3 and Fig.15, we can arrive at the conclusion that position controllers possess rather strong robustness.

Table 3. control performance contrast for different given positions

Given position(°)	Noise variance	Settle time<5%		Steady-State (°) Errors	
		Traditional PID	Fuzzy PID	Traditional PID	Fuzzy PID
90	0	0.142	0.133	0.203	0.036
	0.1	0.142	0.133	0.664	0.266
	1	0.142	0.133	1.602	0.799
180	0	0.261	0.252	0.774	0.093
	0.1	0.261	0.252	0.781	0.274
	1	0.261	0.252	1.98	0.789
360	0	0.505	0.489	2.69	0.032
	0.1	0.505	0.489	2.734	0.291
	1	0.505	0.489	2.88	0.769
720	0	0.994	0.965	9.72	0.024
	0.1	0.994	0.965	9.9	0.532
	1	0.994	0.965	10.08	1.6

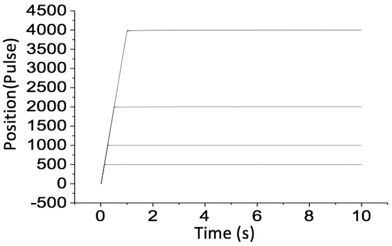

Fig. 15. $y_r = 360°$ contrast of position step response(different noise variance))

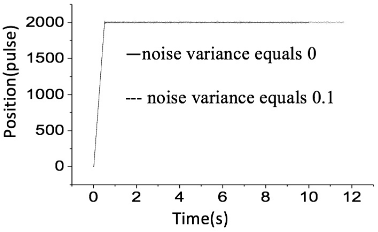

Fig. 16. step response curve contrast for different given positions

4. Conclusion

From what we have discussed above, we can draw the conclusion that excellent flexibility, adaptability and strong anti-interference capability (strong robustness) are obtained in the fuzzy PID parameter self-adjusting controller. With respect to the design of the fuzzy PID parameter self-adjusting controller, quantification factors and scale factors of fuzzy controllers have great influence on control effect. Therefore, we should attach more importance to choose proper quantification factors, scale factors, and fuzzy control disciplines in order to get the better control performance of the system. From the above analysis, we can safely conclude that fuzzy PID controllers possess the better position control effect and higher practicability. In order to get better control effect, we should be engaged in the further research to predict and control its trend and tendency for quantification factors and scale factors by the new control algorithm.

Acknowledgements

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