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SELF-TUNING FUZZY SPEED CONTROLLER OF TRAVELLING WAVE ULTRASONIC MOTOR

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Abstract- Aiming at the nonlinear characteristic of ultrasonic motor, some control strategies have been proposed to control the rotating speed of ultrasonic motor. But most of these strategies are too complex to realize using a low-cost embedded device. In this paper, a simple fuzzy speed controller is designed for ultrasonic motor. Until now, there has no mature and theoretic design method of fuzzy controller. Therefore, experience of expert is often used as the base of design. It makes the design of fuzzy controller become a sophisticated task. In this paper, the design method of fuzzy controller based on fuzzy model is described in detail. Rules of the fuzzy controller are optimized offline using ant colony optimization, and the appropriate parameters of fuzzy controller are also ascertained during the process of optimization. The designed controller is used to control the rotating speed of traveling wave ultrasonic motor with the type of USR60. According to the difference between the actual responses with different speed references, a kind of online tuning method is proposed to modulate the proportional coefficient of fuzzy control. Experiments indicate the validity of the proposed fuzzy controller.

Index terms: ultrasonic motor, speed control, fuzzy, ant colony optimization

I. INTRODUCTION

Ultrasonic motor is a kind of controlled object which is strongly coupled, heavily nonlinear and time-varying [1-4]. Therefore, it is hard to obtain a good motion control performance of ultrasonic motor. Fig.1 shows a photo of ultrasonic motor. Many control strategies have been applied for speed or position control of ultrasonic motor. However, compared with electromagnetic motors, ultrasonic motors exhibit heavily nonlinear characteristic. Thus the potential of ultrasonic motor has not been fully realized yet. Faa-Jeng, Ying-Chih, & Syuan-Yi proposed novel control algorithms which adopt neural network to realize on-line identification and control of ultrasonic motor [5-7]. In contrast, the design of neuron PID seems simple [8].

Figure 1. A photo of ultrasonic motor

The main problem of ultrasonic motor control is how to effectively deal with its obvious nonlinearity and time-varying characteristics. At present, no good solution has been achieved for this problem. For the nonlinear controlled object such as ultrasonic motor, the control strategy should also be nonlinear and have varying characteristics. So that, it can still keep good control performance when the characteristics of ultrasonic motor change. Meanwhile, the control strategy should be as simple as possible to reduce the cost of the system.

Fuzzy control is a kind of nonlinear control method based on fuzzy rules. If it can be designed on the basis of the characteristics of the controlled object and show strong robust, it will be suitable for the strongly coupled and nonlinear controlled object. But there has no mature theories to support the design of fuzzy controller yet. The design process has strong ‘fuzziness’ and it affects the control performance of the actual system. Fuzzy control methods are studied over the years

[9-16]. These methods try to use the nonlinear characteristic of fuzzy control to deal with the nonlinear problems of ultrasonic motor control. Meanwhile, the trade-off between the complexity of the algorithm and its real time implementation should be taken into consideration.

In this paper, fuzzy speed controller is applied for ultrasonic motor. And the design of fuzzy controller is discussed and analyzed in detail. As the important part of fuzzy controller, fuzzy rules are often designed according to control experience. Because of the incomplete experience, the biased expression and the complicated controlled object, usually it is hard to obtain a satisfying control performance by using the designed rules. Especially when the controlled object is highly nonlinear, such as ultrasonic motor. In this paper, in order to ascertain the appropriate parameters of fuzzy controller, the rules of fuzzy controller are optimized offline by using ant colony algorithm. In the experiments, the control performances are different under different speed, so an on-line self-adaptive tuning algorithm is designed to modulate the proportional factors of fuzzy controller. Thus the speed control performance is improved further. Experiments of speed step response indicate that, compared with others, the adjusting time is shorter, the steady-state error is smaller and the control effect is better.

II. THE INITIAL DESIGN OF FUZZY SPEED CONTROLLER FOR ULTRASONIC MOTOR

The input variables of fuzzy controller are speed error e and error rate ec. The output variable is the increment of frequency Δf. The actual universes of discourse of e, ec, Δf are set as $[-e_{max}, e_{max}]$, $[-ec_{max}, ec_{max}]$, $[-df_{max}, df_{max}]$, respectively. After fuzzification, the fuzzy variables are denoted by E, EC, and DF, respectively.

The input and output variables of fuzzy controller are defined in the per unit universe of discourse [-1, 1]. That is, the actual universes of discourse above are converted to per unit universes of discourse by using G_e, G_{ec} and G_{df}.

$$G_e = 1/ e_{max} \tag{1}$$

$$G_{ec} = 1/ ec_{max} \tag{2}$$

$$G_{df} = df_{max} / 1 \tag{3}$$

The motor used in this experiment is Shinsei USR60, a two-phase traveling wave ultrasonic motor. According to the range of speed regulation, set e_{max} = 120rpm. Based on the control experience, set ec_{max} = 600 r/(min•s), df_{max} = 0.3kHz. Then $G_e = 0.0083$, $G_{ec} = 0.0017$, $G_{df} = 0.3$. {NB, NS, ZO, PS, PB} are chosen as the five linguistic values of *E*, *EC*, *DF*, respectively. Their membership functions are triangular functions. Fig.2 shows the shape and description of membership functions.

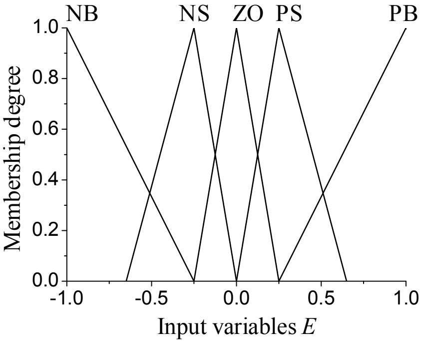

Figure 2. Membership functions of input variable *E*

Fuzzy rules are the core of fuzzy controller. Control experience shows that when the actual speed of ultrasonic motor is greater than its reference speed, that is, when speed error is negative and error rate is negative, its speed increases gradually. In order to eliminate the error of speed, the speed must be decelerated. Hence the increment of frequency, which is the output of fuzzy controller, must be positive to make the frequency increases and the speed decreases. When the speed error is negative and the error rate is positive, its speed is decreasing slowly, so the output of fuzzy controller should be a small positive value or zero. When the actual speed is less than its reference speed, that is, the speed error is positive and the error rate is negative, its speed is increasing gradually, the output of fuzzy controller can be negative or zero. When both the error and the error rate are positive, its speed is decreasing slowly, in order to decrease the error, its speed must be accelerated, and the output of fuzzy controller should be negative. According to these experiences, fuzzy rules are designed as shown in Tab.1.

Table 1. Fuzzy rules

EC \ *E*	NB	NS	ZO	PS	PB
NB	PB	PB	PS	ZO	ZO
NS	PB	PS	PS	ZO	NS
ZO	PS	PS	ZO	NS	NS
PS	PS	ZO	NS	NS	NB
PB	ZO	ZO	NS	NB	NB

By adopting the fuzzy speed controller above, the fuzzy speed control system of ultrasonic motor is shown in Fig.3. The method of fuzzy inference is the Mamdani method. The method of defuzzification is the height method. In Fig.3 N_{ref} is defined as the reference speed and n is the actual speed. The control effect of the above fuzzy control system is simulated by using the dynamic T-S fuzzy model [17]. When N_{ref}= 30rpm, the simulation result of step response control is shown in Fig.4. In the figure, the curve is not straight up in the start stage and its overshoot stage lasts long, the motor reaches the steady-state slowly, the maximum speed is 34.7rpm. Curve 1 of Fig.5 shows the simulation result of the step response when N_{ref} = 90rpm. The curve is not straight up in the start stage. What's more, there appears negative value of speed. The overshoot is 11.0rpm. Thus the control effect should be improved.

The rule table is the core of fuzzy controller. Whether the rules can reflect the control characteristics of ultrasonic motor or not, directly affect the control effect. The 25 rules shown in Table.1 are designed on the basis of previous control experiences and general control rules. It is hard to express the nonlinear characteristics of ultrasonic motor control accurately. In order to reach a relatively good control effect, the rules should be modified by simulation or experiment. The modification is necessary in the process of designing the fuzzy controller.

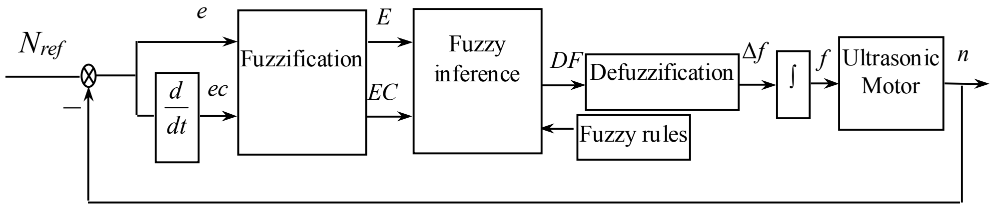

Figure 3. Block diagram of fuzzy control system for ultrasonic motor

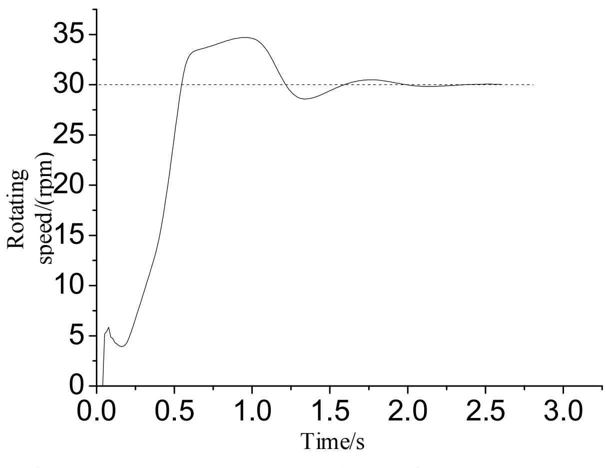

Figure 4. Step response of speed (N_{ref}=30rpm)

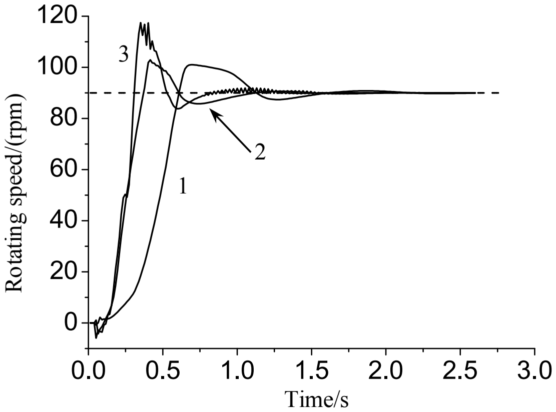

Figure 5. Step responses of speed (N_{ref}=90rpm)

In fact, the process to modify the above rule table is a process to modify the rules gradually to reach a better control effect. If the control effect is quantified as a value, the modification is an optimization process. Therefore, in this paper, the ant colony algorithm is adopted to optimize the rule table of fuzzy controller offline by simulation.

III. FUZZY RULES OPTIMIZED OFFLINE USING ANT COLONY ALGORITHE

Fuzzy rules are optimized by using the ant colony algorithm to obtain appropriate fuzzy rules for speed control. In the algorithm, in order to realize the optimization algorithm, the matrix that the ants are looking for, the object function and the values of related parameters should be ascertained. There are 25 fuzzy rules in Tab.1. There may have 5 linguistic values in the conclusion of fuzzy rules. Thus the matrix is 25*5. Based on the actual condition, in the algorithm the parameters are defined as follows: the number of ants is m = 10; the pheromone residues rate is ρ = 0.7; the number of total pheromone is Q = 1000, the maximum number of cycle is N_m = 100. The program flowchart of adopting the ant colony algorithm to optimize the fuzzy rule table is shown in Fig.6.

a. Determining the object function of ant colony algorithm

To optimize fuzzy rules is to improve the speed control effect. Therefore the object function should reflect the current control effect accurately and it should be quantified to a comparable value. The optimization is finished when the object function reaches the minimum value by the optimization algorithm, that is, the control effect reaches the best at the current fuzzy rule table.

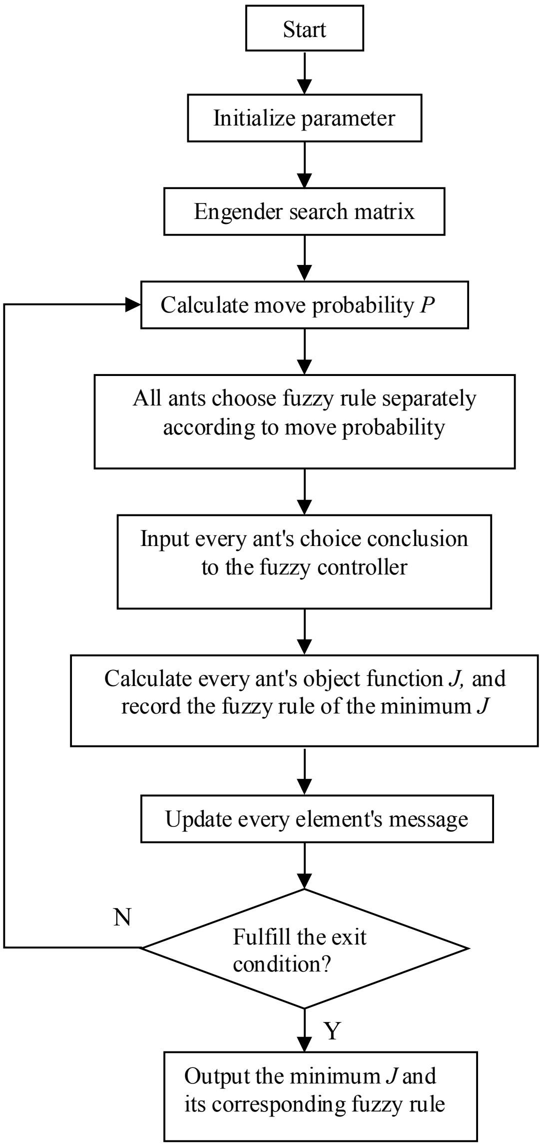

Figure 6. Flowchart for ant colony algorithm optimization

Based on the view above, considering the adjusting time and overshoot are the two main indexes to express the performance of step response, the object function is designed as

$$J=\sum_{N=1}^{2}(1000t_s+5000P) \qquad (4)$$

Where $N = 1$ means the case of $N_{ref} = 30$rpm, $N = 2$ means the case of $N_{ref} = 90$rpm; t_s is the time when the error is within 5%, namely the adjusting time, its unit is s; P is the overshoot, its unit is rpm, it is defined as

$$P = (\text{overshoot speed value- } N_{ref}) / N_{ref} \qquad (5)$$

Constants 1000 and 5000 represent the weights of the adjusting time and the overshoot, respectively. They are designed on the basis of the adjusting time, the relative size of overshoot and the control requirement of the actual system. The greater the weight is, the greater does the control index contribute to the value of the object function, thus this control index should be minimized as far as possible in the optimization process.

The object function above is adopted to optimize the ant colony algorithm, then the optimal object function value is achieved as J = 617190. The optimized results are shown in Fig.7 and Fig.8. In Fig.7, the maximum value of speed is 52.5rpm, it has negative value in the start stage, the minimum value of speed is -144.1rpm, and the final speed is stable at 30.3rpm. In Fig.8 the maximum value of overshoot is 111.3rpm, it has negative value in the start stage, the minimum value of speed is -144.5rpm, and the final speed is stable at 95.1rpm. It is clear that the optimized results of Fig.7 and Fig.8 are not ideal.

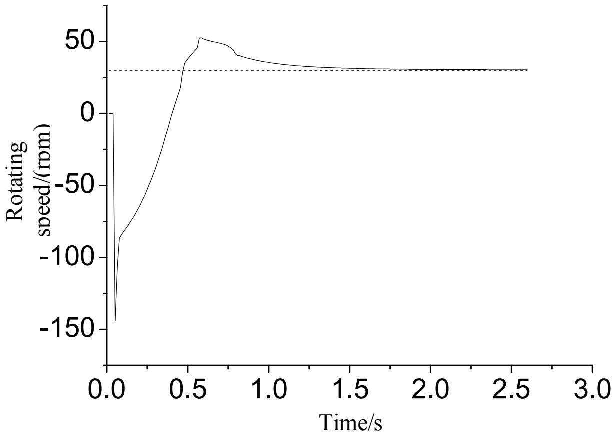

Figure 7. Step response of speed（N_{ref}=30rpm）

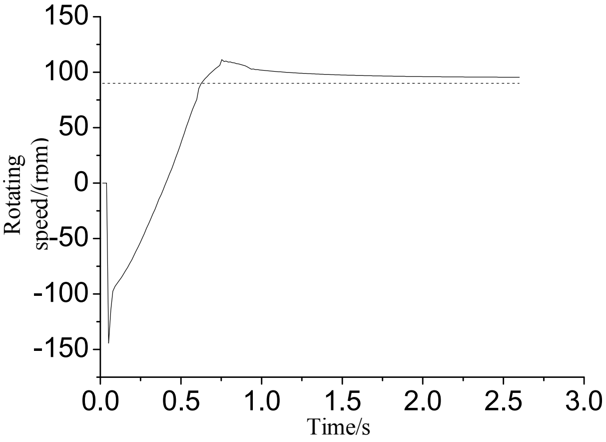

Figure 8. Step response of speed（N_{ref}=90rpm）

Object function J is the standard of guiding the optimization of the ant colony algorithm. By analyzing the process of the optimization algorithm of Fig.7 and Fig.8, it shows that the definition formula (4) of the object function cannot accurately weigh the control effect. So the object function J in the ant colony algorithm should be changed. Based on the situations appear in the figures, in object function J, the minimum speed and final stable speed need to be taken into consideration. Thus object function is changed as

$$J = \sum_{N=1}^{2}(1000t_s + 5000P_{\max} + 5000P_{\min} + 1000e_f) \qquad (6)$$

Where $N = 1$ means the case of $N_{ref} = 30$rpm, $N = 2$ means the case of $N_{ref} = 90$rpm; t_s is the time when error is within 5%, it is the adjusting time, its unit is s; the unit of P_{max}, P_{min} and e_f is rpm.

$$P_{max} = (\text{the overshoot rotate speed} - N_{ref}) / N_{ref} \qquad (7)$$

$$P_{min} = (\text{ the minimum speed} - N_{ref}) / N_{ref} \qquad (8)$$

$$e_f = |n_f - N_{ref}| \qquad (9)$$

Where n_f is the final value of speed which is calculated by simulation.

After the object function has been changed, the rule table is optimized by the ant colony algorithm, then the optimal object function value is achieved as $J = 21247$. Fig.9 and Fig.10 show the control results. In the curve of Fig.9, it is not straight up and there exists turning points in the start stage; there exists oscillation and the maximum value of speed is 47.9rpm in the overshoot stage; it is stable at about 35rpm finally, the steady-state speed error is about 5rpm. In Fig.10 the speed response curve has the same problem in the start stage, there also exists oscillation, and the maximum value of speed is 109.3rpm, it is stable at about 96rpm finally. After the object function has been changed, the results in the steady-state show that none of the final speed error is within 5%. Hence, the object function J should be changed again.

The object functions defined in formula (4) and (6) are based on several performance indexes in the speed response curve. These performance indexes are relatively important, but it can hardly weigh the overall quality of the speed control effect. The object function J is the standard of guiding the ant colony algorithm to find the best value. The defined formula should reflect the control expectation and weigh the control effect accurately. By analyzing the control effect curves from Fig.7 to Fig.10, if a single index can be used to reflect the comprehensive performance of control curve, for example I_{TES} (Integral of Time Multiply Square Error), it may make the object function reflect the optimization purpose more accurately. Thus the object

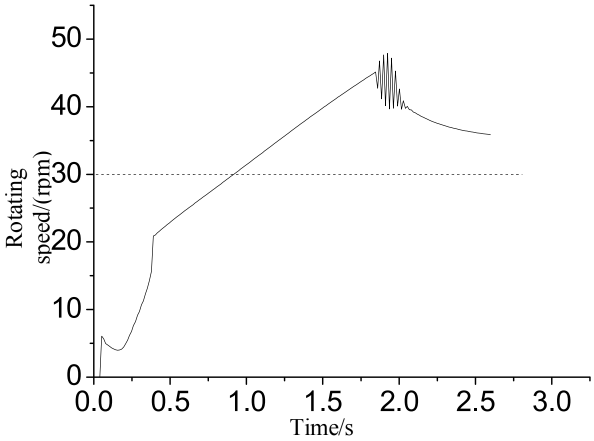

Figure 9. Step response of speed（N_{ref}=30rpm）

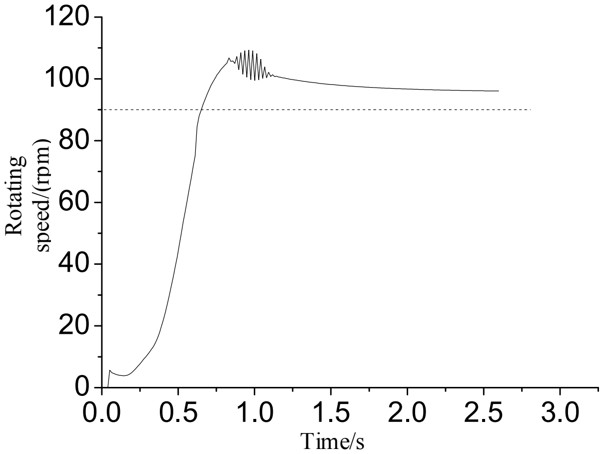

Figure 10. Step response of speed（N_{ref}= 90rpm）

function J is changed as

$$J = \sum_{k=1}^{200} k * t_s * e(k)^2 \qquad (10)$$

Where, k is the time in the simulation process, it can be [1, 200]; t_s is the sampling time, $k*t_s$ is the time corresponding to the moment k, its unit is s; the error of speed is $e(k)$ at the moment k, its unit is rpm.

After the object function is changed, optimal object function value is achieved as J = 18520 by the optimization of the ant colony algorithm. The results are shown in Fig.11 and curve 2 of Fig.5. In Fig.11, the curve is not straight up in the start stage, it appears undershoot after overshoot, it is stable at 30rpm finally, and the maximum value of speed is 34.1rpm. In Fig.5, The response time is shortened. The final value of speed is 90rpm. In the initial stage, the value of speed is below 0rpm. And the response has overshoot.

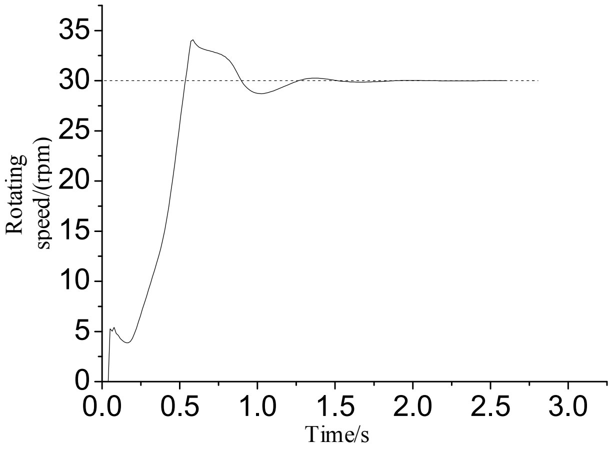

Figure 11. Step response of speed（N_{ref}=30rpm）

b. Determining the scale factors and proportion factors

Fig.11 and Fig.5 indicate that after the object function has been changed, the final values of speed are stable at 30rpm and 90rpm, respectively. But the control effects are not ideal, the parameters of fuzzy controller should be changed further. Parameters of fuzzy controller that can be changed are scale factors, proportion factors, the shape of membership functions, rule table and so on. In the fuzzy controller, the control sensitivity and the control intensity of controlled variable are directly affected by scale factors and proportion factors. The values of scale factors and proportion factors above are determined by the actual universe of discourse of each variable. The optimization algorithm shows that it hasn't make full use of the 25 fuzzy rules. Some rules are invalid all along the control process. According to the distribution of valid fuzzy rules used in the control process, scale factors and proportion factors are changed as G_e= 0.01, G_{ec}= 0.008, G_{df} = 0.35. Fuzzy rules are optimized again by the ant colony algorithm and the rules achieved are shown in Tab.2. The speed step responses are shown in Fig.12 and curve 3 of Fig.5. In Fig.12, it seems to oscillate heavily in the start stage and appears negative value of speed, it also has oscillation in the overshoot stage, at the same time there is a large overshoot, and the maximum value of speed is 41.0rpm. In curve 3 of Fig.5, the corresponding value of object function is less than that in curve 2.

c. Adjusting the control fuzzy rules and determining the initial simulating value of frequency, according to experience

Table 2. Fuzzy rules

EC \ *E*	NB	NS	ZO	PS	PB
NB	NB	ZO	PB	PB	PS
NS	PS	PS	NS	PS	ZO
ZO	ZO	PB	ZO	NB	NB
PS	PB	NB	PS	ZO	PB
PB	NB	NB	PB	PS	NB

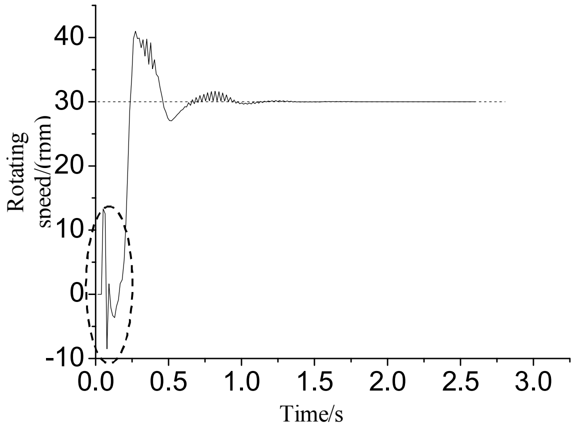

Figure 12. Step response of speed（N_{ref}=30rpm）

The overshoot of step response is large in the curve 3 of Fig.5. Some fuzzy rules in Table.2 should be modified manually for they are obviously inconsistent with the actual control experience. For example, for the oscillation shown in the circle of Fig.12, the effective fuzzy rules, which are used to record these simulation data and control process, are corresponding to the rules 12, 13, 14, 17, 18, 19, 22, 23, 24 in Tab.2 (rules in the table are numbered from top to bottom, from left to right). Among them, rules 12, 14, 19, 24 are disagreement with the actual control experience obviously. For example, in the starting point (k = 1), E = 0.3, EC = 0.24, rules 18, 19, 23, 24 are used. In rule 24, when E is PB and EC is PS, the motor speed is less than its reference value and it is on the decline. At the same time, the output DF should be NB, so that the motor speed can be accelerated quickly to reach the reference value. The modification process is shown as follows: a) Determine the sections which are inconsistent with the expectation in the step response curve; b) Record the valid fuzzy rules and modify the fuzzy rules which are obviously inconstant with the control experience; c) Do the simulation algorithm of the control system again. The step response of simulation is shown as curve 1 of Fig.13.

The above step response is not straight up in the rising stage and there exits negative value. In the simulation algorithm, the dynamic T-S fuzzy model is used in ultrasonic motor. In the beginning, that is $k = 1$, the initial values of frequency for the first three moments should be set. If the initial value is improper, it will make the calculation of the model deviate the practical situation. According to the range of the motor's operating frequency, the initial values of frequency are set as 45.55kHz, 45.4kHz and 45.3kHz. In the practical working condition, the start of ultrasonic motor requires high frequency. Thus the frequency at the starting moment is high. The practical control experience shows that as long as the initial frequency is high enough, the motor can be started normally. That is, the initial value of frequency can be decreased properly. When the three initial values of frequency are modified to 43.95kHz, 43.8kHz and 43.7kHz, the problems appear in the start stage can be solved. The speed step response is shown in curve 2 of Fig.13. The corresponding object function is decreased obviously. The fuzzy rules are modified manually again based on the control experience. Tab.3 shows the new rules. The simulation result of speed step response is shown in curve 3 of Fig.13 by using the rules in Tab.3. The corresponding value of object function is $J = 4631.8$.

Fuzzy controller of ultrasonic motor for speed control is designed above. According to control experience, after the initial design of fuzzy control, the designed fuzzy controller is optimized through simulation by using the ant colony algorithm and dynamic T-S fuzzy model to get better control effect.

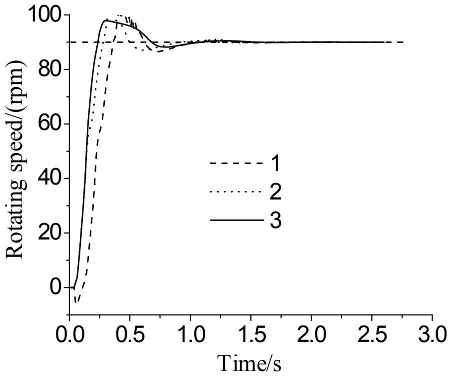

Figure 13. Step response of speed (N_{ref} =90rpm)

Table 3. Fuzzy rules

EC \ E	NB	NS	ZO	PS	PB
NB	PB	PB	PB	PS	ZO
NS	PB	PS	NS	ZO	NS
ZO	PS	PS	ZO	NS	NB
PS	ZO	ZO	PS	NS	NB
PB	ZO	NS	NS	NB	NB

Because control experiences of people cannot be described as the constraints in the process of optimization algorithm easily, it makes the optimization process of the fuzzy controller be blind to some extent. Therefore, in the optimization process, the scale factors, proportion factors, initial model values, the universe of discourse of fuzzy variables and optimized fuzzy rule table should be modified continually based on control experience to get good control effect. By combining the optimization method with the manual adjustment based on control experience, the blindness of optimization process in the optimization algorithm can be overcame to some extent and the design process can be accelerated.

IV. EXPERIMENTS OF THE FUZZY ADAPTIVE SPEED CONTROLLER OF ULTRASONIC MOTOR

To do the experiment on the basis of the design above, it requires that there is no overshoot in the step response of speed control and the response speed should be as fast as possible. The hardware architecture of the speed control system of ultrasonic motor is shown in Fig.14. The motor used in this experiment is Shinsei USR60, a two-phase traveling wave ultrasonic motor. The main control chip is 16 bits DSP56F801. The fuzzy control algorithm is implemented by the program of DSP.

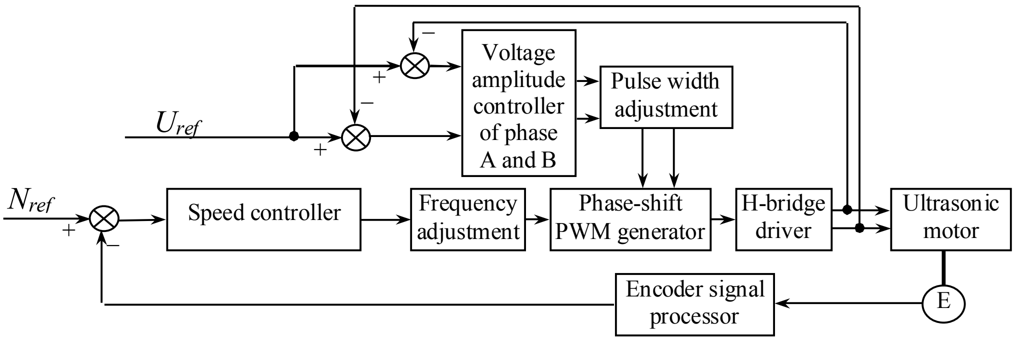

Figure 14. Structure of the experimental system for speed control

Fig.15 shows the step response process, which is measured by the speed step response experiments with different speed references. The dynamic process is smooth, but the adjusting time is relatively long. The output of fuzzy speed controller should be increased to decrease the response time. Considering the response process is smooth in Fig.15, the proportion factor G_{df} of the output variable *DF* can be increased, this is equal to increase the gain of the forward channel of the control system. The output of controller can be increased to accelerate the dynamic

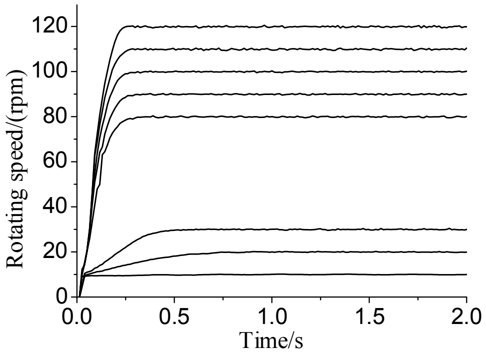

Figure 15. Step responses of speed

response process of speed. In order to avoid the oscillation, even instability of the system, the value of G_{df} should not be too big.

When the reference speed N_{ref} is set as 90rpm, the value of G_{df} is taken as 0.35, 0.45, 0.55, 0.6 and 0.65, respectively. Then the step response curve is shown in Fig.16. When $G_{df} = 0.65$, the step response has slight overshoot. Then the value of G_{df} can be set as 0.6. The simulation and experimental experience indicate that the performances are different at the different reference speeds of the motor. Thus the value of G_{df} may be different at different values of speed. So they should be modified respectively. The corresponding values of G_{df} are shown in Tab.4.

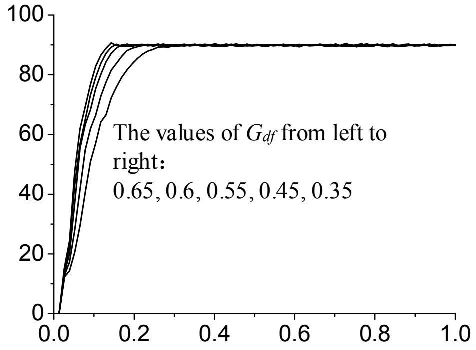

Figure 16. Comparison of step responses with different G_{df} ($Nref$=90rpm)

Table 4. Comparison of G_{df} among different reference values of speed

N_{ref} (rpm)	10	20	30	80	90	100	110	120
The measured value of G_{df}	0.8	0.8	0.75	0.65	0.6	0.6	0.6	0.5
The fitting value of G_{df}	0.81	0.78	0.76	0.65	0.62	0.60	0.56	0.52

The measured values of G_{df} are obtained by experimental adjustment. These data show that the appropriate value of G_{df} is related to the reference value of speed. If the scale factor G_{df} can be tuned on-line adaptively based on different reference values of speed, it can automatically adapt to the varying performance caused by the change of motor speed to keep a good speed control effect. So a relatively simple fuzzy adaptive speed control can be realized. In order to achieve this idea, the measured data in Table.4 are fitted into a polynomial, in which N_{ref} is the independent variable and G_{df} is the dependent variable:

$$G_{df} = 0.84733 - 0.00392 N_{ref} + 3.40316E - 5N_{ref}^2 - 1.99562E - 7N_{ref}^3 \tag{11}$$

The value of G_{df} is calculated according to the polynomial (11) as shown in the third line of Table.4. To make the fitting polynomial (11) be added to the fuzzy control program of DSP. Then the appropriate value of G_{df} can be calculated and the experiment of speed control can be done online. The step responses measured are shown in Fig.17 and Fig.18, the load torque is 0Nm and 0.2Nm, respectively.

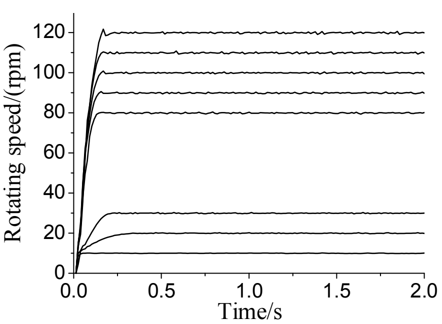

Figure 17. Step responses of speed (no load)

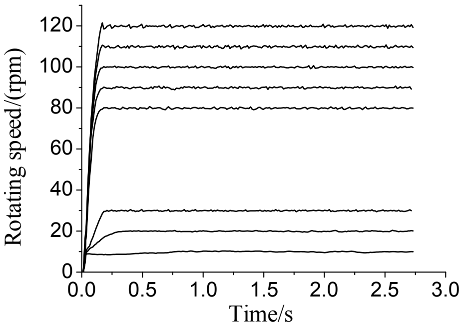

Figure 18. Step responses of speed (load torque is 0.2Nm)

The comparison among Fig.15, Fig.17 and Fig.18 is shown in Tab.5. Compared with Fig.15, the adjusting time of step responses is decreased obviously in Fig.17 and Fig.18. After the values of G_{df} are tuned adaptively, the control effect is better with no load or loading. In order to validate the control performance of fuzzy adaptive speed controller, the reference speed is changed to a slope. The slope responses are shown in Fig.19 and Fig.20. The load torque is 0.2Nm in Fig.20. The comparison of the error between Fig.19 and Fig.20 is shown in Tab.6. The slope responses are in accordance with the reference speeds.

Table 5. Comparison of control performance among Fig.15, Fig.17 and Fig.18

Reference speed N_{ref} (rpm)	Average steady-state error (rpm)			Maximal steady-state error(rpm)			Adjusting time (s)		
	Fig.15	Fig.17	Fig.18	Fig.15	Fig.17	Fig.18	Fig.15	Fig.17	Fig.18
10	0.0913	0.0481	0.1522	0.49	0.39	0.55	0.273	0.039	0.715
20	0.1426	0.1110	0.1561	0.98	0.97	0.76	0.585	0.247	0.273
30	0.1546	0.1431	0.1867	1.31	0.97	0.6	0.416	0.182	0.182
80	0.2129	0.1956	0.2803	2.98	3.32	3.15	0.221	0.117	0.13
90	0.2013	0.2201	0.3126	3.07	1.93	3.87	0.221	0.13	0.13
100	0.2061	0.2295	0.2789	4.05	4.4	4.9	0.208	0.13	0.13
110	0.2849	0.2525	0.383	4.67	2.5	3.62	0.208	0.143	0.143
120	0.2578	0.2855	0.3919	3.82	5.11	5.76	0.208	0.143	0.143

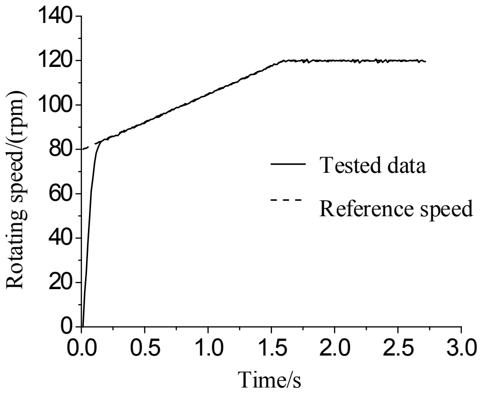

Figure 19. Slope response (no load)

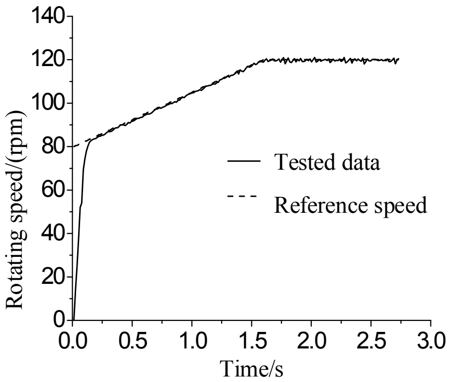

Figure 20. Slope response (load torque is 0.2Nm)

Table 6. Error comparison of Slope Response

	Fig.19(no load)	Fig.20 (load torque=0.2Nm)
The range of tracking error (rpm)	[0,2.45]	[0,2.68]
Average steady-state error (rpm)	0.2921	0.577

V. CONCLUSIONS

Based on the dynamic T-S fuzzy model of ultrasonic motor, fuzzy speed controller of ultrasonic motor is designed in this paper. The fuzzy rules of the fuzzy controller are optimized offline by the ant colony algorithm to reduce the dependence on experiences. The established fuzzy controller is applied to the speed control of ultrasonic motor, the motor can run smoothly, but the response speed is a little slow. To improve the control performance and ensure the simplicity of controller simultaneously, an online adaptive self-tuning method is proposed to modulate the output proportion factors of fuzzy controller.

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