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T-S FUZZY CONTROLLER DESIGN OF SIMULATION TEST TURNTABLE

[1]BAITING ZHAO, [2]XIAOFEN JIA, [3]ZHENBI LI

[123]Electrical and Information Engineering College,

Anhui University of Science and Technology, Huainan, China, 232001

E-mail: [1]zhaobaiting@gmai.com, [2]jxfzbt2008@163.com, [3]i-u@163.com

ABSTRACT

For the control system of a certain type simulation test turntable (STT), a simplified model is established firstly, then the T-S fuzzy controller is designed, finally control results and stability are analyzed by simulation. Simulation results show that the T-S fuzzy controller has the advantages of the fast response and positioning, good stability, strong anti-interference. The designed T-S fuzzy controller has variable gain characteristics, open-loop automatic gain increases along with the interference amplitude, and open-loop automatic gain decreases along with the interference amplitude. It can ensure that the system can work in lower gain state, but has the ability to inhibit the large amplitude of the interference.

Keywords: *Aluminum Alloy; Plastic Anisotropy; Microstructure*

1. INTRODUCTION

Simulation test turntable (STT) plays a vital role in aviation, aerospace and other fields in the simulation and testing of critical hardware. STT is the primary equipment for rating the inertial navigation systems and inertial devices. Its performance affects the testing precision, degree of belief and validity of simulation. The research and manufacture of the STT play the important role in the aerospace industry and the development of national defense construction.

STT has strong non-linear and open-loop unstable characteristics, so the research of STT control system is of great importance to STT. The controller performance has a direct impact on the dynamic performance and other characteristics of STT. Fuzzy control is applicable to STT system, and has the characteristics of simple, practical, no precise mathematical models, etc. In this paper, a T-S fuzzy controller is designed for the STT for the accurate model is difficult to obtain. Simulation results show that the T-S fuzzy controller has the advantages of the fast response and positioning during start-up operation, good stability, and strong anti-interference.

2. MODELING SIMULATION TEST TURNTABLE

The driver of simulation test turntable is brushless DC motor, and using current feedback PWM inverter drive. Brushless DC motor system consists of three parts including permanent magnet synchronous motor, inverter drive circuit and angle measurement circuit. The Brushless DC motor system mathematical model is:

In which P is the number of pole pairs; i_d 、 i_q is the current of axis d and q ; r is stator resistance; ω is rotor angular velocity; K_p is the gain of current ratio regulator; K_f is the coefficient of current feedback; K_s is the equivalent gain of AC drive power; L is the inductance of axis d and q; J is the moment of inertia of the motor load; U is the voltage reference signal

$$\begin{cases} L\times\dfrac{di_q}{dt} = -(r+K_pK_sK_f)i_q - (LPi_d + K_yP)w + K_pK_su \\ L\times\dfrac{di_d}{dt} = -(r+K_pK_sK_f)i_d - LPwi_q \\ \dfrac{dw}{dt} = \dfrac{3PK_y}{2J}i_q \end{cases} \tag{1}$$

Brushless DC motor system is a complex coupled nonlinear systems which shown in formula (1). Under the premise of current loop bandwidth of the

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system is large enough, i_d of axis d converges to zero faster than the change rate of angular velocity ω and i_q of axis q. Thus i_d can be ignored within the system bandwidth, that is $i_d = 0$. Let $K_1 = K_p K_s$, $R = r + K_p K_s K_f$, $K_t = \frac{3K_\psi P}{2}, K_e = K_\psi P$, the linear model of motor system can be drawn as follows:

$$\frac{\omega(s)}{U(s)} = \frac{K_l}{\frac{JL}{K_t} + \frac{JR}{K_t}s + K_e} \tag{2}$$

Let electromagnetic time constant is $\tau_e = \frac{L}{R}$, electrical time constant is $\tau_m = \frac{JR}{K_t K_e}$ and $K = K_1 / K_e$. For the brushless DC motor systems, system always can meet $\tau_m >> \tau_e$ for the introduction of current feedback. Formula (2) can be reduced as follows:

$$\frac{\omega(s)}{U(s)} = \frac{K}{(\tau_m s + 1)(\tau_e s + 1)} \tag{3}$$

Formula (3) shows that simplified linear model of brushless DC motor system is an overdamped second order system, which characteristics similar to the DC motor model.

3. DESIGNING OF T-S FUZZY CONTROLLER

The structure of T-S fuzzy controller has the following rules:

If the error e is A, then controlled variable u= k_1 e

If the error e is B, then controlled variable u= k_2 e

$$\begin{cases} \mu(e) = 0; & e < -2 \\ \mu(e) = e + 2; & -2 \le e < -1 \\ \mu(e) = 1; & -1 \le e < 1 \\ \mu(e) = -(e-2); & 1 \le e < 2 \\ \mu(e) = 0; & e \ge 2 \end{cases} \tag{4}$$

$$\begin{cases} \mu(e) = 1; & e < -2 \\ \mu(e) = -(e+1); & -2 \le e < -1 \\ \mu(e) = 0; & -1 \le e < 1 \\ \mu(e) = -(e-1); & 1 \le e < 2 \\ \mu(e) = 1; & e \ge 2 \end{cases} \tag{5}$$

e is the difference value of expected output and actual output, u is the outputs of the local linear controller, k_1 and k_2 are the ratio coefficient of local linear controller, A and B are the linguistic variables. The analytical expressions are shown in Formula 4 and 5. The shape of membership functions are shown in Figure.1.

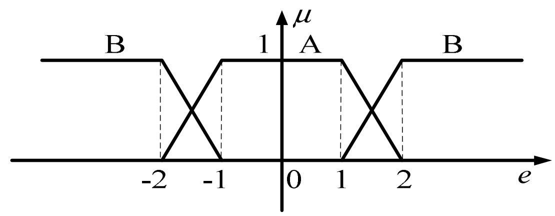

Figure 1 Illustration of the Membership function of A and B

The T-S fuzzy non-linear controller shown in Figure2 can be constructed based on the fuzzy controller shown in Figure.1.

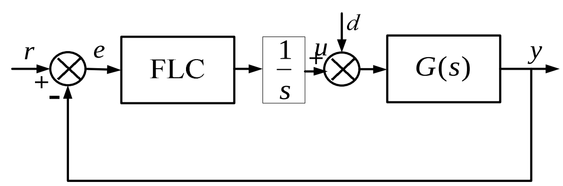

Figure 2 The block diagram of the T-S Fuzzy control system

FLC is the T-S fuzzy controller, r is reference input, d is interference signal and the parameter of controller $k_1 = 1, k_2 = 3$.

4. SIMULATION OF THE T-S FUZZY CONTROLLER

The response of system to different amplitude step signal is analyzed under the assuming of interference signal d is zero. In Figure.3, the solid line correspond to the input response of fuzzy control system, dotted line is the input response of liner controller $C_1(s)$ and $C_2(s)$.

Shown from simulation curves, the performance of T-S fuzzy controller is close to the linear controller with small performance gain when the amplitude of input signal is small. With the increase

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of input signal amplitude, the performance of T-S fuzzy controller is close to the linear controller with larger performance gain. So the response of T-S fuzzy control system will faster with increase of input signal amplitude.

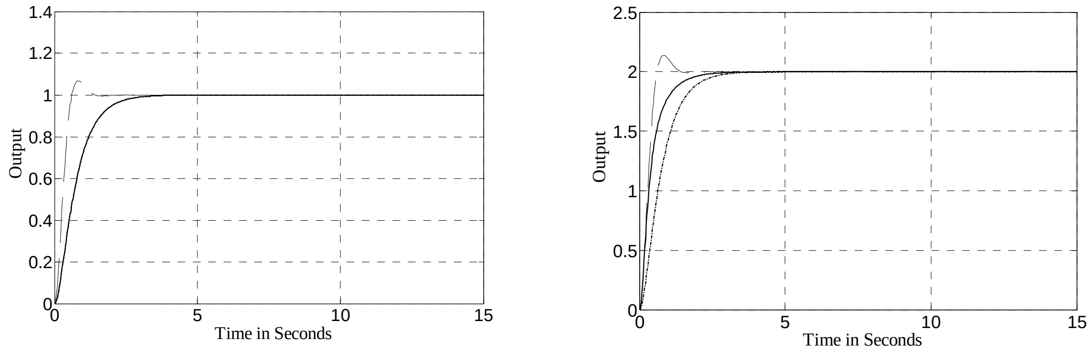

Figure. 3 Responses to the unit step signal with different amplitude

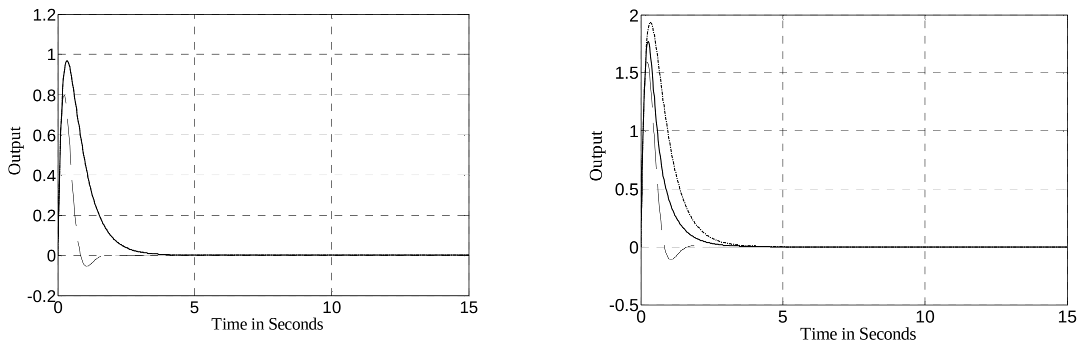

Figure. 4 Responses to the step disturbance signal with different amplitude

Assuming input signal is zero, the response of system to different amplitude disturbance signal is analyzed. In Figure.4, the solid line correspond to the input response of fuzzy control system, dotted line is the input response of liner controller $C_1(s)$ and $C_2(s)$.

Shown from the simulation curves in Figure.4, the performance of T-S fuzzy controller is close to the linear controller when the disturbance signal is small. With the increase of disturbance signal amplitude, the performance of T-S fuzzy controller is close to the linear controller.

Simulation results show that the T-S fuzzy controller is equivalent to a variable gain controller. The controller gain increases with the increasing of amplitude of input signal, and has good inhibitory effect to disturbance signal. When the amplitude of interference signal is changing, it needs a large gain linear controller. But it will increase the noise response and decrease the stability of the system. The designed T-S fuzzy controller can ensure that the system working in lower gain state, but has the ability to inhibit the large amplitude of the interference. It has the variable gain characteristics, open-loop automatic gain increasing following the increase of interference amplitude, and open-loop automatic gain decreasing following the decrease of interference amplitude.

5. STABILITY ANALYSIS OF T-S FUZZY CONTROL SYSTEM

The T-S fuzzy control system is composed of the T-S fuzzy controller and a linear controlled object. The Lyapunov stability of the T-S fuzzy control system is analyzed.

To the T-S fuzzy control system shown in Figure.2, let the state-space realization corresponding to the transfer function expression G(s) of controlled object is shown in formula (6).

$$\begin{cases} \dot{X} = AX + Bu \\ y = CX + Du \end{cases} \tag{6}$$

Assume $D = 0$, and $X(0) = x_0$. T-S fuzzy control rules can be described as follows:

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If the error e is Ma, then controlled variable $u_1 = k_1$ e

If the error e is Mb, then controlled variable $u_2 = k_2$ e

By the fuzzy reasoning process we can get:

$$u(e) = \frac{\mu_{Ma}(e)u_1 + \mu_{Mb}(e)u_2}{\mu_{Ma}(e) + \mu_{Mb}(e)} = \frac{\mu_{Ma}(e)k_1 e + \mu_{Mb}(e)k_2 e}{\mu_{Ma}(e) + \mu_{Mb}(e)} = \frac{\mu_{Ma}(-y)k_1(-y) + \mu_{Mb}(-y)k_2(-y)}{\mu_{Ma}(-y) + \mu_{Mb}(-y)}$$
$$= \frac{\mu_{Ma}(-CX)k_1(-CX) + \mu_{Mb}(-CX)k_2(-CX)}{\mu_{Ma}(-CX) + \mu_{Mb}(-CX)} = -\phi_1(X)k_1 CX - \phi_2(X)k_2 CX$$
$$= -\sum_{i=1}^{2} \phi_i k_i CX \tag{7}$$

$\mu_{(\cdot)}(\cdot)$ is the value of membership function corresponding to the input variables, and $\phi_1(X) = \mu_{Ma}(\cdot)/\{\mu_{Ma}(\cdot) + \mu_{Mb}(\cdot)\}$, $\phi_2(X) = \mu_{Mb}(\cdot)/\{\mu_{Ma}(\cdot) + \mu_{Mb}(\cdot)\}$

With the formula (6) and (7), formula (8) can be obtained as follows:

$$\dot{X} = \sum_{i=1}^{2} \varphi_i (A - k_i BC)X = \sum_{i=1}^{2} \varphi_i Q_i X \tag{8}$$

In formula (8) $Q_i = (A - k_i BC)$.

The sufficient condition of equilibrium point globally asymptotically stable of the system is the existence of positive definite matrices P, which satisfy $Q_i^T P + PQ_i^T < 0$ to every Q_i and i=1, 2.

The system can be a generalized controlled object combining the original controlled object together with integral element.

$$G_e(s) = \frac{1.25}{s(0.15s+1)(0.007s+1)} \tag{9}$$

The transfer function corresponding to a state space form as follows:

$$A = \begin{bmatrix} -149.5238 & -952.3810 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix};$$

$$B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix};\quad C = [0 \quad 0 \quad 1190.5];\quad D = 0。$$

Let $k_1 = 1$, $k_2 = 3$, the value of Q_i can be obtained as follows:

$$Q_1 = A - k_1 BC = \begin{bmatrix} -149.5238 & -952.3810 & -1190.5 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

$$Q_2 = A - k_2 BC = \begin{bmatrix} -149.5238 & -952.3810 & -3571.4 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

When there is a positive definite matrix P which meets Formula 10, then the T-S fuzzy control system is globally asymptotically stable.

$$\begin{cases} Q_1^T P + PQ_1^T < 0 \\ Q_2^T P + PQ_2^T < 0 \end{cases} \tag{10}$$

P can be obtained which meet Formula 10:

$$P = \begin{bmatrix} 0.0002 & 0.0016 & 0.0009 \\ 0.0016 & 0.3350 & 0.5301 \\ 0.0009 & 0.5301 & 4.0144 \end{bmatrix}$$

The maximum eigenvalue Max=4.0892, and the minimum eigenvalue Min=0.002, then according to the conditions, the T-S fuzzy control system is globally asymptotically stable.

6. CONCLUSION

For the simulation test, turntable is difficult to obtain accurate mathematical models; a T-S fuzzy controller is designed. Simulation results show that the T-S fuzzy controller has the advantages of the fast response and positioning, good stability, strong anti-interference. The designed T-S fuzzy controller has variable gain characteristics, open-loop automatic gain increases along with the interference amplitude, and open-loop automatic gain decreases with the interference amplitude. It can ensure that the system can work with lower gain state, but has

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the ability to inhibit the large amplitude of the interference.

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