A fuzzy PID controller for laser tracking system under low speed and high friction condition

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KEYWORDS : Fuzzy controller , Crawl, Torque detect I, Laser tracker I, Measurement

Abstract: Spherical coordinates laser tracking measuring system is a kind of high precision of great size measurement instrument. In order to obtain a mechanical construction with high rotation accuracy, dense ball bearing is adopted. But because of its special structure and processing technology, the friction torque of it is great, the static and kinetic frictions vary greatly and the distribution of friction along the shaft circumference difference a lot. All of these make the control torque that needed to drive the system fluctuate dramatically, the system crawl at low speed and can not provide enough acceleration.

In order to grasp the variation of friction torque, the paper provides a constant-torque method to detect it . Experimental result shows that the friction torque signal changes accord with chaos rule. So it is difficult to eliminate the influence of friction through signal compensation method.

On this basis , a controller based on fuzzy theory is designed which makes the tracking target's speed and acceleration as the inputs and the motor PID parameters as the outputs. The input variables and the membership functions of output variables are respectively divided into seven and two universes. The input variables adopt triangle membership functions and the output variables use exponential membership functions. Through calculating the weighed sum of every PID parameters to solve ambiguity. Finally for the tracking system ,experimental results show that the crawling at low speed is eliminated sharply and the acceleration is increased a lot.

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

NOMENCLATURE

M_F=The constant drive torque provided to rotation system
M_f= Friction torque
J= Moment of inertia
α= Angular acceleration
m= Embedded dimension of phase space
T= Delay time
N=Vector number
μ_{max}=Maximum Lyapunov exponent
M= Iteration times of evolution process
D_i=Distance of the nearest two vectors at t_i moment
D_i' =Distance of the two vectors at t_{i+1} moment

1. Introduction

Laser tracking coordinate measuring system is a kind of high precision measuring equipment of large size which uses spherical coordinates to record data points[1]. Its horizontal measuring angel is 360 degree, vertical angel is 290 degree and the biggest measuring radius is 160 meters. Its distance measuring accuracy in whole scope is less than 0.1millimetre. Even in some system the distance measuring accuracy does not exceed 10μm within a scope of 80 mete rs measuring radius. The key structure of laser tracking system is tracking head, currently the most used tracking head is multi-axial structure whose axis of the two shafts perpendicularly intersect to each other. Driven by the control system, tacking head make a tracking mirror or a laser rotate in two dimension to achieve the tracking to the target mirror as shown in Fig.1. Its maximum tangential tracking speed is 6m/s , so laser tracker shaft always works at a speed of 0-10rpm during the whole measurement process. In this low speed condition the influence of friction to the stability and steadiness of the rotation becomes worse. In order to guarantee the measuring accuracy of the whole system dense ball bearing is adopted. By increasing the roller, the contact area between the roller and the shaft is increased and the axial and radial jumps are decreased . But because of its special structure and processing technology, the friction torque of it is great, the static and kinetic frictions vary greatly and the distribution of friction along the shaft circumference difference a lot. All of these make the control torque that needed to drive the system fluctuate dramatically, the system crawl at low speed and can not provide enough acceleration. Therefore this paper analyzed the friction of the shafts and established a set of fuzzy PID control strategies to realize the high performance control to the system.

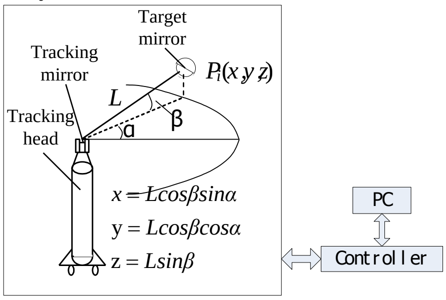


Fig. 1 Schematic of laser tracking system

2. Extraction and analysis of friction torque signal

In order to obtain high performance control system, the friction torque is analyzed through experiments. This method is named as *constant torque method*. In term of the torque equation M_F-M_f=J*α, there is M_f =－J*α+M_F, where M_F and J are constant and obviously Mf is proportional to α. The change rule of the friction torque can be obtained by analyzing the α's fluctuation.

2.1Extraction of the friction torque signal

Through a harmonic drive gearing with a gear ratio of 100:1 the dense ball bearing shaft is driven by a dc motor whose controller only contains a close current loop. The controller can generate a constant current signal to the motor to ensure the drive torque is unchangeable. During the experiment, increase drive current from 0 gradually until the drive torque can overcome maximum static friction torque and drive shaft rotation with constant acceleration. The shaft speed is sampled by a grating scale. One-order differential signal of the speed data is the acceleration signal which is reaction to the friction torque.

2.2 Friction signal analysis

4,000 speed signals have been collected through experiment. But because of the resolution of the grating scale when the speed increases to 1300rpm, grating scale can't read the signal correctly, so eventually 668 sample points are chosen as research object. Speed curve is shown in Fig2 and the acceleration curve is shown in Fig. 3. As mentioned in above paper,change of acceleration is the reaction of the friction torque variation. Observing acceleration signal schematic, it can be seen that the signal has wide continuous power spectrum. According to the theory of digital signal processing, periodic signal's power spectrum is discrete, which comprises the fundamental frequency and its harmonics. Quasi-periodic signal's power spectrum is also discrete, besides the fundamental frequency and its harmonics, but also contains frequency due to the nonlinear effects, thus quasi-periodic signal's power spectrum diagram unlike that of periodic signals which is in the same interval. However, because its internal nonlinear effect chaotic signal makes system evolves randomly, so its power spectrum diagram or other spectrum diagram is broadband continuous spectrum[3]. Therefore, after the initial judgment this acceleration signal has shown characteristics of chaos.

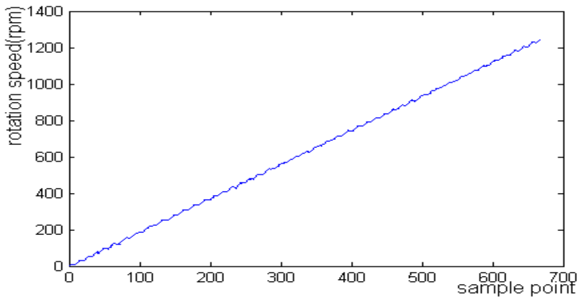


Fig. 2 Speed data

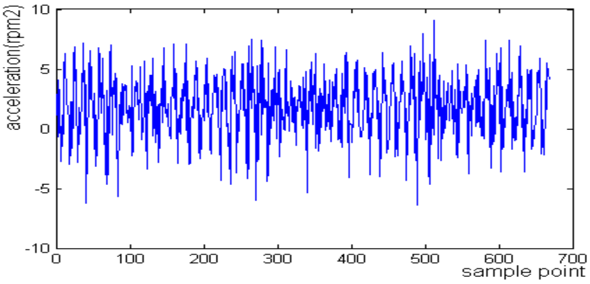


Fig. 3 Acceleration data

2.3 Lyapunov exponent discriminance

In order to further prove that friction torque has a chaotic characteristics, Lyapunov exponent method is used. Lyapunov exponent is a quantitative index to research chaotic system. It says the average divergence rate of two adjacent trajectories. Lyapunov exponent of dynamical system has three kinds of situation , positive, negative and zero. As long as there is a Lyapunov exponent is positive, the system can proved to be a chaotic system. Therefore, through judging whether the maximum Lyapunov exponent is positive or not to we can examine chaotic characteristics of friction torque.

Firstly construct a series of vectors with following type from acceleration signals

$$a(t_i)=\{x(t_i),x(t_i+T),x(t_i+2T),...,x(t_i+(m-1)T)\}$$

$$i=1,2,\ldots,N$$

Then calculate the maximum Lyapunov exponent s under different embedded dimension of phase space according the following equation[4]

$$\mu_{\max}=\frac{1}{t_M-t_0}\sum_{i=0}^{M}\frac{D_i^{'}}{D_i}$$

Write a computer program to calculate the maximum Lyapunov exponents, all the data is shown in table1.

Phase space dimension m	μ max
3	2.2743
4	1.2054
5	0.8331
6	0.7962
7	0.7774
8	0.7658
9	0.7536
10	0.7399

Table.1 Maximum Lyapunov exponents

According to table1, in different embedded dimension of phase space the maximum Lyapunov exponent of acceleration signal is always greater than zero, which proves that acceleration namely friction torque signal is chaotic.

3. Fuzzy PID controller for the system

In tracking system the movement of target is unknown. The tracking mirror is expected to rotate smoothly, slowly and be able to change rotation direction and stop frequently. When the system works at low speed the key factors that determine whether the system has good dynamic properties or not is friction condition, load condition and outside interference. For this system because the load is changeless and not big and there is nearly no outside interference, the friction condition becomes the most important factor. However, as mentioned in the preface, dense ball bearings are used to obtain a mechanical structure with small axial and radial beatings, due to its special structure and technological processing, the friction torque of the system becomes greater, the static and kinetic frictions vary greatly and the distribution of friction along the shaft circumference difference a lot[5]. All of this makes the control torque that needed to drive the system fluctuates dramatically, and the system crawls at low speed and can not provide enough acceleration.

In addition ,constrained by the interference conditions of the double-frequency laser interferometer, the absolute value of position error must be less than 1.5mm. In other words the maximum overshoot of position loop is ±1.5 mm. So the position loop should have fast and very smooth response.

All of these shows there must be an effective method to eliminate the influence of friction torque to set up a high performance control system.

In order to meet the requirements a close-loop control system with current, speed and position loops is provided and a fuzzy PI controller is designed for the position loop. The construct of the controller is shown as Fig.4.

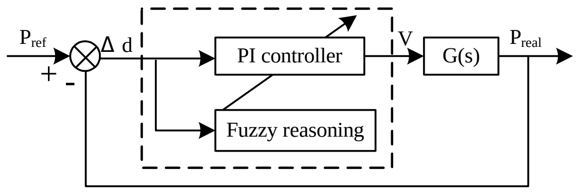


Fig. 4 Schematic fuzzy PI controller of position loop

Expression of the PI controller is

$$v(t) = K_p * \Delta d + K_i \int \Delta d(t)dt$$

where $\Delta d = P_{ref} - P_{real}$. Scale coefficients K_P and integral coefficient K_i are all the function of the position error Δd and the position error rate Δd'. Their values are determined by fuzzy reasoning.

For the fuzzy reasoning controller, the input variables are Δd and Δd', and the outputs are K_P and K_i. The details of the fuzzy reasoning controller are as follows.

The input variables are divided into seven domains [NB,NM,NS,ZO,PS,PM,PB] and triangular membership functions are adopted which is shown as Fig.5.

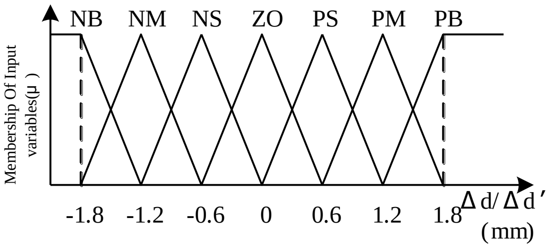


Fig. 5 Schematic for memberships of input variables

The output variables are divided into two domains [S, B] and its membership functions are shown in Fig.6

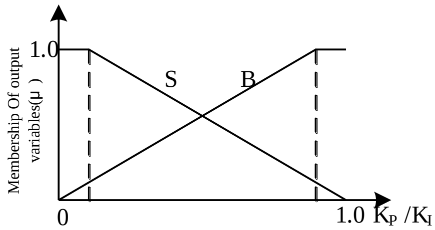


Fig. 6 Schematic for memberships of output variables

Every fuzzy rule is expressed as IF-THEN mode. For example: if Δd is NB and Δd' is NS then KP is B, Ki is S, which means if the position error is big and its changing rate is small then a relative big KP and small Ki should be given to the PI controller to make the system response quickly to eliminate the error. So in this case, KP should be mostly determined by the domain B while the Ki should be determined by domain S. Then the tracking head can catch up with the cat-eye quickly. In this way, according to expert experiences, a series of fuzzy rules can be obtained. See Table.2 and Table.3.

Δd′	Δd						
	NB	NM	NS	ZO	ZS	ZM	ZB
NB	Z	S	S	S	S	S	B
NM	B	B	S	S	S	B	B
NS	B	B	B	S	B	B	B
ZO	B	B	B	B	B	B	B
PS	B	B	B	S	B	B	B
PM	B	B	S	S	S	B	B
PB	B	S	S	S	S	S	B

Table.2 Fuzzy reasoning rules for K_p

Δd′	Δd						
	NB	NM	NS	ZO	ZS	ZM	ZB
NB	S	S	S	S	S	S	S
NM	S	S	S	B	S	S	S
NS	S	S	B	B	B	S	S
ZO	S	B	B	B	B	B	S
PS	S	S	B	B	B	S	S
PM	S	S	S	B	S	S	S
PB	S	S	S	S	S	S	S

Table.2 Fuzzy reasoning rules for K_i

Fuzzy rules only determine the domain of K_P and K_i, their membership is calculated by

$$\mu_i = \mu_i(\Delta d) * \mu_i(\Delta d')$$

Where $\mu_i(\Delta d)$ is the membership of Δd in its fuzzy subsets and $\mu_i(\Delta d')$ is that of Δd'. Final K_P and K_i are

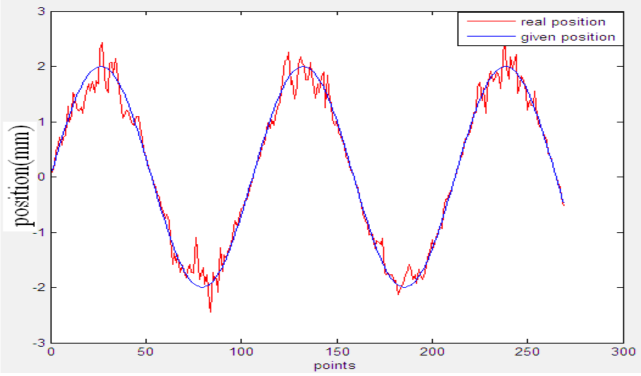
$$K_p = \sum_{i=1}^{m} \mu_i k_{p,i}$$

$k_{p,i}$ is the value that determined by μ_i in its domain S or B. The same to $k_{I,i}$.

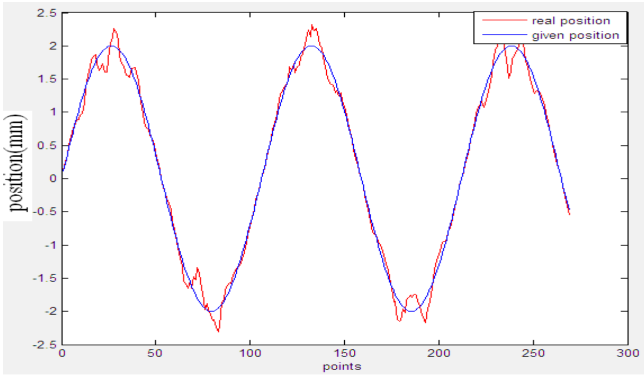
$$K_I = \sum_{i=1}^{m} \mu_i k_{I,i}$$

4. Experiments

Due to the optional movement of the cat-eye and operator can't take cat-eye move along two totally same trajectories that is essential to contrast test, so a sine signal with the amplitude of 2mm and a frequency of 1Hz is generated by the PC. The system tacks the position signal respectively in general PI controller mode and fuzzy PI controller mode. The response curves are shown in Fig.7.



(a)



(b)

Fig.7 Position responses in different controller: (a)PI controller (b)Fuzzy PI controller

Experimental results show that fuzzy PI controller can effectively reduce position overshoot and improve the stability of response.

5. Conclusions

Dense ball bearing can effectively reduce axial beat and radial beat of shaft and improve rotation accuracy . But, it increases the friction torque of rotation system, reduce running smoothness at low speed. After testing, the time sequence of friction torque signal shows obvious chaotic characteristic. Fuzzy PID controller can effectively eliminate the influence of friction torque, improve the low speed running performance.

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