The Ultra-low Speed Research on Friction Drive of Large telescope

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ABSTRACT

No periodical error and free of backlash are the main advantages of friction drive. So friction drive is applied in many ultra-low speed systems in the past years. With the trend that the aperture of optical telescope becomes bigger and bigger, there are some reports about friction drive employed to drive the telescopes. However friction drive also brings up challenge to control system because the inherent nonlinear characteristics of friction drive. This report describes the study on the friction drive finished in an experiment arranged by LAMOST project. It comprises three main parts. First, it introduces the experiment apparatus and presents a friction nonlinear curve to indicate the nonlinear characteristics of friction drive. Subsequently, this report illuminates the negative result that influenced by the nonlinear characteristic. Secondly, this report use nonlinear PID control algorithm to control friction drive. It achieves ultra-low speed and high precision position control. The ultra-low velocity is 0.2″ /S and error is 0.032″ (RMS). This report also lists some factors that influence the precision of speed. Lastly, this report gives the analysis fluctuating speed of friction drive and applies acceleration feedback to diminish this fluctuating.

Key word: large telescope, friction drive, ultra-low speed, nonlinear PID control

1. INTRODUCTION

Scientists hope to observe dimmer and remoter stars than before with the development of astronomy, so the aperture of astronomical telescope become bigger and bigger. Meanwhile, the demand of tracking accuracy is higher and higher. In comparison to worm drive and gear drive, friction drive possesses some advantages over them, such as no significant short-term irregularities which is difficult to model and correct in the control system, free of backlash if components of system are carefully designed and fabricated, high precision tracking capabilities against outside disturbance. So friction drive is widely and successfully used in some large astronomical telescopes.

The Large Sky Area Multi-object Fiber Spectroscopic Telescope (LAMOST), a national major scientific project in the process of construction in China, is a special reflecting Schmidt telescope with 4-meter aperture and 5° field of view. LAMOST consists of three parts: the reflecting Schmidt plate (M_A), the focal plane mechanism and the spherical primary mirror (M_B). The light from the observing celestial objects is reflected by Schmidt plate M_A, spherical mirror M_B and imaged on focal plane. During the observation, three tracings are needed if the system wants to get high quality image. They are azimuth-tracking, altitude tracking of Schmidt plate and focal plane rotating. The tracking speed of the telescope is very slow (0～15″ /s), but the demand to tracking accuracy is very high (0.4″)[1]. Friction drives are used in these motions of the telescope.

But friction drive does possess several inherent weaknesses. This paper presents the analysis of friction nonlinear

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characteristic and stability of friction drive. Experiments also show that the stable lowest speed reaches 0.2″/s with precision of 0.032″(RMS). Meanwhile, the paper analyses the factors that affect the precision of friction drive system.

2. EXPERIMENTAL APPARATUS AND FRICTION THEORY

2.1 Overview

In early 2003, LAMOST project arranged the friction experiment to investigate the static and dynamic characteristics of friction drive system. Figure 1 is the picture of the friction drive system. It mainly consists of roller assembly, big wheel, measure and adjust assembly and control system [2]. The control system consists of DC servomotor, tachometer, position feedback device, and servo amplier.

The diameter of the big wheel is one meter. Moment of inertia is 34.54Kg.m^2. The continuous locked-rotor torque of moment motor is 21.02N.m(current of armature is 4.1A). Tachometer is installed coaxial with moment motor and output slope of tachometer is 13.2V/(r.min^{-1}). A high-precision optical incremental encoder (Heidenhain RON-905, 36000 lines on disc, with 4096-fold increase in resolution) is directly coupled to the wheel axis to measure the position and feedback to the drive control system. The resolution of the encoder is 0.008 arc-seconds.

Traditionally, three closed loops control system is adopted. The position control, velocity control and current control are cascade. Velocity control loop and current control loop are analog controllers. Position loop uses digital controller. Analog controller is regulated to second order system in order to get fast response and stability. Position controller calculates the error signal based on the position command and position feedback from increment encoder and sends it to the velocity controller through D/A converter. The velocity controller processes the control signal according to the velocity error between the reference velocity and the actual tachometer readings and sends the control signal to current control loop. The current control loop can restrain the vibration of torque.

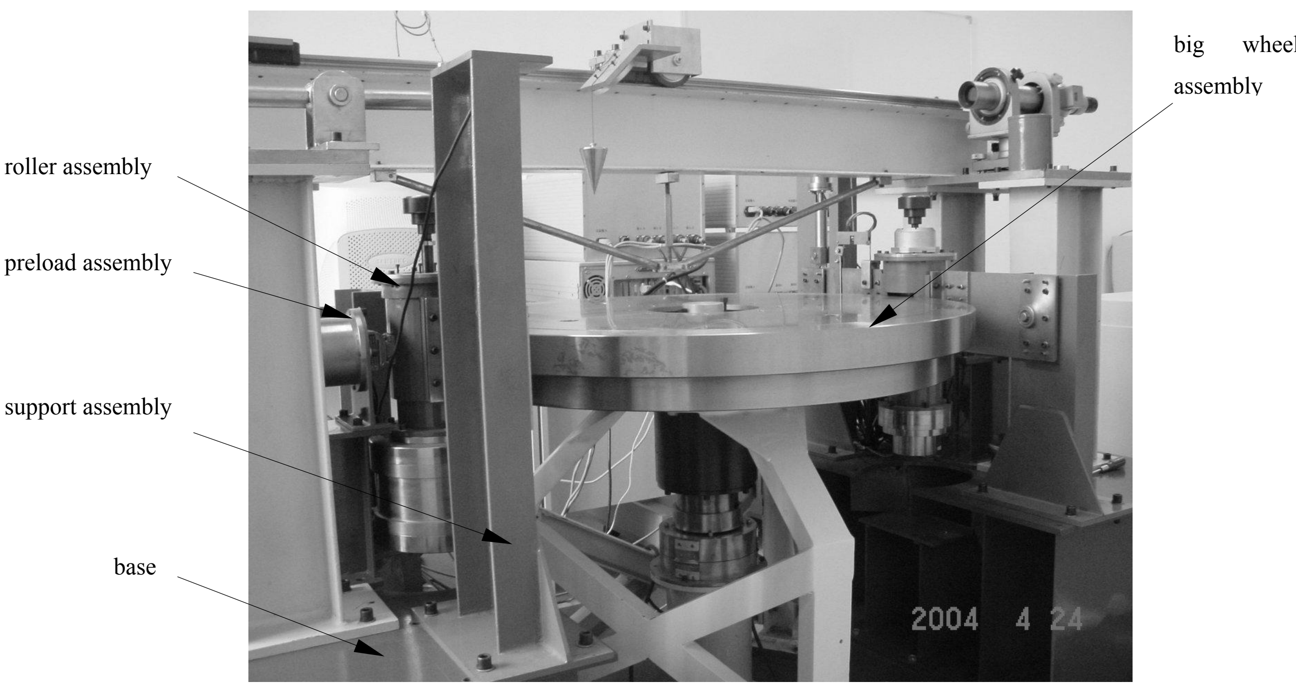

Figure 1. Experimental apparatus picture

Friction dynamic characteristics of servo system are very complex and posses uncertainty. Now many models of friction drive are put forward [3]. Stribeck curve is the most famous friction phenomenon description among these, which describes the static and dynamic relation between friction force and low-speed as shown in figure 2. The curve shows that the relative speed between big wheel and roller is different at different friction state. The Stribeck curve can be described by the following formula, especially at low-speed state.

$$F(t) = J\ddot{\theta}(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

When $\left|\dot{\theta}(t)\right| < \alpha$, the static friction force is

$$F_f(t) = \begin{cases} F_m \cdots\cdots\cdots F(t) > F_m \\ F(t)\cdots\cdots\cdots -F_m < F(t) < F_m \\ -F_m \cdots\cdots\cdots F(t) < -F_m \end{cases} \quad \ldots\ldots\ldots\ldots\ldots(2)$$

And when $\left|\dot{\theta}(t)\right| > \alpha$, the dynamic friction force is

$$F_f(t) = \left(F_c + (F_m - F_c)e^{-\alpha_1\left|\dot{\theta}(t)\right|}\right)\cdot \mathrm{sgn}(\dot{\theta}(t)) + k_v\dot{\theta} \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Here $F(t)$ is the driving force, F_m is the maximum static friction force, F_c is the Coulomb friction force, k_v is the coefficient for viscous friction force, $\dot{\theta}(t)$ is the angle speed, α and α_1 are positive constants respectively. The curve shows that friction force has the inherent nonlinear characteristic with velocity. So it is difficult to control friction drive system.

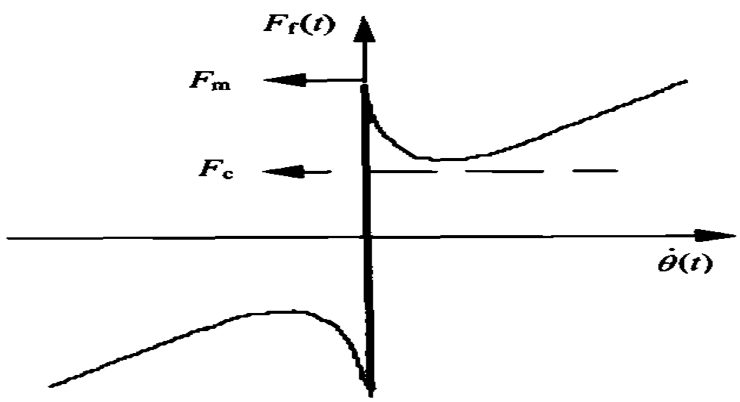

Figure 2. Relationship between friction force and velocity (Stribeck curve)

2.2 The challenge of friction drive control

Friction drive must overcome the slippage if friction drive system runs steadily. Big wheel and roller would slip relatively if torque of friction less than torque of load. Slippage is major factor that influence the accuracy of tracking. To avoid slippage, the system must reduce the load or increase the torque of friction. It is difficult to reduce the load to a complete system. So it can only increase torque of friction to avoid slippage. There are some ways to increase the torque of friction, including: ①increase the positive pressure to big wheel. But it will damage the surface of friction wheel if the pressure is too high. ②increase the coefficient of friction. In this system, the only way to avoid slipping is to increase positive pressure. The positive pressure is 150N in this system because the pressure has little influence on steady speed [2].

The other challenge to friction drive is that there exists creeping at the low speed. Creeping is that the motor runs on and off. It mainly results from the nonlinear characteristic of friction. Especially, creeping serious influence the accuracy of tracking at ultra-low speed. In this system, acceleration feedback is introduced to increase the damp of system to avoid creeping.

3. Control arithmetic of position controller and result of experiment

3.1 control arithmetic

There are many factors that will influence the speed stability when the speed is too low. Furthermore, the fiction has nonlinear characteristic. So it is difficult to achieve stable speed. It is necessary to design a better controller to overcome the weakness. Nowadays, PID control arithmetic is used in many control fields because it's parameters are easy to adjust and the structure is simple. But traditional PID control arithmetic has inherent disadvantage, the contradiction between rapidness and overshooting. So the traditional PID control arithmetic cannot achieve ideal result if the demand of accuracy of tracking is very high [4].

Nonlinear PID control arithmetic is used in this system to adapt the nonlinear characteristic. The nonlinear PID control arithmetic is described as: three gain parameters of PID control arithmetic are the function of error. The parameters of proportion, integral and differential vary with the error's magnitude and trend. So the system can achieve rapidness and no overshooting if the coefficients of gain of PID are adjusted to a suitable value. The nonlinear PID control arithmetic formulas are described as follow:

$$k_p(e(t)) = a_p + b_p(1 - \sec h(c_p e(t))) \quad ①$$

$$k_d(e(t)) = a_d + b_d/(1 + c_d \exp(d_d \cdot e(t))) \quad ②$$

$$k_i(e(t)) = a_i \sec h(c_i e(t)) \quad ③$$

In the formula ① , k_p is the gain coefficient of proportion. a_p, b_p, c_p is positive constant. The maximum value of k_p is $a_p + b_p$ when the error $e \to \pm\infty$; The minimal value of k_p is a_p when $e = 0$; To adjust the value of c_p can adjust the change speed of k_p. In the formula ②, k_d is the gain coefficient of differential. a_d , b_d , c_d , d_d are positive constant. The minimal value of k_d is a_d. The maximum value of k_d is $a_d + b_d$, $k_d = a_d + b_d/(1 + c_d)$ when e=0, To adjust the value of d_d can adjust the variety speed of k_d. In the formula ③, k_i is the gain coefficient of integral, a_i, c_i is positive constant. k_i ranges between 0 and a_i , k_i is the maximum value when $e=0$, c_i adjust the variety speed of k_i. Figure 3, figure 4 and figure 5 are the curves of proportion, differential and integral along with error. The output of nonlinear control arithmetic is:

$$u(t)=k_p(e(t))e(t)+k_i(e(t))\int_0^t e(t)dt+k_d(e(t))\frac{de(t)}{dt}$$

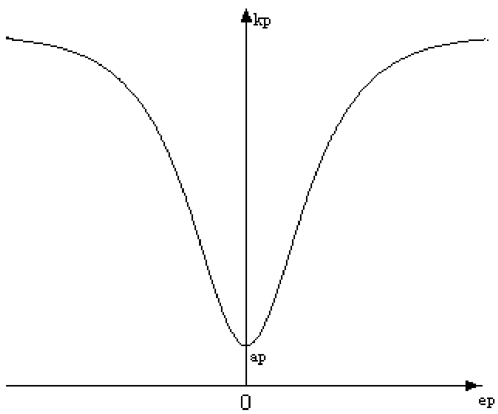

Figure 3. Curve of Kp vs. error

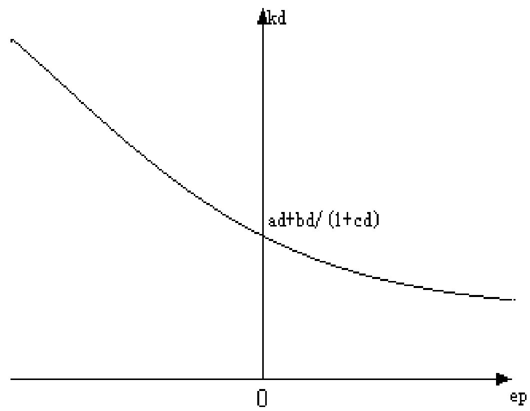

Figure 4. Curve of Kd vs. error

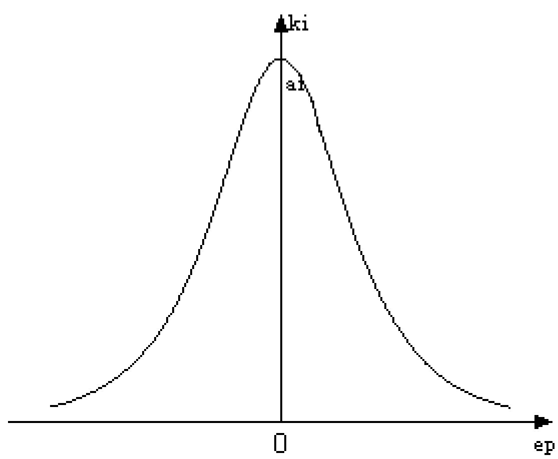

Figure 5. Curve of Ki vs. error

3.2 result of experiment

The nonlinear PID is introduced to actual experimental system and the parameters of controller are adjusted to a suitable value. The system get ideal result when $a_p=300$, $b_p=100$, $c_p=30$, $a_d=0.5$, $b_d=1.5$, $c_d=3.5$, $d_d=3$, $a_i=100$, $c_i=40$. Figure 6 and figure 7 are the curves of position and error of position when the speed is set to 0.2″ /s. The frequency of sampling is 100HZ and the error of position is 0.032″ (RMS).

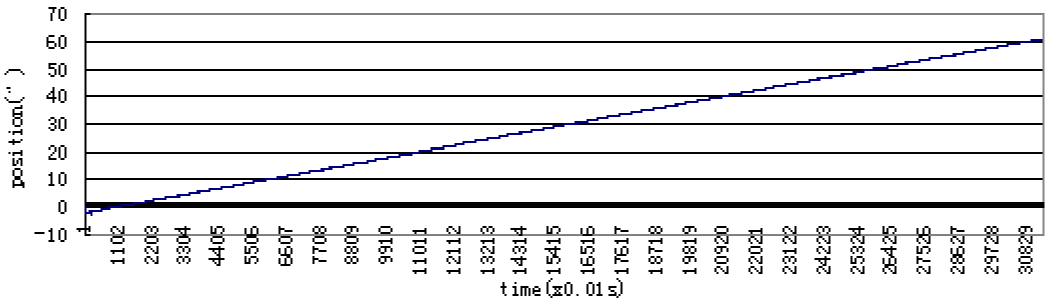

Figure 6. Position curve (0.2″/s)

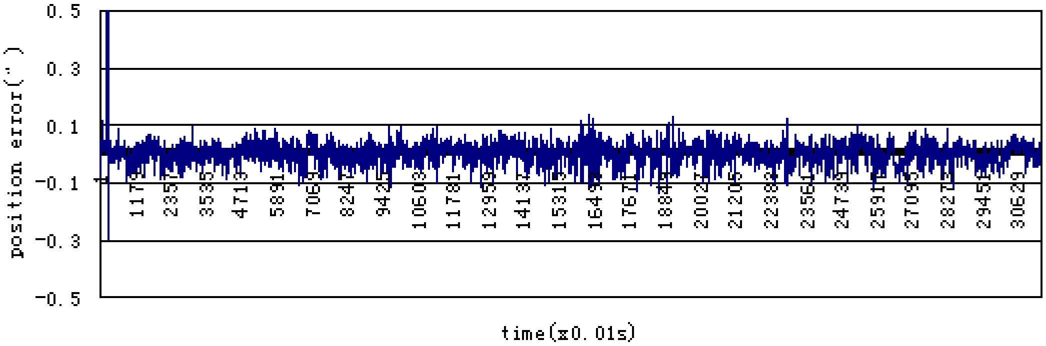

Figure 7. Position error curve (0.2″/s)

The position curve and position error curve show that the system achieves ultra-low speed steadily through nonlinear PID controller.

4. Analysis error of position and acceleration feedback

4.1 analysis error of position

There are many factors that will lead to the error of position, including: ⑴measure error of encoder. The output signal of encoder has serious random noise because surrounding environment disturbs it. Figure 8 is the curve of the output signal of encoder when the motor stops. It shows that the peak-valley value of disturbed signal is 0.2″. This disturbing signal can serious influence the actual signal of position because the speed of the system is too low. In order to decrease the influence of noise, second order butterworth filter is used to process the signal of encoder. The peak-valley value of disturbed signal can decreased to 0.06″ if the cut-off frequency of filter is set to 5HZ. ⑵ error from the environment. The output signal of encoder increases with the temperature of environment. The operating temperature of encoder is 10℃~30℃. Meanwhile, humidity also influence the coefficient of friction. So the system must be placed in a stable temperature and stable humidity environment. ⑶ torque of friction and torque fluctuation of motor. The coefficient of static friction is bigger than the coefficient of dynamic friction. The speed of motor will run on and off. This is called creeping. Creeping seriously influences the accuracy of tracking. Furthermore, the only way to eliminate this factor is to select more advanced equipment. ⑷ the factor of fabrication and installtion. The friction torque between the big wheel and roller will fluctuate if the surface of big wheel is not an ideal circle or the axis of big wheel and roller is not parallel.

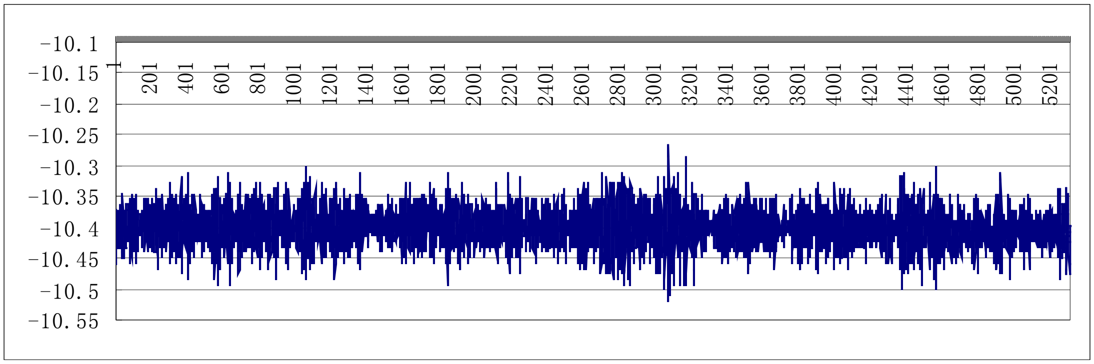

Figure 8. Encoder output signal while motor stop

4.2 Acceleration feedback

Figure 9 is the speed curve of big wheel when the speed is set to 0.2″ /s. The speed is calculated by the position data of big wheel. The vibrations of speed are mostly arisen by noise of output signal of encoder and error of sampling period. But we also can know that the vibration of speed is great as a whole. This means that there exists the creeping of motor. There are many reasons that can explain the creeping, including: the coefficient of static friction is not the same as the coefficient of dynamic friction, the change of force of friction, the actual contact point is welded between two metal surface etc. But the main factor is that the coefficient of static friction is bigger than the coefficient of dynamic friction. The motor will start when the output torque is bigger than the torque of static friction. The torque of static friction will change to the torque of dynamic friction after the motor starts. So the speed of motor will accelerate. The acceleration is proportion to $(T_{fr1} - T_{fr2})/J$. Here T_{fr1} is the torque of static friction. T_{fr2} is the torque of dynamic friction. J is the moment of inertia. The speed will decrease when the speed is greater than the setting speed. Motor would be on and off. This is called creeping.

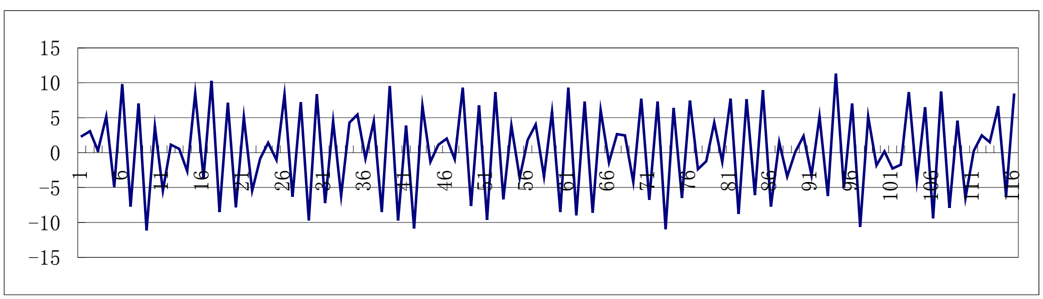

Figure 9. The vibration of speed

To resist the vibration of speed and avoid creeping, acceleration feedback is introduced to the control system. Acceleration negative feedback is the feedback of differential of speed. In theory, the speed differential has effect to the control system when the speed doesn't change but has the trend to change. It can not only suppress the overshoot but also resist the vibration of speed [5]. Figure 10 is the structure figure of acceleration feedback. The forward transmission function is $W_1(S) = \dfrac{K}{S(TS+1)}$. The feedback transmission function is: $H(S) = \dfrac{T_0 S}{T_1 S + 1}$, $T_0 S$ is feedback of differential of output. The transmission function without acceleration feedback is $G(S)=\frac{W_1(S)}{1+W_1(S)}=\frac{K}{TS^2+S+K}$. The transmission function with acceleration feedback is

$G_a(S)=\frac{G(S)}{1+G(S)H(S)}==\frac{K}{TS^2+(1+KT_0)S+K}$. When $K=10$, $T=1$, $T_0=0.1$, the figure 11 is the response of step.

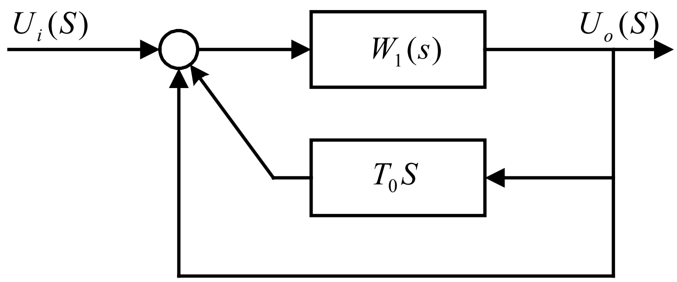

Figure 10. The structure figure of acceleration feedback

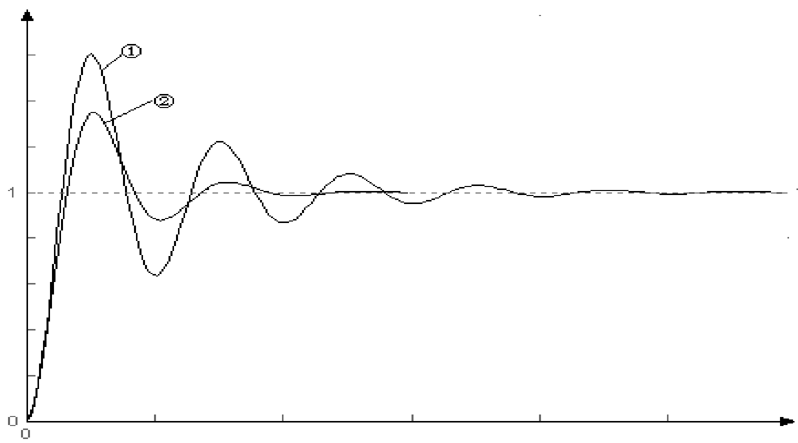

Figure 11. The influence result of acceleration to response of step

In figure 11, curve ① is the response of step without acceleration feedback. Curve ② is the response of step with acceleration feedback. It can draw conclusion from figure 11 that acceleration feedback can suppress the overshoot of system and restrain the vibration of speed. The following two curves are sampling data in the same environment and control parameter. Figure 12 is the curve of error of position without acceleration feedback and the accuracy of position is 0.0311″ (RMS). Figure 13 is the curve of error of position with acceleration feedback and the accuracy of position is 0.0245″ (RMS). The two figures prove that acceleration feedback can resist the vibration of speed.

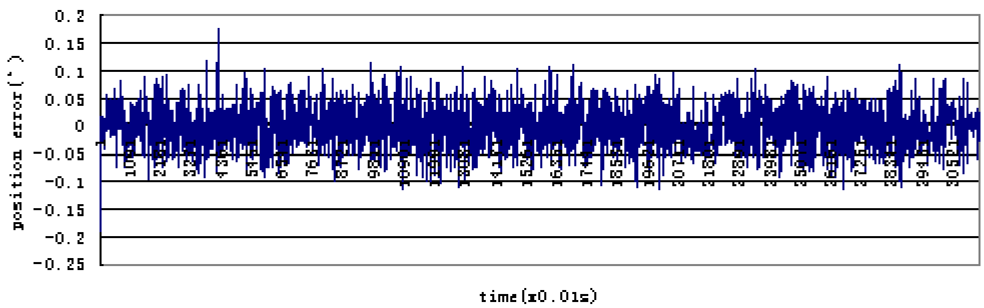

Figure 12. Position error without acceleration feedback

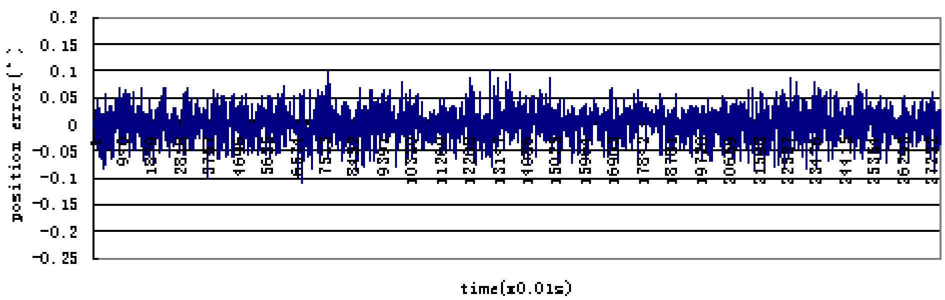

Figure 13. Position error with acceleration feedback

5. Conclusion

1. Friction drive has advantage over other drive system in large telescope. Especially, friction drive can get excellent result in low speed system.
2. Ultra-low speed and high tracking precision can be achieved through friction drive. The experiment shows that the lowest stable speed reaches 0.2″/s with precision of 0.032″(RMS)
3. Nonlinear PID control arithmetic is suitable for friction drive system. Nonlinear PID can compensate the nonlinear characteristic of friction. The system achieves better result through nonlinear PID controller.
4. The result of experiment demonstrates that acceleration feedback can resist the vibration of speed.
5. There are many factors that can influence the accuracy of tracking in ultra-low speed, including: ⑴ the measuring error of encoder, ⑵ the error of circumstance changing, ⑶ the error of friction torque and motor fluctuating torque, ⑷ the error of machining and installation. In addition, the friction torque of total drive chain is not constant and there also exist fluctuation.

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