Active Disturbance Rejection Control of Friction for Optoelectronic Telescopes

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***Abstract* — Friction is the key factor that influences the low velocity performance of optical tracking servo system. An improved active disturbance rejection control is proposed in this paper to solve the problem. The algorithms and principles were analyzed. The extended state observer estimates the system disturbances, and a two-parameter proportional-derivative controller can guarantee the system's good dynamic characteristics. The experimental results show that compared to the PI controller, the proposed method can estimate and compensate friction torque using ADRC compensation with a reduction in peak value of speed error from 0.6º/s to 0.3º/s for the sinusoidal input, and in RMS error of speed from 0.018º/s to 0.011º/s for the step input. Experimental results show that the proposed method has higher tracking precision, and improve the speed smoothness.**

Keywords- servo control; friction compensation; low velocity performance; active disturbance rejection control

I. INTRODUCTION

Friction torque direct impact the tracking performance of high-precision optical tracking servo system, especially low-speed smoothness.

In traditional engineering design, mostly ignore the effects of friction torque, and do the controller design just as the usual PID control. This method has the advantage of simple structure and easy to implement. But it focuses on the tracking capability of input signal, and lacks the disturbance suppression into account, which results that the system affected by the disturbance torque in practical applications, and results the speed fluctuation and the tracking is not smooth. The compensation for the friction has been the focus of many research interests. The issue of compensation for the friction torque can be divided into two categories, one is model based compensation, and the other is non-model based compensation. For model-based compensation, a good friction model is very important, the current proposed model are the Coulomb friction + viscous friction model, Stribeck friction model, Lugre friction models[1]; Non-model based compensation algorithm refers to estimating friction without attempting to model the complicated physical phenomena that lead to friction. Such as high-gain PD control [2], the neural network predictive control [3] and so on.

For optical telescopes, in addition to the friction torque disturbance, but also the motor torque ripple, the wind torque and other disturbances, if the control algorithm can only compensate for the friction torque, the ability to improve the tracking accuracy is limited absolutely.

To address the above issues, this paper introduces a simplified disturbance rejection control strategy. The algorithm is completed in the speed loop, and the disturbance is estimated from speed signal by the extended state observer which is unique in the algorithm, and then to suppress the disturbance. The algorithm does not rely on the object model, has strong robustness and ease of implementation. The experiment results prove the effectiveness of the method.

The paper is organized as follows. The control problem is introduced in Section 2. The principle and design of the ADRC is presented in Section 3. Experimental setup and results are show section 4. Finally, some conclusions are given in Section 5.

II. PROBLEM DEFINITION

First, the typical mathematical equation of motion using a DC motor-driven for electro-optical tracking systems can be described as equation 1[4]:

$$\begin{cases} u(t) = R \cdot i(t) + L\, di(t)/dt + K_b \omega(t) \\ T_m(t) = K_m \cdot i(t) \\ T_L(t) = T_m(t) + T_d(t) \\ T_L(t) = J \cdot d\omega(t)/dt + n \cdot \omega(t) \end{cases} \tag{1}$$

where ω (t) is the motor speed, u (t) represents the input voltage, R is the armature resistance, L is the motor inductance, i(t) is the armature current, Tm (t) is the electromagnetic torque, Td (t) represents disturbance torque, Km is the torque coefficient, Kb is the back-EMF coefficient, n is the viscous coefficient, J is the total inertia of the motor and load.

By equation (1) we know the torque acting on the load side has both the electromagnetic torque and disturbance torque, in which the friction torque is a kind of disturbance torque.

III. CONTROLLER DESIGN

The architecture of ADRC is shown in Figure 1. It mainly consists of three components: the nonlinear tracking differentiator (NTD), the extended states observe (ESO) and nonlinear proportional derivative control law (NPD).

NTD is used to improve the transition process to reduce the overshoot of the process output; ESO is a state observer, which can give an estimate of the input signal, its derivative and the disturbance. ESO is the core of ADRC, it can observation the model uncertainties in the control system and external disturbances in real time, and compensate the disturbance by the controller. NPD is the control law which is used to improve the system dynamic and stability.

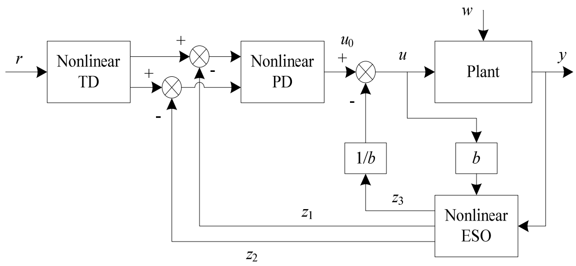

Figure 1. Structure of the ADRC.

The conventional ADRC controller takes the non-linear characteristics, and has a number of parameters to tune, so it is not easy to project implementation [5, 6, 7]. To solve this problem, the ADRC system introduces a linear control strategy. Its implementation process is as follows:

First, sort the mathematical model of electro-optical tracking system in equation (1) into a voltage input u(t) and disturbance Td(t) and an output for the speed ω(t) :

$$\ddot{\omega} + a_1\dot{\omega} + a_0\omega = b_0 u + c_1\dot{T}_d + c_0 T_d \tag{2}$$

In the above formula, a1 = (Ln + JR) / JL, a0 = (KMKB + nR) / JL, b0 = KM / JL, c1 = 1/J, c0 = R/JL.

Introduce a control volume b in equation (2) and sort the equation:

$$\ddot{\omega} = (b_0 - b)u - a_1\dot{\omega} - a_0\omega + c_1\dot{T}_d + c_0 T_d + bu \tag{3}$$

For the DC motor speed control system, the motor speed ω is the measurable output signal, and then in the second-order ESO, introduce the state variables z3 to estimate the $(b_0 - b)u - a_1\dot{\omega} - a_0\omega + c_1\dot{T}_d + c_0 T_d$ in equation (3). The state equation is as follows:

$$\begin{cases} e = \omega - z_1 \\ \dot{z}_1 = z_2 + L_1 e \\ \dot{z}_2 = z_3 + L_2 e + bu \\ \dot{z}_3 = L_3 e \end{cases} \tag{4}$$

Where z1 estimate for the speed signal, z2 is the estimated value of the acceleration, u is the system control input; L1, L2 and L3 as adjustable parameters.

Equation (4) that is a linear structure of the ESO, compared to the non-linear structure, reducing the number of parameters to adjust, reduce system complexity. For the gain L1, L2 and L3, the choice of parameters by introducing ωo to determine its formula is as follows [8].

$$\begin{cases} L_1 = 3\omega_o \\ L_2 = 3\omega_o^2 \\ L_3 = \omega_o^3 \end{cases} \tag{5}$$

ωo reflect the size of ESO's bandwidth, the greater its value, the stronger ability to track the input signal, but too high ωo value will introduce more noise, so to weigh the options.

The NPD controller becomes a linear non-linear proportional-derivative controller (PD controller), the linear control law as follows:

$$u_0 = k_p(r - z_1) - k_d z_2 \tag{6}$$

Where r is the given input signal, kp is the proportional coefficient, kd is the differential coefficient.

Proposed controller abolishes the NTD module. The adjustment of the control process is mainly relying on the adjustment of kp and kd. To facilitate the controller design, introduce two parameters ωc and ξ, their relationship with kp and kd are as follows[9]:

$$\begin{cases} k_p = \omega_c^2 \\ k_d = 2\xi\omega_c \end{cases} \tag{7}$$

Where ωc is the characterization of the control system bandwidth, ξ is the damping factor.

Conventional ADRC controller arranges the transition process by adding a NTD to solve the conflict between the fast and the overshoot. In this paper, the damping factor ξ can achieve the same purpose, and greatly simplifies the controller structure. In general, the larger ωc is, the faster the system responses. If request there is no overshoot in the system, we can select a larger value of ξ(>1), if request the quick response, we can select a smaller value of ξ(<=1).

The control law is defined as

$$u = u_0 - z_3 / b \tag{8}$$

In physical sense, b value is equivalent to the role of compensation factor, reducing the value of b is equivalent to enhance the compensation effect, but this is not conducive to

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noise suppression, therefore, has to be adjusted to determine the practical application.

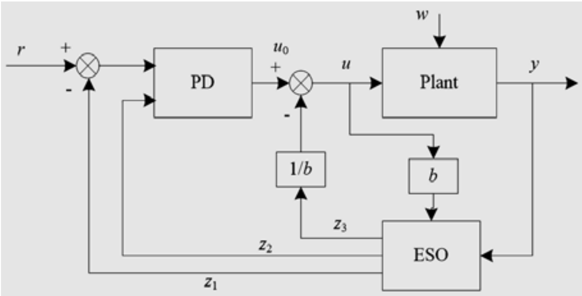

Figure 2. Structure of the Simplified ADRC.

In summary, the simplified control block diagram of ADRC shown in Figure 2. It only contains four adjustable parameters ωo, ωc, ξ and b. For the DC motor speed control system, the action of the figure have the following physical meaning: r is a given speed, u is the control input, w is the system disturbance, y is the output speed, z1 is the estimated value of speed, z2 is the estimated value of acceleration, z3 is the estimated value of the system disturbance.

IV. EXPERIMENTAL RESULTS

In order to verify the practical application of ADRC controller, we performance some experiments on the telescope. The experimental device is composed of a DC torque motor driver, PWM power amplifiers, digital servo controllers and some other components. Among them, mechanical platform and motor are directly coupled. The servo controller use the embedded computer based on PC104 bus as the core to complete the closed-loop control of this system. The position feedback device of experimental system use Renishaw incremental optical encoder. The number of the lines in encode is 47200. The sine and cosine output signal is sub-segmented for 1000, so the position resolution is 0.0274″. The sampling period of control system is 1ms. The speed feedback signal is extracted by the position-difference algorithm, and the corresponding speed resolution is 0.0076º /s. The architecture of this system is shown in Figure 3.

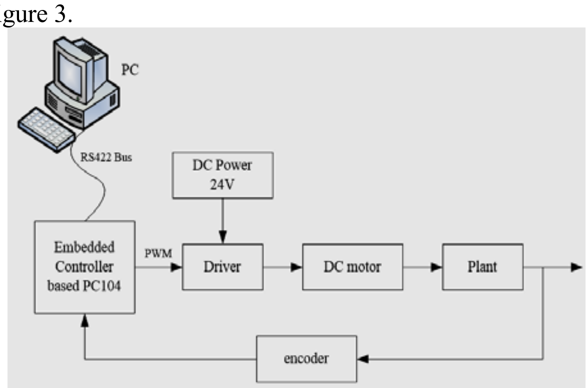

Figure 3. Composition of the Experimental Flat

Figure 4 is a velocity curve which is obtained when there is a sine control voltage applied directly to the motor. It can be seen from the figure that the speed waveform has distortion due to the presence of friction torque. When the velocity crosses zero, there was a "dead zone" phenomenon. Friction blocks the acceleration when the motor is in acceleration process and increase the deceleration when the motor is in deceleration process which makes the speed up slow and slow fast.

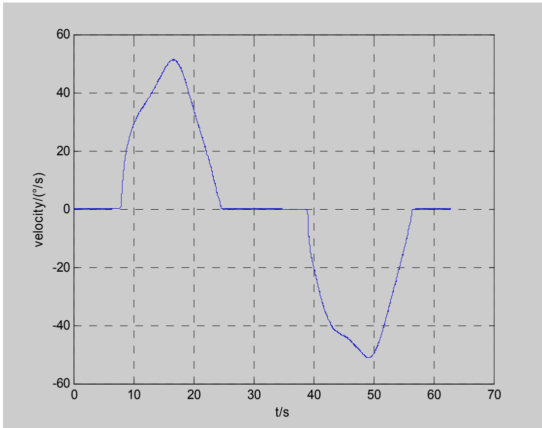

Figure 4. Curve of the Velocity at 1º/s.

In the closed-loop speed control, the experimental system was compared by PI controller and ADRC controller. The PI controller proportional coefficient KP is 150, integral coefficient KI is 10, ADRC controller ωc is100, ωo is 400, b is 1.5, ξ is 1.5.

Control system uses PI controller and ADRC controller for speed control respectively. Sinusoidal input signal is given as $10\sin(0.087t)$, which shows in the figure 5.

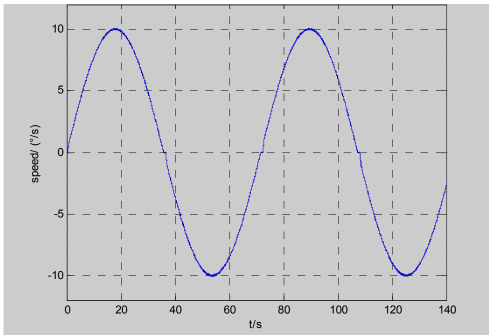

Figure 5. Curve of the Input Velocity Signal.

Figure 6 and Figure 7 are the output curve of the speed error which are obtained from using PI controller and ADRC controller respectively. It can be seen from the figure: velocity error has a larger peak when the speed is in the zero-crossing point which is due to the switch of dynamic and static friction. After the use of ADRC controller, the peak of speed error decreases from 0.6º/s to 0.3º/s. The results have demonstrated the effectiveness of the friction compensation algorithms.

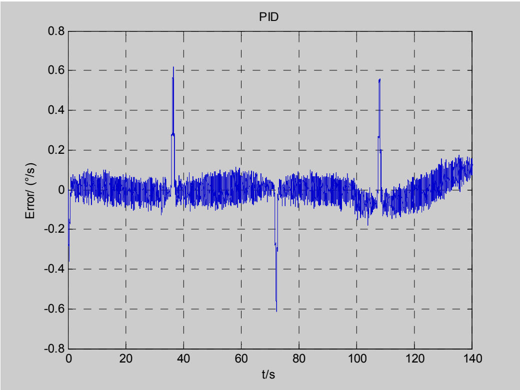

Figure 6. Curve of the Velocity Error of PID.

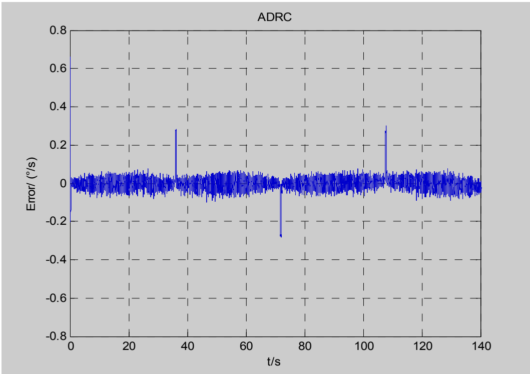

Figure 7. Curve of the Velocity Error of ADRC.

Control system was also compared of velocity smoothness using PI controller and ADRC controller respectively. Step input signal is given at 1 °/s. Figure 8 and Figure 9 are the output curve of the speed error which are obtained from using the two controllers respectively.

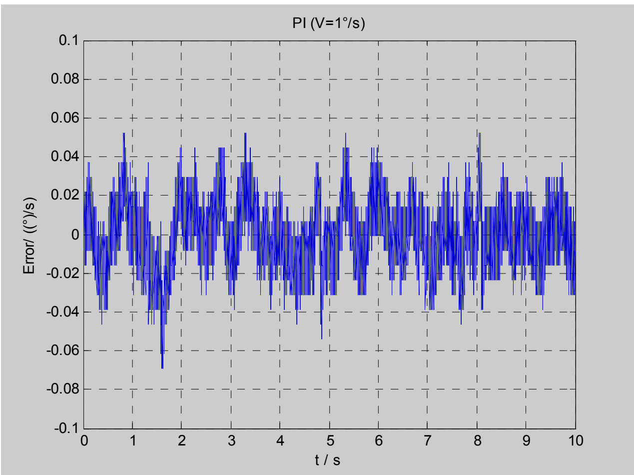

Figure 8. Curve of the Velocity Error at 1°/s of PID

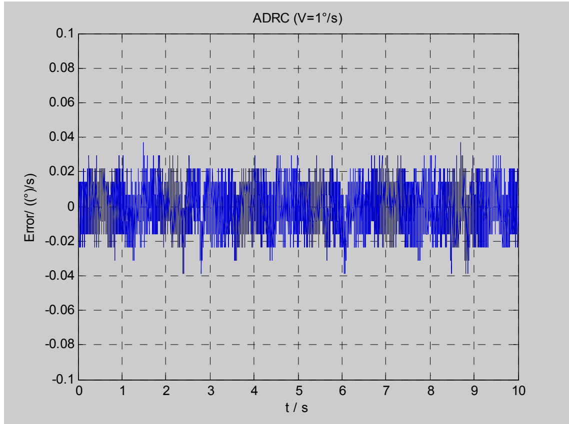

Figure 9. Curve of the Velocity Error at 1°/s of ADRC.

V. CONCLUSIONS

To solve the problem of compensation for the friction torque, this paper introduces a simplified disturbance rejection control strategy. The algorithm does not rely on the object model, has strong robustness and ease of implementation. It estimates the disturbance signal from speed signal through an extended state observer, and then the disturbance is feed forwarded to the control volume. The practical application shows that in the speed sine guide experiment, compared to the PI controller, the ADRC controller decreases the peak error of speed from 0.6°/s to 0.3°/s for the sinusoidal input, and the RMS error of speed from 0.018 °/s to 0.011 °/s for the step input, the smoothness of speed has been effectively improved.

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