Study on high precision positioning of actuator system integrating PMSM with ball screw

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Ballscrew drive system has non-linear frictional element, so it makes ballscrew control accuracy worse. It is also required to construct a mechanism with robustness against any disturbance including nonlinear friction. And the system integrating PMSM with ballscrew leads toughness more increasing, so it is able to make higher output. But the motor becomes affected more directly by disturbance, it is more increased requirements of high precision driving.

In this paper, we target that realizing high precision positioning servo system without affected disturbance, we experimentally considered improving control response from a view of motor control by applying variable gain controller and feed forward control.

Keywords: ballscrew system, high resolution encoder, disturbance observer, disturbance compensation, non linear friction, variable gain controller, feed forward control, high precision positioning system.

1. Introduction

In the ball screw driving system, since it has a nonlinear frictional element including ball rolling friction and viscous friction, which makes control ability worse and constrict speed-up and accuracy[1]. It is also required to construct a mechanism with robustness against any disturbance including nonlinear friction. The system integrating PMSM with ballscrew leads toughness more increasing, so it is able to make higher output. But the motor becomes affected more directly by disturbance, it is more increased requirements of high precision driving.

Therefore, in this paper, we target that realizing high precision positioning servo system without affected disturbance, and propose the mechanism integrating PMSM rotor with ballscrew shaft. Using this system, we focus on following 3 points from a view of motor control.

i. Becoming sensor high precision with using super-high resolution encoder.

ii. Estimation and compensation of disturbance by using disturbance observer.

iii. Improvement of control response by applying variable gain controller and feed forward control.

It is reported that point1 and point2 are effective for high precision positioning servo system[4]. About point3, we try to improve drive characteristics at very low speed by changing speed PI control and speed I-P control continuously, and try to compensate control response delay by adding feed forward control to position P control.

2. Configuration of Ballscrew Positioning System

2.1 Specification of Ballscrew Drive System

Fig.1 shows outline of the ballscrew system used in this paper. And Table 1 shows the parameters.

The ball screw drive system consists of four elements which are ball screws, stage, servomotor, high resolution encoder, and inverter board combined with controller. The lead pitch of the ballscrew is 20[mm], and the total length is 500[mm]. “TSM3202N2300E040” (manufactured by Tamagawa Seiki Co., Ltd.) was used for the servo motor, and 23-bit absolute encoder (manufactured by Tamagawa Seiki Co., Ltd.) was used as the high resolution encoder. We use a self-made inverter of DC24V input of 500W class equipped with Renesas RX 62T microcomputer on the inverter board.

2.2 Configuration of Control System

Using the equipment described in Section 2.1, we construct the position control system of the control block diagram shown in Fig.2. In the experimental equipment used in this paper, the ballscrew does not have a liner position sensor. So a semi-closed loop is constructed by using data of a rotary encoder attached to the motor.

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To improve drive characteristics at very low speed and improve control response delay, we construct a position control system added with variable gain control and feed forward control. The control system which we proposed has a normal PI current loop, variable gain PI or I-P speed loop, and feed forward added P position loop.

To improve control accuracy at very low speed range mainly, variable gain PI or I-P controller is added. Q-axis current reference value is calculated by variable gain PI or I-P controller, expressed by equation (1) [7].

\[
\dot{\omega}_r = K_{sp} (\alpha \cdot \omega_r - \omega) + \frac{K_{si}}{s} (\omega_r - \omega)
\]  

where, \( K_{sp} \) is speed proportional gain, \( K_{si} \) is speed integral gain, \( \omega_r \) is speed reference, \( \omega \) is speed, and \( \alpha \) is PI rate value (0 to 1 ). PI rate value \( \alpha \) decides a rate of PI control and I-P control, then the value is changed by speed reference shown in equation (2).

\[
\alpha = \begin{cases} 
1 & (\omega_r \geq 0.41888) \\
(\text{abs}(\omega_r) - 0.10472) \times 3.1831 & (0.10472 \leq \omega_r \leq 0.41888) \\
0 & (\omega_r \leq 0.10472)
\end{cases}
\]

Equation (2) shows that PI rate value is changed in range of speed reference between 1rpm and 4rpm (absolute value). And the rate is fixed to 1 at over 4rpm of speed reference, and fixed to 0 at under 1rpm of speed reference. In example, when PI rate is 0, the speed controller works as I-P controller, and when the PI rate is 1, the speed controller works as PI controller.

To improve control response delay mainly, feed forward controller is added. Speed reference value is calculated by position P controller and position feed forward controller, shown in equation (3).

\[
\dot{x}_r = K_{pp}(x_r - x) + sK_{ff} \cdot x_r
\]  

where, \( K_{pp} \) is position proportional gain, \( K_{ff} \) is feed forward gain, \( x_r \) is position reference, and \( x \) is position. Fig. 3 shows block diagram of these proposed controller.

In the control cycle, the current loop is 100 [us] and the speed and position loop is 1 [ms]. The control gain of the current loop are the proportional gain \( K_{cp} = 3 \), the integral gain \( K_{ci} = 0.0005 \). The control gain of the speed loop are proportional gain \( K_{sp} = 1.0 \), integral gain \( K_{si} = 0.06 \). The control gain of the position loop is proportional gain \( K_{pp} = 0.000025 \), feed forward gain \( K_{ff} = 1 \). Also, a disturbance observer is inserted for disturbance estimation, and the presence or absence of disturbance compensation can be adjusted by “observer gain”. In this system, disturbance compensation by disturbance observer is used all time, observer gain is fixed to 0.1.

| Parameter          | Value [unit]        |
|-------------------|---------------------|
| Rated Torque      | 0.64 [Nm]           |
| Rated Speed       | 3000 [rpm]          |
| Rated Output      | 200 [W]             |
| Rated Current     | 6.2 [A]             |
| Encoder Resolution| 8388608 [pulse/rev] |
|                   | (23bit)             |
| Lead pitch of ballscrew | 20 [mm]         |
| Length of ballscrew | 500 [mm]           |

Table 1 Specification of Ballscrew Drive System.
2.3 Configuration of Disturbance observer model

In order to construct the disturbance observer in the ballscrew drive system, it is necessary to model the ballscrew mechanism. Table 2 shows the parameters of the ballscrew mechanism. Using the 2 inertia system model which is the simplest model as the ballscrew model, the model when the motor rotation angle $\theta$ is given to the ballscrew is expressed by the following equation.

$$ x_m = R \theta $$  \hspace{1cm} (4)

$$ F = K_t (x_m - x_t) $$  \hspace{1cm} (5)

$$ F - C_i v = s^2 M_t x_t $$  \hspace{1cm} (6)

Where, $x_m$ is the amount of movement of the motor converted into the linear system, $F$ is the thrust applied to the ball screw table, $v$ is the speed of the table, $R$ is the conversion coefficient of the rotary system and linear system, $K_t$ is the axial stiffness coefficient, $C_i$ is the viscous damping coefficient, and $M_t$ is the mass of the table. In general, it is known that ballscrews include nonlinear friction elements such as viscous resistance. We incorporate a nonlinear friction model into this model. Although many nonlinear friction models have been proposed, in this paper we used the simplest Coulomb friction model. The frictional force $F_{friction}$ in the Coulomb friction model is defined by the following equation using the table speed $v$.

$$ F_{friction} = \text{sgn}(v) \times (C_i \times \text{abs}(v) + \text{StaticFriction}) $$  \hspace{1cm} (7)

Table 2 Parameter of Ballscrew Mechanical Model

| Parameter            | Symbol | Value[unit] |
|----------------------|--------|-------------|
| Table Weight         | $M_t$  | 5[kg]       |
| Viscous damping coeff.| $C_i$  | 0.003[Ns/m] |
| Axial stiffness of ballscrew | $K_t$  | $4.16 \times 10^5$[N/m] |
| Transformation coeff. of rotation-linear motion | $R$    | $0.02 / 2\pi$[m] |
| Static Friction      | $0.1$  | [Nm]        |

Where, StaticFriction is a static friction force. Expression (4) - (7) are represented by a block diagram as shown in Fig.3.

Based on the model shown in Fig. 4, we constructed a model of the disturbance observer. In this paper, we do not specify where disturbance is added, but estimate all the disturbances that were added between the motor input and the ball screw output in a lump. Therefore, as shown in equations (8) - (10), the disturbance can be estimated by calculating the difference between the reference torque of the motor and the torque obtained from the movement amount of the ballscrew.

$$ \hat{T}_m = pK_eiq_{ref} $$  \hspace{1cm} (8)

$$ \hat{F} = sM_t v + F_{friction} $$  \hspace{1cm} (9)

$$ T_{disturbance} = \hat{T}_m - R\hat{F} $$  \hspace{1cm} (10)

Where, $p$ is the pole pair number, $K_e$ is the back-EMF constant, and $iq_{ref}$ is the q axis current reference. Fig.5 shows the block diagram of the disturbance observer derived from equations (8) - (10).

Since the estimation system includes a differential term, LPF is inserted as shown in Fig.5 in order to suppress the divergence of the value. The cutoff frequency of the filter was $159$[Hz].

3. Improving Ballscrew Positioning System

3.1 Experiment Condition

In this chapter, we compare the operating characteristics of both actual machine and simulation using the control system and model constructed in the previous chapter. In the experiments, we examine the following four control cases.

(a) Normal position P control and speed PI control
(b) Position P control and variable gain speed control
(c) Position P + feed forward control and speed PI control
(d) Position P + feed forward control and variable gain speed control

Comparing (a) with (b), it can be found that improvement effect of control accuracy at very low speed range by applying variable gain control. And comparing
(a) with (c), it can be found that compensation effect of control response delay by applying feed forward control. Then comparing (a) with (d), it can be found that final improvement effect of control characteristics by applying both of variable gain control and feed forward control.

We use a position operation pattern that 20mm trapezoidal round trip in period of 3 seconds, and we observe the position, position reference, speed, and q-axis current, then compared the characteristics. Maximum motor speed is set to 80rpm.

### 3.2 Experiment Results of Simulation

In this section, we used MATLAB / Simulink for simulation and reproduced the hardware configuration, and compare the characteristics. Fig.6 shows the characteristics of simulation results in each control case. (a), (b), (c), (d) in Fig.6 is corresponded to each control cases shown in 3.1.

Compare Fig.6(a) with Fig.6(b), when the position reference is 20mm, both of position is moved to 20mm, so it can be seen no difference of position error. But in point of convergence time to reference position, Fig.6(a) takes 76 milliseconds, and Fig.6(b) takes 73 milliseconds. It is shown that convergence time can decrease 3 milliseconds by variable gain controller. Therefore, variable gain speed controller can improve response of control amount in tiny position moving, and improve control accuracy in very low speed range. It is thought that variable gain controller can increase tiny adjustment effect at near position reference. It is not found a difference of speed and q-axis current characteristics between Fig.6(a) and Fig.6(b).

Then, compare Fig.6(a) with Fig.6(c), it can be found a difference at the point of tracking delay between position reference and position. In Fig.6(a) at moving maximum speed, it can be seen 12 milliseconds of tracking delay between position reference and position. But in Fig.6(c), it can be seen no tracking delay. Therefore, it is thought that feed forward controller can compensate tracking delay between position reference and position which is distinctive to Proportional
controller。In this comparison, it is not found big difference of speed and q-axis current characteristics between Fig.6(a) and Fig.6(c).

Finally in a result of Fig.6(d), when the position reference is 20mm, position is moved exactly to 20mm, and it can be seen no tracking delay too. Therefore, it is thought that these two methods of improvement can contribute improvement of control accuracy, and do not affect each other.

3.3 Experiment Results of Actual Machines

Compare Fig.7(a) with Fig.7(b), when the position reference is 20mm, both of position is moved to 20mm, and it can be seen no difference of position error. But in point of convergence time to reference position, Fig.7(a) takes 0.2seconds, and Fig.7(b) takes 0.1seconds. It is shown that convergence time can decrease 0.1seconds by variable gain controller. Therefore, variable gain speed controller can improve response of control amount in tiny position moving, and improve control accuracy in very low speed range. So it is found that variable gain controller can increase tiny adjustment effect at near position reference. In speed characteristcs, that of Fig.7(a) changes more vibrataly than the one of Fig.7(b). Q-axis current characteristics changes same as speed characteristics too.

Then, compare Fig.7(a) with Fig.7(c), it can be found a difference at the point of tracking delay between position reference and position. In Fig.7(a) at moving maximum speed, it can be seen 0.01 seconds of tracking delay between position reference and position. But in Fig.7(c), it can be seen no tracking delay.

Therefore, it is found from actual machine result that feed forward controller can compensate tracking delay between position reference and position which is distinctive to Proportional controller. In speed characteristics, vibration of speed and q-axis current characteristics in Fig.7(c) are increase than these of Fig.7(a) because feed forward controller leads speed reference more closely to step form. Especially in near zero speed range, 30rpm of speed overshoot is caused, which is noted.
Finally in a result of Fig.7(d), when the position reference is 20mm, position is moved exactly to 20mm, and it can be seen no tracking delay too.

By the way, comparing Fig.7(c) with Fig.7(d), it can examine the effects of using variable gain speed controller in situation of using feed forward controller all time. In Fig.7(c), convergence time to reference position is 0.1seconds, but 0.16mm of position overshoot is occurred. In Fig.7(d) which using variable gain speed controller, convergence time to reference position is 0.15seconds, but 0.08mm of position overshoot is occurred. This is 0.05seconds longer convergence time, but half smaller onds, but 0.08mm of position overshoot is occurred. This controller, convergence time to reference position is 0.15seconds, but 0.08mm of position overshoot is occurred. This is 0.05seconds longer convergence time, but half smaller position overshoot than Fig.7(c). It is found that Fig.7(d) can make more smoothly controller than Fig.7(c), because of difference in near zero speed range between PI control and I-P control. So it is thought that high precision control needs smooth controller like Fig.7(d).

Then, comparing Fig.7(b) with Fig.7(d), it can examine the effects of using feed forward controller in situation of using variable gain speed controller all time. In Fig.7(b) at moving maximum speed, it can be seen 0.02seconds of tracking delay between position reference and position. But in Fig.7(d), tracking delay is decreased to 0.01seconds. Therefore, it is found that feed forward controller can compensate tracking delay between position reference and position which is distinctive to Proportional controller with or without using variable gain speed controller.

From these comparison results, it is found following results of study.

I. Variable gain controller can increase tiny adjustment effect at near position reference and near zero speed.
II. Variable gain controller can suppress speed control becoming to vibrataly.
III. Feed forward controller can compensate tracking delay between position reference and position which is distinctive to Proportional controller.
IV. Speed overshoot by feed forward controller can be suppressed by using variable gain speed controller.

Therefore, in the position control system, by using both of variable gain speed control and position feed forward control, it can compensate tracking delay and speed vibration. Then it is confirmed that control accuracy in near zero speed area and tiny moving amount area can improve.

Consequently, it is confirmed that proposed methods in this paper contribute improving control accuracy, and do not affect each other.

4. Conclusion

In this paper, we target that realizing high precision positioning servo system without affected disturbance, and propose the mechanism integrating PMSM rotor with ballscrew shaft. Using this system, we try to improve drive characteristics at very low speed (near by zero speed) by changing speed PI control and speed I-P control continuously, and try to compensate control response delay by adding feed forward control to position P control. We examined these proposed methods in both of simulation and actual machines.

From these examinations, it is found that proposed position control system, by using both of variable gain speed control and position feed forward control, can compensate tracking delay and speed vibration. Then it is confirmed that control accuracy in near zero speed area and tiny moving amount area can improve.

Consequently, it is confirmed that proposed methods in this paper contribute improving control accuracy, and do not affect each other.

Therefore, to construct and improve high precision positioning servo system, it is found that it is effective to use the proposed methods, which are using superhigh resolution encoder, compensation of disturbance by using disturbance observer, and applying variable gain controller and feed forward control.

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