Research on Current Loop Bandwidth under Limits of Delay Time and Overshoot

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Abstract. The delay of the forward channel and the feedback channel is one of the main factors that affect the current loop control effect. However, a large amount of literature currently only pays attention to the forward channel delay, which has a great impact on the system, and ignores the influence of the feedback channel delay on the system. Based on the actual current loop model, the bandwidth and dynamic response of the servo control system when the forward channel delay and the feedback channel delay exist simultaneously are analyzed. Provide theoretical reference for engineering practice.

Keywords: PMSM, servo control, dynamic response.

1. Introduction

Since the current loop directly provides torque for the entire system, the change in torque will directly affect the rotation speed, thereby changing the operating state of the entire system. There are many factors that affect the control effect of the current loop, including delay time.

For example, the calculation time of the control chip, the switching time of the power switch, the control algorithm, etc. will cause the forward channel delay, and the sampling time for current, voltage, speed, position, the calculation time of the control chip, etc. will cause a feedback channel delay. These delay times have a negative effect on the operation of the system and make the dynamic and static of the system worse.

Accordingly, the bandwidth and dynamic response of the current loop are obtained through approximate processing. According to the limitation of dynamic response in engineering practice, an ideal bandwidth range is obtained.
2. Current loop bandwidth analysis

2.1. The basic model of the current loop of the servo control system

As shown in Figure 1, a proportional integral (PI) controller is used as the controller of the system. The controlled object is a PMSM, its transfer function is $\frac{1}{Ls + R}$.

Assume that PMSM operates under ideal conditions:

a). Magnetic saturation and the loss caused by electromagnetism inside the motor is ignored.

b). The resistance and inductance of PMSM remain constant and do not change with other variables

c). PMSM has the same winding of three phases.

d). The effect of the counter electromotive force (EMF) on the motor is ignored.

2.2. Current loop model under the action of forward channel delay and feedback channel delay

When the feedback channel delay and the current channel delay exist at the same time, for the system, its closed-loop transfer function can be expressed as:

$$
G_c(s) = \frac{G(s)}{1 + G(s)H(s)} = k_p \frac{T_f s + 1}{LT_d T_f s} + \frac{s + 1}{T_d} \frac{s + 1}{T_f} + \frac{k_p}{LT_d T_f}
$$

In embedded systems using microprocessors, the delay time is very small, so the delay element can be replaced by the inertial element when analyzing the system. According to reference [3], because the actual system is difficult to analyze in the form of analytical solutions, approximate processing methods are adopted.

$$
G_a(s) = G(s)H(s) = \frac{k_p}{Ls(T_d s + 1)(T_f s + 1)}
$$

The approximated system frequency domain equation is:
\[ G'_d(j\omega) = \frac{K}{j\omega(j\omega T + 1)} = \frac{k_p}{L} \frac{1}{j\omega[1 + j\omega(T_d + T_f)]} \]  \hspace{1cm} (3)

\[ G'_c(s) = \frac{k_p}{Ls(Ts + 1)} \]  \hspace{1cm} (4)

In equation (4), \( T = T_d + T_f \)

\[ G_t(s) = \frac{G(s)}{1 + G_0(s)} = \frac{\frac{1}{T_d} \cdot \frac{k_p}{LT}(Ts + 1)}{(s + \frac{1}{T_d})(s^2 + \frac{1}{Ts} + \frac{k_p}{LT})} \]

In order to facilitate the analysis, the model is further simplified and the zero point and pole point which has great influence on the system performance is found.

The zero point of this system is \( z = -\frac{1}{T_d} \).

It can be seen from the reference [4] that the poles \( p_{1,2} \) meets the above conditions, that is to say, it has a great impact on the operation performance of the system, and they are regarded as the closed-loop main pole.

\[ G_c(s) = \frac{T}{s^2 + \frac{1}{Ts} + \frac{k_p}{LT}} = \frac{K \cdot \omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \]  \hspace{1cm} (5)

In equation (5),

\[ \omega_n = \sqrt{\frac{k_p}{LT}} = \sqrt{\frac{2\pi f}{T}} \]

\[ \xi = \frac{1}{2T \omega_n} = \frac{1}{2\sqrt{2\pi fT}} \]

Defined by bandwidth and equation (5),

\[ 20\log|G_c(j\omega)| = 20\log\sqrt{\frac{(\frac{T}{T_d})^2}{\left(1 - \frac{\omega^2}{\omega_n^2}\right) + \left(\frac{2\xi\omega}{\omega_n}\right)^2}} = -3 \]  \hspace{1cm} (6)
According to equation (6), it can be calculated that
\[
\omega = \omega_n \sqrt{\left(1 - 2\zeta^2\right) + \left(1 - 2\zeta^2\right)^2 - \left(1 - 2\frac{T^2}{T_d^2}\right)}
\]  
(7)

It can be seen from equation 5 that the unit step of the system is
\[
C(s) = G_c(s)R(s) = \frac{\frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \cdot \frac{1}{s}}{s^2 + 2\zeta\omega_n s + \omega_n^2} = K \cdot \left(\frac{s + \zeta\omega_n}{s + \zeta\omega_n^2 + \omega_d^2} - \frac{\zeta\omega_n}{\omega_d} \cdot \frac{\omega_d}{(s + \zeta\omega_n^2 + \omega_d^2)} \right)
\]  
(8)

The time domain equation of Equation 8 can be obtained as
\[
c(t) = K \cdot c_i(t) = K \cdot L^{-1}[C_i(s)]
\]
\[
= \frac{T}{T_d} \cdot [1 - e^{-\frac{\zeta\omega_n t}{\sqrt{1 - \zeta^2}}} \sin(\omega_d t + \beta)], t \geq 0
\]  
(9)

In Equation 9, \( \beta = \arctan \frac{\sqrt{1 - \zeta^2}}{\zeta} \).

Take the derivative of Equation 9, and then obtain the peak time of the system at the point where the derivative is equal to zero.
\[
T_p = \frac{\pi}{\omega_n \sqrt{1 - \zeta^2}}
\]

Substituting the peak time into Equation 9, the overshoot of the system can be obtained.
\[
\sigma\% = e^{-\frac{\pi^2}{1 - \zeta^2}} \times 100\%
\]  
(10)

In engineering practice, there are often restrictions on the overshoot, and the overshoot is limited to no more than 4\%.

As shown in equation 11, it is known that the bandwidth and delay time are inversely proportional to each other under the limitation of dynamic response.
\[
\omega \cdot T = 2\pi f \cdot (T_d + T_f) \leq 0.496
\]  
(11)

Figure 11 visually shows the restriction relationship between bandwidth and delay time under the limit of overshoot.
Figure 2. The influence of delay on system bandwidth under the condition of overshoot limitation

3. Conclusion

As can be seen from Figure 2, the bandwidth of the entire system is limited by the delay time, and the ideal range of bandwidth is limited by overshoot. Within this limit, it can be seen that the forward channel has a greater impact on the bandwidth, and the delay of the feedback channel also has a great impact on the system bandwidth due to the limitation of overshoot.

Therefore, for the servo control system in engineering practice, it is difficult to reflect the actual operation of the system by simply considering the forward channel delay due to the limitation of overshooting in engineering practice, so the feedback channel delay needs to be taken into consideration.

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