# Anti-Disturbance Study of Position Servo System Based on Disturbance Observer

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**Abstract:** In this paper, the mechanism and method of using disturbance observer (DOB) to eliminate the disturbance are studied and applied to the control of position servo system. The DOB consists of an inverse model of the controlled object and a filter, and suppresses the external disturbance acting on the servo system. Based on the traditional proportional integral derivative (PID) controller, simulations on MATLAB/Simulink and tests on Quanser semi-physical experiment platform are performed for the PID controller with DOB and without DOB. Simulation and experimental results show that the introduction of DOB can effectively suppress the external disturbance and improve the dynamic response performance and stability of the servo system.

*Keywords:* Proportional Integral Derivative Control, Disturbance Observer, Anti-Disturbance, Position Servo System, Quanser Experiment Device.

## 1. INTRODUCTION

The servo system has been widely used in various fields such as national defense and industry because of its high precision, strong stability and fast response speed (Zhang & Ma, 2016). Nowadays, in the actual industrial production, the control method of the servo system is still dominated by proportional integral derivative (PID) control. Traditional PID control is especially sensitive to the system parameter change and external disturbance. Requirements of the servo system are keeping rising with the development of technology, industrial production, and other areas. In order to meet the needs of production, many scholars have developed a variety of advanced control methods, including fuzzy control (Gao & Li, 2013), neural network control (Zou et al., 2015), adaptive control (Gan et al., 2016), sliding mode control (Ren & Fan, 2016), etc. These methods have some improvements in stability and anti-disturbance of the system, but most of them are complicated to implement and difficult to be widely used in engineering.

When analyzing the actual system, no matter how its model is obtained, there are differences between the actual model and the nominal model. These differences include unmodeled dynamic characteristics and disturbance existing in the system. The basic idea of a disturbance observer (DOB) is looking at the difference between the actual output and the nominal model output as the equivalent disturbance acting on the nominal model. This equivalent disturbance is then estimated and added to the control terminal as a feedback signal to counteract the effects of external disturbances (Kempf & Kobayashi, 1999). DOB is very suitable for improving the anti-jamming ability of motion control system because of its simple structure, small amount of calculation and effective suppression of external disturbances (Jia et al., 2007) (Li et al., 2011). Therefore, more and more scholars are involved in the research of the DOB. It has also been widely used in the fields of DC servo motor control, aircraft, robotics, numerical control, and so on.

On the basis of traditional PID control method, this paper studies a disturbance rejection method based on the DOB. This method can predict and compensate system interference in real time and reduce the influence of various disturbances and parameter changes on system stability. Simulations in MATLAB/Simulink and tests on Quanser semi-physical experiment platform are performed after the study of the DOB for position servo system. The simulation and experimental results show that the PID controller with DOB has faster response speed, smaller overshoot, and stronger robustness compared with PID controller.

## 2. DISTURBANCE OBSERVER RESEARCH

### 2.1 Brief Introduction of DOB

The idea of DOB was first proposed by Japanese scholar Ohnishi in 1987 (Ohnishi, 1987). The general structure of DOB is shown in Fig. 1.

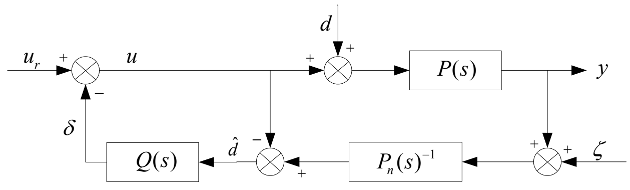


Fig. 1. General structure of DOB

Where $u_r$ is the reference input, $d$ is the external disturbance, $\zeta$ is the measurement noise, $y$ is the output, $P(s)$ is the real system and $P_n(s)$ is the nominal model. External disturbances $d$ are determined by the intrinsic characteristics of the external environment, system nonlinearity, and uncertainty, $d$ is low-frequency noise, and measurement noise $\zeta$ is high-frequency noise; the error signal $u$ is the difference between the reference input signal $u_r$ and the disturbance compensation signal $\delta$ ; disturbance compensation signal $\delta$ is obtained by $Q(s)$ filter filtering.

In Fig. 1, $P_n(s)$ is generally a causal system, namely the order of the denominator is generally greater than the order of the numerator. Then $P_n(s)^{-1}$ is a non-causal system, which is unprocurable in practice. In order to guarantee the realizability of DOB, the structure is equivalent as shown in Fig. 2. It can be observed from Fig. 2 that $Q(s)P_n(s)^{-1}$ can be achieved if the degree of order difference between the numerator and denominator of $Q(s)$ are greater than or equal to $P_n(s)$.

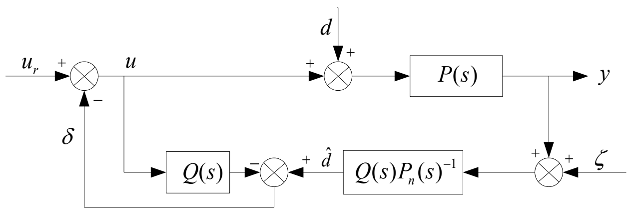


Fig. 2. Equivalent structure of DOB

As can be seen from Fig. 2, the system output $y$ can be expressed as a function of the reference input $u_r$ , the external disturbance $d$ and the measurement noise $\zeta$ :

$$\begin{aligned} y = & \frac{P(s)P_n(s)}{P_n(s)+[P(s)-P_n(s)]Q(s)}u_r \\ & + \frac{P(s)P_n(s)[1-Q(s)]}{P_n(s)+[P(s)-P_n(s)]Q(s)}d \\ & - \frac{P(s)Q(s)}{P_n(s)+[P(s)-P_n(s)]Q(s)}\zeta. \end{aligned} \tag{1}$$

According to (1), the sensitivity function and the complementary sensitivity function of DOB are defined as shown in (2) and (3) respectively.

$$S_{DOB}(s) = \frac{P(s)P_n(s)[1-Q(s)]}{P_n(s)+[P(s)-P_n(s)]Q(s)} \tag{2}$$

$$T_{DOB}(s) = \frac{P(s)Q(s)}{P_n(s)+[P(s)-P_n(s)]Q(s)} \tag{3}$$

It is known from the definition of sensitivity function and compensatory sensitivity function that these two functions are respectively determined by low-frequency disturbance and high-frequency measurement noise. When $|Q(s)| \approx 1$, the sensitivity function $S_{DOB}(s) \approx 0$ . This shows that when the filter $Q(s)$ approaches 1, the system can suppress external disturbances at the input terminal. When $|Q(s)| \approx 0$ , the compensatory sensitivity function $T_{DOB}(s) \approx 0$ . This shows that when the filter $Q(s)$ approaches 0, the system can attenuate measurement noise at the input terminal. It can be seen from the above analysis that the different values of $Q(s)$ determine the system's performance of suppressing disturbance and noise. Therefore, the input low-frequency disturbance and output high-frequency noise can be both suppressed by selecting an appropriate $Q(s)$ . In ideal conditions, the filter $Q(s)$ is close to 1 at low frequencies to suppress low-frequency disturbances at the input and close to 0 at high frequencies to suppress high-frequency noise at the output. In other words, $Q(s)$ should be designed as a low-pass filter to meet the above requirements.

### 2.2 *Design of Low Pass Filter* $Q(s)$

Analysis result shows that the main part of the DOB is the low-pass filter $Q(s)$ design. The design of the filter mainly considers two points: orders of the numerator and denominator and bandwidth of the filter.

Assuming the numerator order of $Q(s)$ is $n$ and denominator order is $m$ , then, the low-pass filter can be expressed as $Q_{mn}(s)$ , the corresponding system model is:

$$P(s) = \frac{(s+z_1)\cdots(s+z_m)}{s^l(s+p_1)\cdots(s+p_n)} \tag{4}$$

where $p_i > 0$, $z_j > 0$, and $l+n > m$.

Umeno and Hori give the general form of a low-pass filter (Umeno et al., 1993) for the system described in (4):

$$Q(s) = \frac{1+\sum_{k=1}^{N-r} a_k(\tau s)^k}{1+\sum_{k=1}^{N} a_k(\tau s)^k}. \tag{5}$$

Where $N$ is the highest exponent power in the denominator polynomial, $\tau$ is the time constant of the filter, $r$ is the difference between the order of numerator and denominator of $Q(s)$.

In order to ensure that the DOB can be realized, it is necessary to make the degree of order difference between the denominator and numerator of $Q(s)$ not less than $P_n(s)$. After analysis, it can be seen that the greater the degree of order difference between the denominator and numerator of $Q(s)$, the stronger the rejection of high-frequency noise at the output, but the weaker the suppression ability of the low-frequency interference at the input. When $Q(s)$ has a certain degree of order difference between the numerator and denominator of $Q(s)$, the higher order of $Q(s)$, the stronger suppression of the low-frequency interference at the input but the weaker rejection of high-frequency noise at the output. Based on the above analysis, it needs to be comprehensively considered and rationally selected when designing the order of the low pass filter $Q(s)$, according to the specific control system.

In addition, the definitions of sensitivity function and compensatory sensitivity function show that they are respectively corresponding to low-frequency disturbance and high-frequency measurement noise. Due to the different influence of high-frequency noise and low-frequency disturbance on the system, a compromise between $|Q(j\omega)|$ and $|1-Q(j\omega)|$ must be combined with the actual system (Kim & Chung, 2002a) to meet the sensitivity $S_{DOB}(s)$ and compensatory sensitivity $T_{DOB}(s)$ requirements.

A common design method of $Q(s)$ is making the right half of the $|Q(j\omega)|$ slope equal to the left half of $|1-Q(j\omega)|$. In the frequency domain, the slope of $|Q(j\omega)|$ in the low-frequency region and the slope of $|1-Q(j\omega)|$ in the high-frequency region are approximately described as:

$$\frac{Lm|1-Q(j\omega)|}{Lm(\omega)} \approx N-r-1 \tag{6}$$

$$\frac{Lm|Q(j\omega)|}{Lm(\omega)} \approx -r. \tag{7}$$

Making (6) equals to (7) can get

$$r=\frac{N+1}{2}. \tag{8}$$

From (8), it can be known that if $r$ increases $k$, then $N$ should increase $2k-1$, which means that $Q(s)$ is more complicated and more difficult to realize.

Without loss of generality, Bong Keun Kim (Kim & Chung, 2002b) gives two forms of low-order filters:

The smallest order filter for first order system:

$$Q(s)=\frac{1}{\tau s+1}. \tag{9}$$

The smallest order filter for second order system:

$$Q(s)=\frac{3(\tau s)+1}{(\tau s)^3+3(\tau s)^2+3(\tau s)+1}. \tag{10}$$

The bandwidth of $Q(s)$ mainly depends on the unmodeled dynamic characteristics. Assuming that the error between the nominal model $P_n(s)$ and the actual model $P(s)$ is defined as multiplicative perturbation $\Delta$, there are:

$$P(s)=P_n(s)(1+\Delta). \tag{11}$$

According to the multiplicative perturbation relation (11) and the small gain theorem, if $\Delta$ is stable, there must be:

$$\|\Delta \circ Q(s)\|_\infty \le 1. \tag{12}$$

Therefore, the bandwidth of the filter can be selected according to (12). If $\Delta$ is stable, the amplitude-frequency curve of $1/\Delta$ on the Bode plot should fall above the amplitude-frequency curve of $Q(s)$. If $\Delta$ is not stable, all points on the amplitude-frequency curve of on the Bode plot must be greater than $Q(s)$'s at any point.

## 3. SIMULATION ILLUSTRATIONS

In order to verify the effect of the DOB on the external disturbance and the high-frequency noise, some simulation experiments are carried out on the control system with and without DOB. The selected research object is Quanser SRV02 rotary servo plant, consists of a DC motor that is encased in a solid aluminum frame and equipped with a planetary gearbox. PID controller is designed for the nominal model of position servo system. The structure of control system with DOB is shown in Fig.3.

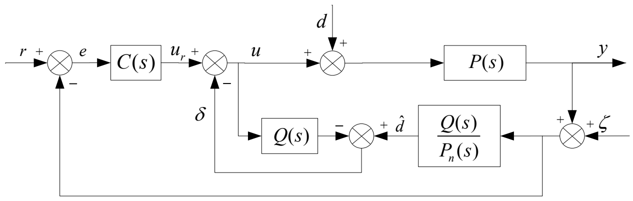


Fig. 3. The structure of control system with DOB

The actual model of the servo system:

$P(s)=\dfrac{15.985s+18.75}{0.239s^3+10.107s^2+0.634s+0.00677}$; nominal model: $P_n(s)=\dfrac{1.53}{0.0254s^2+s}$; PID controller: $C(s)=10+\dfrac{40}{s}+0.2s$; simulation time: 8s.

Since the difference between the order of numerator and denominator of the nominal model $P_n(s)$ is 2, $Q(s)$ should be a second-order low-pass filter. In order to simplify the simulation implementation and reduce the computational intensity, this paper uses the filter form as shown in (13), taking the time constant $\tau$=0.001, there are:

$$Q(s)=\frac{1}{10^{-6}s^2+0.002s+1}. \tag{13}$$

Fig. 4 shows the unit step response of the position servo system with and without DOB. As can be seen from the figure, because the DOB can estimate and compensate the disturbance in real time, the overshoot and response time of the step response are reduced and the dynamic performance of the servo system is improved. After adding disturbance with amplitude value of 0.5 at 4s, the step response curve of the system without DOB changed significantly and the settling time is longer than the system with DOB.

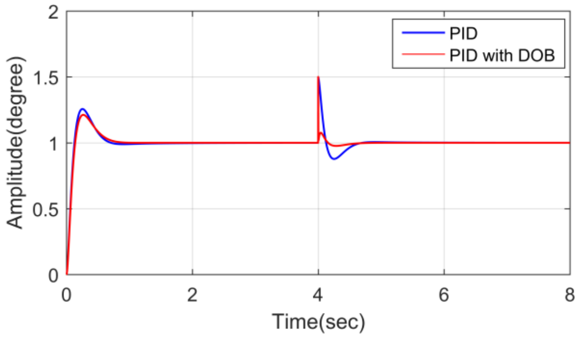


Fig. 4. The unit step responses with disturbance

Fig. 5 and Fig. 6 show the position servo system output curve comparison with 0 inputs and external sinusoidal disturbance with amplitude value of 3 and frequency value of 1 Hz. It can be seen from the figures that the amplitude of the output curve is reduced by 2 orders after introducing the DOB. This shows that the introduction of the DOB can significantly improve the suppression ability of disturbance.

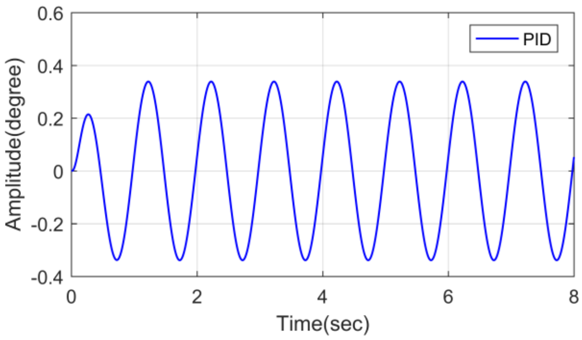


Fig. 5. Output curve without DOB

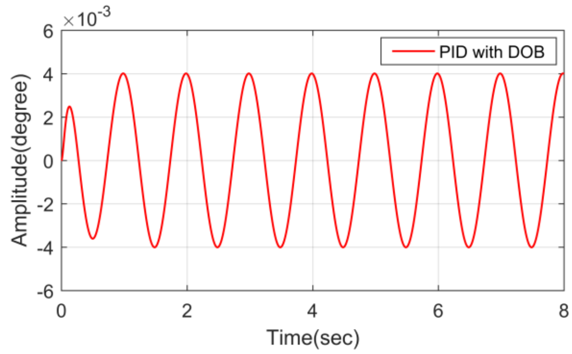


Fig. 6. Output curve with DOB

Fig. 7 shows a sinusoidal signal with amplitude value of 1 and frequency value of 1 Hz adding a sinusoidal disturbance with amplitude value of 5 and frequency value of $2\pi$ Hz. It can be seen from the figure that without introducing DOB, the distortion of the waveform is rather serious and the suppression of external disturbances is poor. When the DOB is introduced, the system can track the sinusoidal signal better, the distortion of output waveform is smaller, and the tracking effect has been significantly improved.

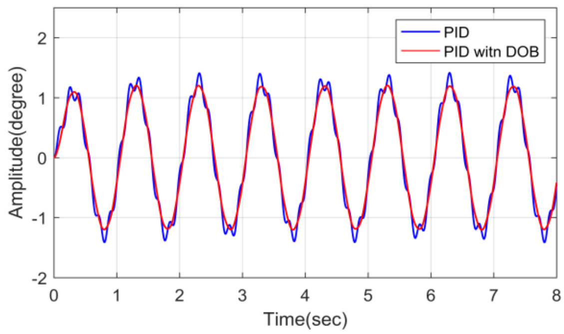


Fig. 7. The sinusoidal signal tracking with disturbance

## 4. EXPERIMENTAL VALIDATION

In this section, the PID controller and the PID controller with DOB designed in this paper are used to experiment on Quanser SRV02 rotary servo plant. The architecture of the experimental platform is shown in Fig. 8. Fig. 9 shows the simulink model of Quanser SRV02 DC motor position servo control system：PID controller with DOB.

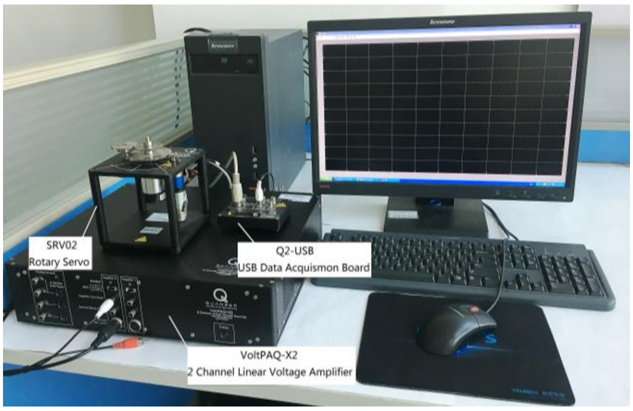


Fig. 8. The architecture of the experiment platform

The experiments compare the unit step response, disturbance rejection, and sinusoidal signal tracking performance of the position servo system under the two control systems. The experimental results are shown in Fig. 10-13. Fig. 10 is the unit step response curve, corresponding to the Fig. 4 in the previous simulation section. Fig. 11 and Fig.12 respectively correspond to Fig. 5 and Fig. 6 in the previous section. In Fig. 12, due to the limited accuracy of the sensors in the lab equipment, the output curve is not smooth, but the trend of the curve is still consistent with Fig. 6. Fig. 13 corresponds to the sinusoidal signal tracking in the previous simulation section (Fig. 7), which is very similar to the simulation result in Fig. 7. However, due to the influence of environment and equipment, error existing in the model of Quanser SRV02 DC motor position servo control system, so there is a gap between the actual response and the simulation.

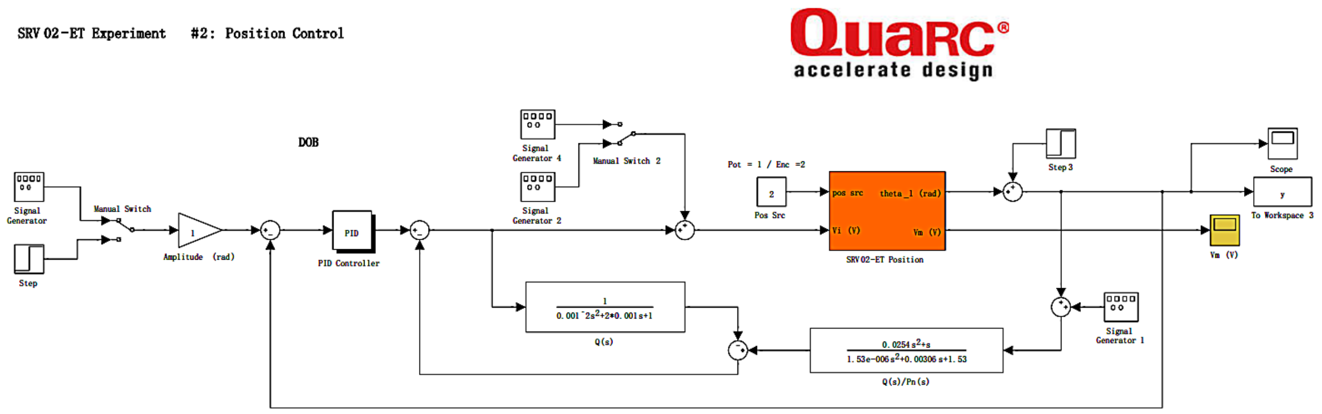


Fig. 9. Architecture diagram of Matlab/Simulink control system

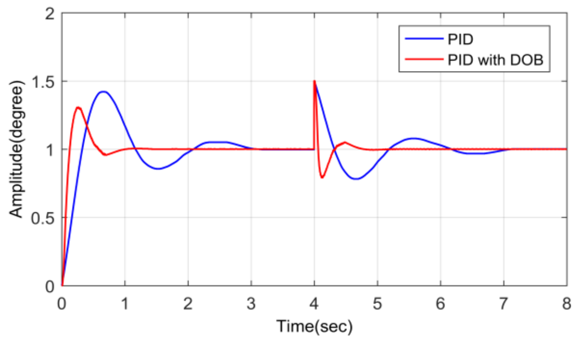


Fig. 10. The unit step responses with disturbance

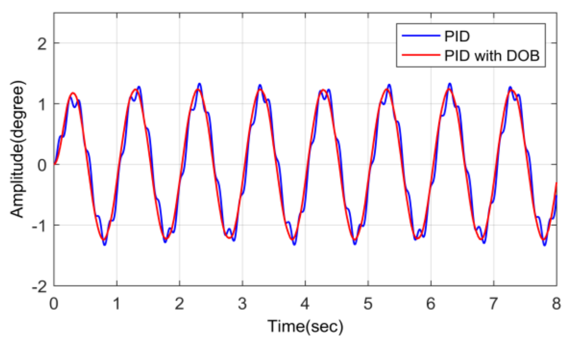


Fig. 13. The sinusoidal signal tracking with disturbance

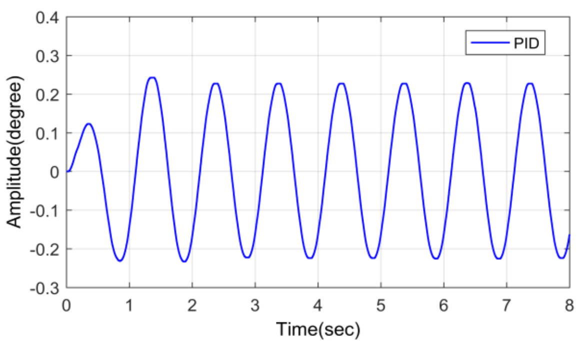


Fig. 11. Output curve without DOB

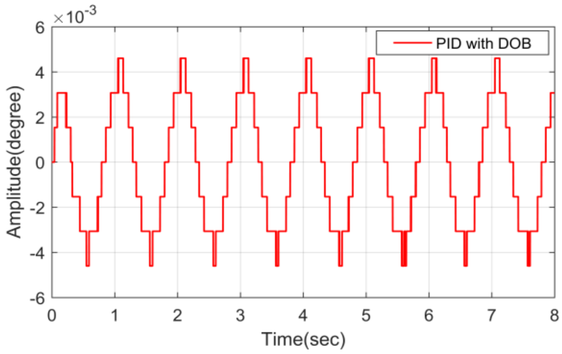


Fig. 12. Output curve with DOB

## 5. CONCLUSIONS

In order to improve the position servo system's suppression ability of disturbance, a method which can compensate external disturbance by using DOB is studied in this paper. The disturbance suppression of servo system with DOB is simulated and experimentally verified. Simulation and experimental results show that the control system with DOB can reduce the adjustment time and overshoot. Control system with DOB can compensate the received external disturbances obviously and improve the robustness and stability of the system. Thus, introducting the DOB in servo system is an effective way to improve the system's disturbance suppression performance.

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