Proceedings of the 37th Chinese Control Conference
July 25-27, 2018, Wuhan, China

On Disturbance Rejection Control of Servo System Based on the Improved Disturbance Observer

Jing Sun, Chunyang Wang*, Ruihao Xin

Department of Electronic and Information Engineering, Changchun University of Science and Technology, Changchun 130022
E-mail: wangchunyang19@163.com, sunjing1777@126.com

Abstract: Requirements of the servo system are keeping rising with the development of technology, industrial production and other areas. Traditional proportional integral derivative (PID) control cannot meet the control requirements of servo system when there is external disturbance and measurement noise in the system. In this paper, the mechanism and method of using improved disturbance observer (DOB) to eliminate the disturbance and noise are studied and applied to the control of speed servo system. Based on the traditional PID controller, simulations on MATLAB/Simulink and tests on Quanser semi-physical experiment platform are performed for the PID controller with and without improved DOB. Simulation and experimental results show that the improved DOB overcomes the problem of noise amplification in classical DOB and can effectively suppress external disturbance and noise at the same time.

Key Words: Disturbance Observer, Disturbance rejection, Speed servo system, Quanser experiment device

1 Introduction

Servo system is widely used in industrial manufacturing because of its excellent dynamic characteristics and high control accuracy. In the actual industrial production, the industrial production environment is complex and external interference is widespread, which has a direct impact on the control effect of the servo system. The control method of most servo system is still dominated by proportional integral derivative (PID) control. Traditional PID control is simple to implement and has high reliability. It is widely used in control systems with precise mathematical models [1]. However, the stable output characteristics and robustness will both deteriorate when the system model cannot be accurately obtained, the system parameters change or the external interference exists. In order to solve these problems, domestic and foreign scholars have conducted a lot of research and proposed various improved methods, including sliding mode control [2], robust control [3], fuzzy control [4], fractional order control [5], etc. Although these methods have some improvements in robustness and anti-jamming ability of the system, they are difficult to be widely used in the industry because of their complexity.

The use of a disturbance observer (DOB) does not require the accurate mathematical model of controlled object, but only the approximate model (nominal model) can be used to estimate and compensate for the external disturbances existing in the system. Therefore, DOB is increasingly used in modern industrial control. The basic idea of a 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 [6]. This disturbance may be from the external environment, nonlinear disturbance of the controlled object itself or other unknown disturbances. 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 [7]. It has been widely used in the fields of DC servo motor control, aircraft, robotics, numerical control and so on [8].

In this paper, an anti-disturbance control method based on the improved DOB is studied based on the traditional PID control method. The improved method can effectively solve the problem of noise amplification in the classical DOB. It can also predict and compensate the system interference in real time, and improve the system's anti-jamming capability and robustness to parameter changes. Simulations in MATLAB/Simulink and tests on Quanser semi-physical experiment platform are performed after the study of the improved DOB for speed servo system. The simulation and experimental results show that the PID controller with improved DOB has better anti-interference ability and stronger robustness compared with PID controller.

2 Improved Disturbance Observer Research

2.1 Classical Disturbance Observer

The concept of DOB was proposed by Japanese scholar K. Ohnishi in 1987. In 1991, T. Umeno and Y. Hori improved the theoretical framework of DOB in a two degree of freedom servo controller and factorization approximation design[9-11].

The general structure of DOB is shown in Fig. 1.

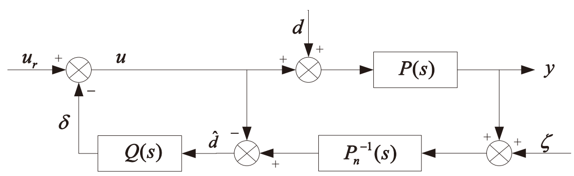

Fig. 1: General structure of DOB

Where u_r is the reference input, d is the external disturbance, ζ is the measurement noise, y is the output,

*This work is supported by Design and Research of Fractional Control System for Large Load Gyro Stabilized Platform under Grant 20160101279JC.

$P(s)$ is the real system, $P_n(s)$ is the nominal model and $Q(s)$ is the filter. 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 ζ is high-frequency noise; the error signal u is the difference between the reference input signal u_r and the disturbance compensation signal δ; disturbance compensation signal δ is obtained by $Q(s)$ filter filtering.

In general, the relative order of $P(s)$ is not zero, so $P_n^{-1}(s)$ is unachievable. In order to guarantee the realizability of DOB, under the condition that $Q(s)P_n^{-1}(s)$ can be achieved, the equivalent structure of DOB can be obtained as shown in Fig. 2.

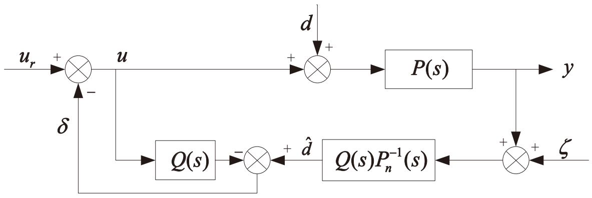

Fig. 2: Equivalent structure of DOB

Experimental studies show that the structure shown in Fig. 2 can achieve suppression of low-frequency disturbances, but it amplifies high-frequency measurement noise, which affects the stability and robustness of the control system.

2.2 Improved Disturbance Observer

In order to solve the problem of noise amplification of classical DOB, this paper selects an improved DOB [12] to realize the suppression of low-frequency disturbance and high-frequency noise. The structure of the control system is shown in Fig. 3.

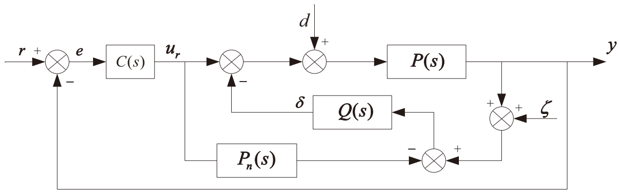

Fig. 3: The structure of control system with improved DOB

As can be seen from Fig. 3, the system output y can be expressed as a function of the input r, the external disturbance d and the measurement noise ζ:

$$y = G_{ry}(s)r + G_{dy}(s)d - G_{\zeta y}(s)\zeta \tag{1}$$

Where,

$$G_{ry}(s) = \frac{C(s)P(s)[1+Q(s)P_n(s)]}{1+Q(s)P(s)+C(s)P(s)[1+Q(s)P_n(s)]}$$

$$G_{dy}(s) = \frac{P(s)}{1+Q(s)P(s)+C(s)P(s)[1+Q(s)P_n(s)]}$$

$$G_{\zeta y}(s) = \frac{Q(s)P(s)}{1+Q(s)P(s)+C(s)P(s)[1+Q(s)P_n(s)]}$$

The control system function without improved DOB can be expressed as:

$$y = \frac{C(s)P(s)}{1+C(s)P(s)}r + \frac{P(s)}{1+C(s)P(s)}d - \frac{C(s)P(s)}{1+C(s)P(s)}\zeta \tag{2}$$

When $P(s) = P_n(s)$, $G_{ry}(s) = \frac{C(s)P(s)}{1+C(s)P(s)}$ in formula (1) and the coefficient of input r in formula (2) are the same. It can be seen that when the controlled system model is estimated accurately, the introduction of the improved DOB does not change the transitive relation between the system input and output. This illustrates the design of the controller and the improved DOB is completely independent.

In addition, it can be seen from formula (1) that when $P_n(s)$ is constant, the relation between output, disturbance and noise can be adjusted by adjusting the filter $Q(s)$. When $|Q(s)| \approx 0$, $G_{\zeta y}(s) \approx 0$. This means that when the filter $Q(s)$ approaches 0, the system can attenuate measurement noise at the output terminal. When $|Q(s)| \approx 1$, the value of $G_{dy}(s)$ is the smallest. This means that when the filter $Q(s)$ approaches 1, the system can suppress external disturbances at the input terminal. From the above analysis, it can be seen that the value of $|Q(s)|$ determines the system's ability to suppress disturbances and noise. In ideal conditions, $|Q(s)|$ close to 0 at high frequencies to suppress high-frequency noise at the output and close to 1 at low frequencies to suppress low-frequency disturbances at the input. Obviously, low-pass filter can meet the above requirements.

2.3 Design Method of Low Pass Filter $Q(s)$

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

Umeno and Hori give the general form of a low-pass filter [13]:

$$Q(s) = \frac{1+\sum_{k=1}^{N-r} a_k(\tau s)^k}{1+\sum_{k=1}^{N} a_k(\tau s)^k} \tag{3}$$

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

After analysis, it can be seen that the greater the r, the stronger the rejection of high-frequency noise at the output, but the weaker the suppression ability of the low-frequency disturbance at the input. When $Q(s)$ has a certain r, the higher order of $Q(s)$, the stronger suppression of the low-frequency disturbance at the input but the weaker rejection of high-frequency noise at the output. At the same time, the smaller the r, the higher the order of $Q(s)$, the better the robustness of the system. 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 order to produce a good suppression of noise and disturbance, a common design method of $Q(s)$ is making the right half of the $|Q(j\omega)|$ slope equal to the left half of $|1-Q(j\omega)|$ [14]. In the frequency domain, the slope of $|Q(j\omega)|$ in the low-frequency region is approximate to $-r$, and the slope of $|1-Q(j\omega)|$ in the high-frequency region is approximate to $N-r-1$. Making $N-r-1$ equals to $-r$ can get

$$r=\frac{N+1}{2} \tag{4}$$

From formula (4), 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 [15] gives two forms of low-order filters:

The smallest order filter for first order system:

$$Q(s)=\frac{1}{\tau s+1} \tag{5}$$

The smallest order filter for second order system:

$$Q(s)=\frac{3(\tau s)+1}{(\tau s)^3+3(\tau s)^2+3(\tau s)+1} \tag{6}$$

The time constant of $Q(s)$ determines the frequency range of the suppression disturbance. The smaller the time constant τ, the wider the frequency band, the stronger the system's ability to suppress disturbance, but the worse the robust stability and the weaker the ability to suppress measurement noise. The larger the time constant τ, the narrower the frequency band, the better the robust stability, the stronger the ability to suppress measurement noise, but the weaker the ability to suppress disturbance. The general choice of time constant is much smaller than the system time constant.

2.4 Robustness of Improved Disturbance Observer

Assuming that the error between the nominal model $P_n(s)$ and the actual model $P(s)$ is defined as multiplicative perturbation $\Delta(s)$, there are:

$$P(s)=P_n(s)(1+\Delta(s)) \tag{7}$$

Where $\Delta(s)$ is a variable transfer function used to describe the uncertainty of the object. In general, when the frequency increases, the uncertainty of the object increases, and $\Delta(j\omega)$ shows an increasing function of ω.

Generally, the small gain theorem is used to ensure the robust stability of the system. The sufficient condition for the robust stability of the improved DOB is known from the multiplicative perturbation relation (7) and the small gain theorem as:

$$\|\Delta \circ Q(s)\|_\infty \le 1 \tag{8}$$

3 Simulation Results

In order to verify the effect of the improved DOB on the external disturbance and the high-frequency noise, some simulation experiments are carried out on the control system with and without the improved DOB. The selected research object is Quanser SRV02 rotary servo plant. PID controller is designed for the nominal model of speed servo system. The specific simulation parameters are as follows:

The actual model of the speed servo system: $P(s)=\dfrac{1.5306}{0.025421s+1.0214}$; nominal model of the system: $P_n(s)=\dfrac{1.53}{0.0254s+1}$; PID controller: $C(s)=16+\dfrac{9}{s}+0.002s$; Simulation time: 8s.

This paper uses the filter form as shown in formula (5), taking the time constant τ=0.005, there are:

$$Q(s)=\frac{1}{0.005s+1} \tag{9}$$

Fig. 4 shows a comparison of the unit step response with disturbances and noise with and without the improved DOB. It can be seen from the figure that both curves are distorted, but the disturbance and noise of the step response curve with improved DOB are both suppressed.

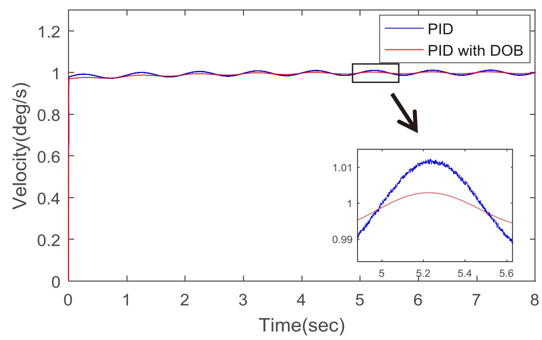

Fig. 4: The unit step responses with disturbance and noise

Fig. 5 shows the speed servo system output comparison curve when the input is 0 and only contains external sinusoidal disturbances. It can be seen from the figure that the amplitude of the output curve is significantly reduced after introducing the improved DOB. This shows that the introduction of the improved DOB can improve the suppression ability of disturbance.

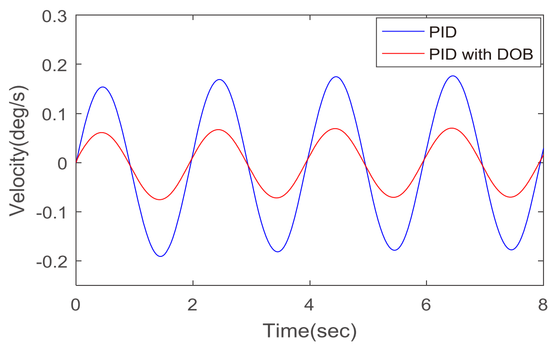

Fig. 5: Output curve with disturbance

Fig. 6 shows the speed servo system output comparison curve when the input signal is 0 and only include high-frequency noise. The output curve with noise of the improved DOB introduced in Fig. 6 is enlarged to shown in Fig. 7. It can be seen from the figures that the amplitude of the output curve is reduced by 2 orders after introducing the improved DOB. This shows that the improved DOB can significantly improve the suppression ability of high-frequency noise.

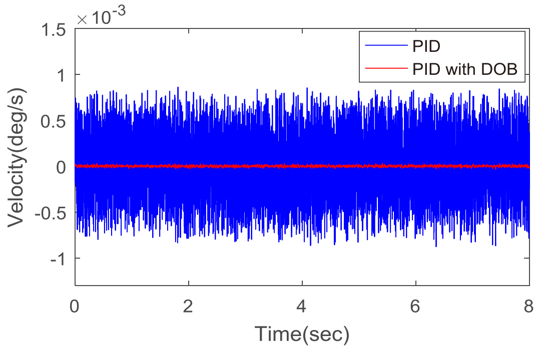

Fig. 6: Output curve with noise

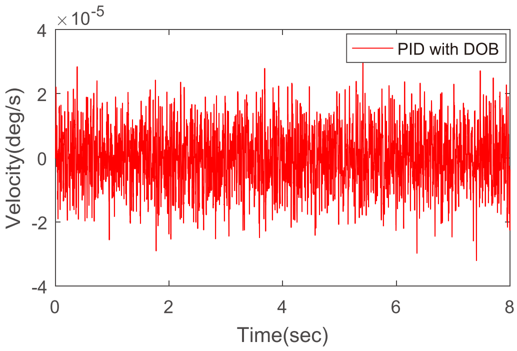

Fig. 7: Output curve with noise introducing improved DOB

As shown in Fig. 8, introducing the improved DOB, the unit step responses are plotted with open-loop gain changing by 30%. It can be seen from the figure that the gain change has no significant effect on the system step response after introducing the improved DOB. This shows that the controller with the improved DOB has strong robustness to gain changes.

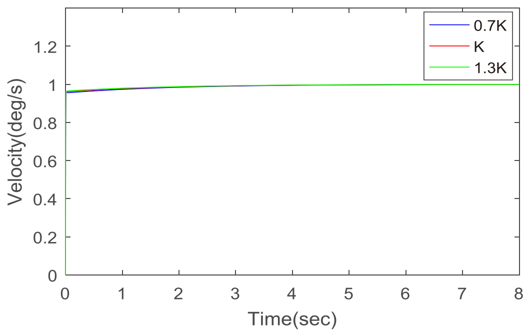

Fig. 8: The unit step responses with the improved DOB

4 Experimental Validation

In this section, the PID controller and the PID controller with improved 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. 9.

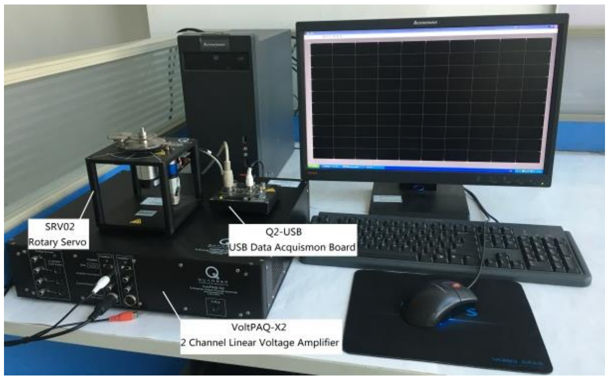

Fig. 9: The architecture of the experiment platform

Fig.10 shows the Simulink model of Quanser SRV02 DC motor position servo control system：PID controller with improved DOB.

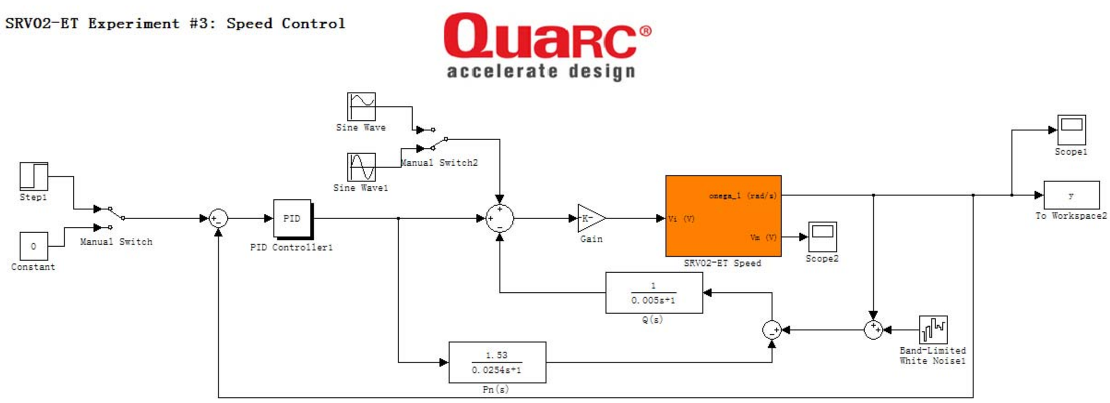

Fig. 9: Architecture diagram of experimental control system

The experiments compare the unit step response, disturbance and noise rejection performance and robustness of the speed servo system under the two control systems. The experimental results are shown in Fig. 11-15. Fig. 11 is the unit step response comparison curve with disturbance and noise, corresponding to the Fig. 4 in the previous simulation section. It can be seen that in the semi-physical experiments, the improved DOB has more pronounced inhibitory effect on disturbance and noise. Fig. 12-14 corresponds to Fig. 5-8 in the previous section. In Fig. 14, due to the limited accuracy of the sensors in the experimental equipment, the output curve is not smooth, but the noise suppression effect of the improved DOB can already be demonstrated. Fig. 14 corresponds to the Fig. 8, which is very similar to the simulation result in Fig. 8. Fig. 11-15 show the correctness of the theoretical and simulation experiments described in this paper. However, due to the influence of environment and equipment, error existing in the model of Quanser SRV02 DC motor speed servo control system, so there is a gap between the actual response and the simulation.

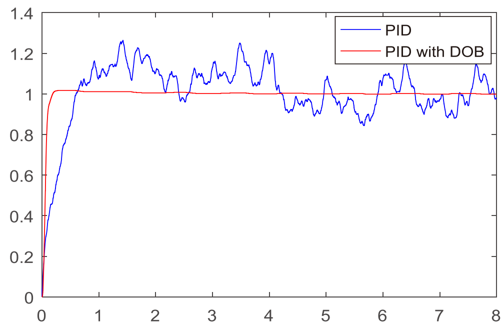

Fig. 11: The unit step responses with disturbance and noise

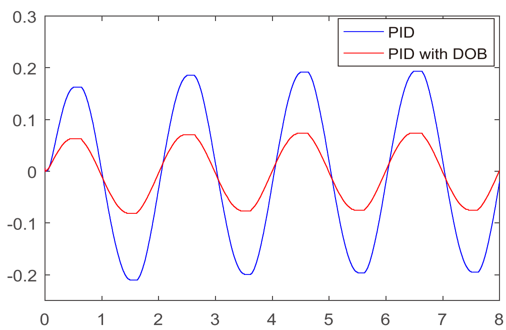

Fig. 12: Output curve with disturbance

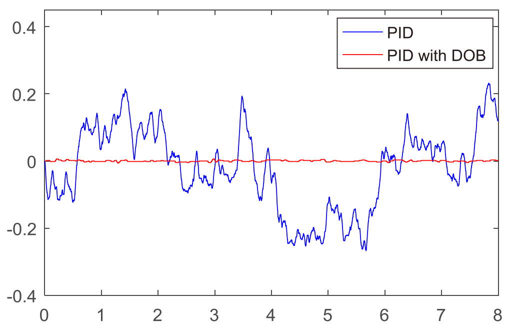

Fig. 13: Output curve with noise

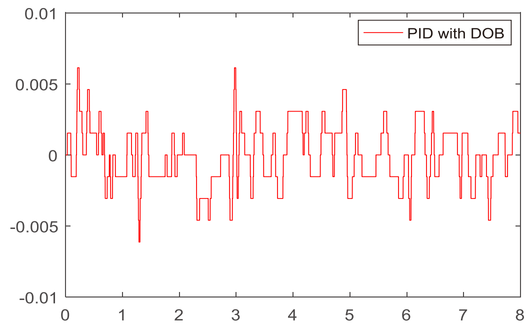

Fig. 14: Output curve with noise introducing improved DOB

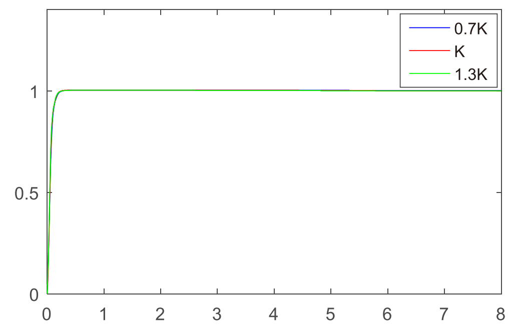

Fig. 15: The unit step responses with the improved DOB

5 Conclusion

In order to avoid the problem of noise amplification in classical DOB, an improved DOB is studied in this paper. At the same time when compensating external disturbances, noise suppression is realized. The simulation and experimental results show that the control system with the improved DOB has a very obvious inhibitory effect on the external disturbances and high-frequency noise, and can significantly improve the system's immunity to disturbances and robustness. Therefore, the improved DOB studied in this paper is an effective method to improve the disturbance and noise suppression performance of servo system.

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