Improved ADRC Controller based on Model Information and Special Filter Parameter Methods

Ze Yang[1, a, *], Baoqing Yang[1, b] and Jie Ma[1, c]
[1]Harbin Institute of Technology, School of Aerospace, Control and Simulation Center, China

Keywords: ADRC, model information, Bessel filter, total disturbance, linear extended state observer (LESO).

Abstract: In the LADRC controller, the former proposes a parameter adjustment method based on bandwidth design, but the effect still has room for improvement. This article will improve the effects of the controller in two ways. First, the known model information of the controlled object is introduced into the controller design to reduce the observer's interference observation load. On the other hand, the filtering methods of Bessel, Butterworth and Chebyshev are used to design the equivalent design of the extended state observer parameters, thereby increasing the overall performance of the controller by approximately 60%.

1 INTRODUCTION

The ADRC controller consisting of tracking differentiator (TD), extended state observer (ESO) and nonlinear state error feedback control law (NLSEF) (Jingqing Han, 2009). Among them, ESO is the core of the controller.

ESO is based on the state observer concept, which expands various known disturbances or unknown disturbances that can affect the output of the system into new state variables that are easily observed. In theory, there is no need to rely on the exact mathematical model of the controlled object.

Any second-order victim system and its LESO can be described as (Jingqing Han, 2007) the Equation (1):

Among them, x_1, x_2 are internal states, y is output for the system. $f(x_1, x_2)$ is acceleration acting on the open loop system. And think of the $f(x_1, x_2)$ as an extended state, recorded as x_3 (Jingqing Han, 2007). And record $\dot{x}_3$ as $\eta(t)$ .According to the existing theory, the above formula is designed as a linear extended state observer.

Through the observer of the above structure, the controlled object is compensated as $G_0(s) = b_0 / s^2$. The parameters z_1, z_2, z_3 in (3) is the observation of the system state x_1, x_2, x_3 , e_1 is the error signal of the observed value z_1 . b_0 is the controller gain, the selection of this parameter is determined by the equivalent series integration form of the controlled object (QIN Chang-mao, QI Nai-ming, ZHU Kai, 2010). If the three parameters $\beta_{01}, \beta_{02}, \beta_{03}$ are selected reasonably, LESO can accurately observe the system state variables.

The parameter adjustment method of ESO is not perfect, and it is difficult to implement under nonlinear conditions, including neural network algorithm (YIN Jin-song, WANG Rong-line, GAO Qiang, ZHANG wei, 2019), particle swarm optimization algorithm (Wang Boyu, 2018) and so on.In the traditional LESO parameter tuning, there is a more widely used method called pole placement method (GAO Zhiqiang, 2003). Through laplace transform on (2), and after constant transformation the following results can be obtained.

$$\dot{x}_1 = x_2, \dot{x}_2 = f(x_1, x_2) + b_0 u, y = x_1, e_1 = z_1 - y, \dot{z}_1 = z_2 + \beta_{01}(y - z_1), \dot{z}_2 = z_3 + \beta_{02}(y - z_1) + b_0 u, \dot{z}_3 = \beta_{03}(y - z_1) \quad (1)$$

$$z_1 = y - \frac{s(s^2 y - b_0 u)}{s^3 + \beta_{01}s^2 + \beta_{02}s + \beta_{03}}, z_2 = sy - s^2 + \frac{\beta_{01}s(s^2 y - b_0 u)}{s^3 + \beta_{01}s^2 + \beta_{02}s + \beta_{03}}, z_3 = \frac{\beta_{03}(s^2 y - b_0 u)}{s^3 + \beta_{01}s^2 + \beta_{02}s + \beta_{03}} \quad (2)$$

Yang, Z., Yang, B. and Ma, J.
Improved ADRC Controller based on Model Information and Special Filter Parameter Methods.
DOI: 10.5220/0008387603170322
In *Proceedings of 5th International Conference on Vehicle, Mechanical and Electrical Engineering (ICVMEE 2019)*, pages 317-322
ISBN: 978-989-758-412-1

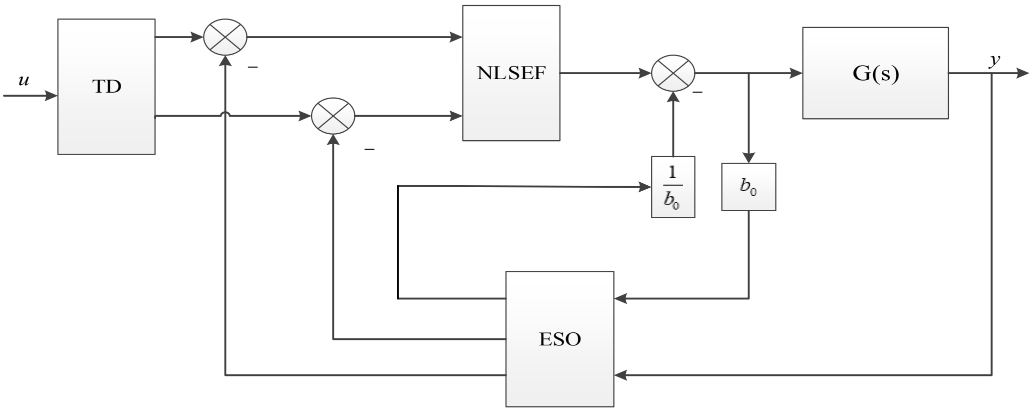

Figure 1. Second-order ADRC controller structure.

$$G(s) = z_3 / f = \beta_{03} / (s^3 + \beta_{01}s^2 + \beta_{02}s + \beta_{03}) \tag{3}$$

In the Equation (2), $f = s^2 y - b_0 u$ is the total disturbance. So we can get the transfer function $G(s)$ from f to z_3:

Through the transfer function relationship between f and z_3, we can design the ESO's observation performance of the total disturbance to be equivalent to a low-pass filter of the form. The traditional pole placement method or bandwidth method is to arrange the poles of the characteristic equations in the same position. The classic method is as follows, $\beta_{01} = 3\omega_q, \beta_{02} = 3\omega_q^2, \beta_{03} = \omega_q^3$ (GAO Zhiqiang, 2003). In the equation, ω_q is the bandwidth configuration requirement of the observer.

2 LESO BASED ON MODEL INFORMATION AND FILTER METHOD

The content of this section is mainly based on the previous text. Because the traditional ESO does not need to rely on the precise information of the controlled object in theory, it makes it have certain performance limitations in the process of use. The combination of ESO and model information can further reduce the observation burden and improve the overall performance of the controller (Yao Xiaoyan, 2018). As mentioned earlier, the parametric design of the observer can be equivalent to a specific form of low-pass filter parameter design, so we can introduce some better filter methods with better performance than the traditional pole placement method.

We can design a similar LESO observer equation through such a system state equation.

Similarly, the system model compensated by the above observer is changed from b_0 / s^2 to $b_0 / (s^2 + a_1 s + a_2)$.

Obviously, the system model of the improved compensation is closer to the ordinary second-order controlled object in our actual modeling. We can apply more known parameters to the controller, so that the total disturbance observation can be reduced. Reduce the burden on the observer and avoid the problem of saturation of the system.

The image is a simple second-order controlled object to perturb the signal, using two ESOs to compare the results of the total disturbance signal observation. From the image, we can clearly see that the improved ESO disturbance observations are much smaller than the ESO of the traditional structure, leaving a lot of room for the performance improvement of the controller.

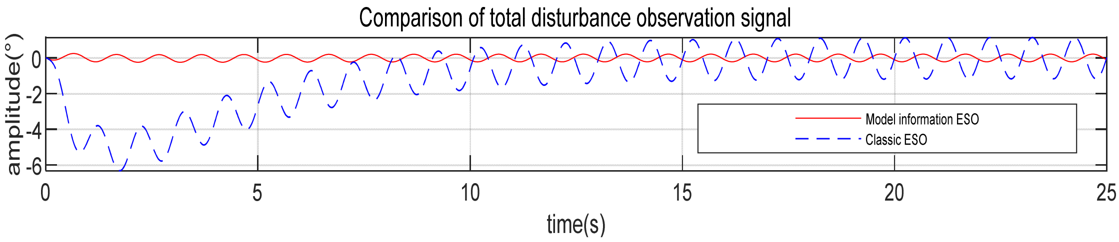

Figure 2. Comparison of disturbance observations between traditional ESO and improved ESO.

$$e_1 = z_1 - y, \dot{z}_1 = z_2 + \beta_{01}(y - z_1), \dot{z}_2 = z_3 + \beta_{02}(y - z_1) + b_0 u - a_1 z_2 - a_2 z_1, \dot{z}_3 = \beta_{03}(y - z_1) \quad (4)$$

2.1 Introducing Four Filter Methods to Improve LESO Parameter Tuning Method

The Bessel filter is a linear filter with a maximum flat linear phase response. The transfer function of the Bessel filter is $T_n(s) = B_n(0)/B_n(s)$,where $B_n(s)$ is Bessel polynomial, which can be obtained by a recursion formula, $B_0 = 1, B_1 = s+1$, and B_n can be written as $B_n = (2n-1)B_{n-1} + s^2 B_{n-2}$.

According to the pole configuration form we need, we choose the third-order Bessel low-pass filter. Its transfer function is in the Equation (5):

Therefore, according to the transfer function structure parameter comparison, the parameter formula of LESO can be obtained, $\beta_{01}=6\omega_q$, $\beta_{02}=15\omega_q{}^2, \beta_{03}=15\omega_q{}^3$.

The amplitude-frequency characteristic of the Chebyshev filter is $|Q(\omega)|=\sqrt{1/(1+\varepsilon^2 T_n^2(\omega/\omega_q))}$, ω_q is the cutoff frequency, ε is passband ripple factor, and n is filter order. $T_n(\omega)$ is Chebyshev polynomial, can be written as $\cos(n\cos^{-1}(\omega))$, when $|\omega| \le 1$,and $\cosh(n\cosh^{-1}(\omega))$,when $|\omega| > 1$.

Chebyshev polynomial is selected as 6 times. The specific form is $T_6(\omega) = 32\omega^6 - 48\omega^4 + 18\omega^2 - 1$

Take $\alpha_{\max}$ as 1, then bring it into amplitude-frequency characteristic equation, Solve the filter transfer function by writing a Matlab program.

So we can get the parameter expression of the filter in the Equation (6):

Therefore, according to the transfer function structure parameter comparison, the parameter formula of LESO can be obtained, $\beta_{01} = 0.98834\omega_q$, $\beta_{02} = 1.2384\omega_q^2$, $\beta_{03} = 0.49131\omega_q^3$.

The amplitude-frequency characteristic expression of the Butterworth filter is $Q(\omega) = \sqrt{1/(1+\left(j\omega/j\omega_q\right)^{2N}})$.

Under ideal conditions, meet the condition $(\omega/\omega_q) < 1$ in the passband, and so $(\omega/\omega_q)^{2N}$ decreasing gradually and gradually approaching 0 as N increases. Its amplitude squared function can be decomposed into 2N poles, and uniformly symmetrically distributed over the circumference of radius ω_q . We use a third-order Butterworth filter, considering the stability requirements of the system, so we only select the three poles of the left half plane. They can be written as $s_{p1} = \omega_q e^{j\frac{2}{3}\pi}, s_{p1} = -\omega_q, s_{p1} = \omega_q e^{-j\frac{2}{3}\pi}$

So after a simple transformation and comparison with (6), the relationship between the observer parameters and the set bandwidth can be obtained, $\beta_{01} = 2\omega_q$, $\beta_{02} = 2\omega_q^2$, $\beta_{03} = \omega_q^3$.

3 SIMULATION VERIFICATION

In this chapter, we model and simulate the above theory and method to verify the theoretical feasibility and effect, and combine the turntable motor to simulate and verify the performance after applying the new method.

We changed the LESO used in the simulation to an improved LESO which based on model information, and compared several of the above parameter adjustment methods to verify the performance of the observer under different filter design methods.

$$H(s) = 15/(s^3 + 6s^2 + 15s + 15) = Q(s) = (15\omega_q^3)/(s^3 + 6\omega_q s^2 + 15\omega_q^2 s + 15\omega_q^3) \quad (5)$$

$$Q(s) = 0.49131\omega_q^3 / (s^3 + 0.98834\omega_q s^2 + 1.2384\omega_q^2 s + 0.49131\omega_q^3) \quad (6)$$

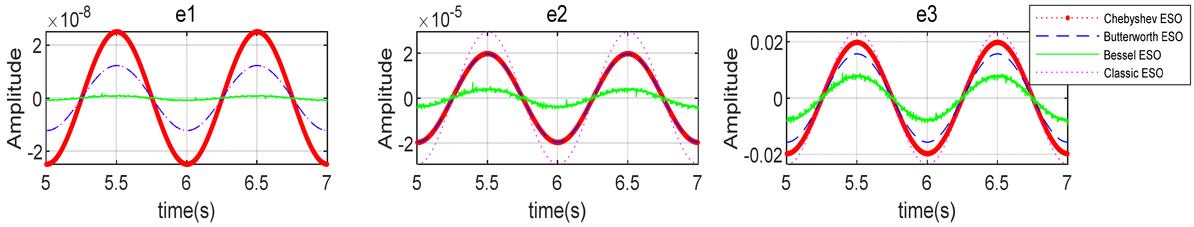

Figure 3. Comparison of classical bandwidth and Chebyshev filter ESO observation error.

Among the above simulation images, since these parameters tuning methods all depend on the given bandwidth parameters, we set it as 800 to facilitate the performance comparison of the observer. e_1, e_2, e_3 are the observation errors of x_1, x_2 and x_3 respectively. The observation value of e_3 is the error signal of the total disturbance, which is an important indicator for measuring the performance of the observer. It can be seen that under the method of using the Chebyshev filter, the observation error value of the total disturbance signal has reduced compared with the conventional bandwidth method. And these four LESO parameters are set in same bandwidth condition compared with each other. The decrease of the observation error value, which can help to improve system performance, and which result will be verified in subsequent simulations. We can see from the observation error signal curve that the LESO with Bessel filter equivalent parameter design has the highest observation accuracy, and its error value reduced by about 50%, compared with the classical bandwidth method and other filter equivalent parameter design methods.

At present, most of the turntable devices use permanent magnet synchronous motors as the actuator. Therefore, in order to verify the application effect of the above theory, we use permanent magnet synchronous motor as the controlled object. Its system block diagram is shown in Fig 4.

We take τ_e as 0.00391909482, τ_m as 0.98095377, K as 89.55074799.

In the simulation verification test, the parameters of the previous turntable are selected as the basic conditions, and the system is subjected to disturbance signals and dead zone characteristics. Dead zone characteristics are -10 N•m to +10 N•m. Rate perturbation and position perturbation are 50% of the input signal amplitude and frequency is 1rad/s.

We use the most common types of signals as inputs to simulate and verify the performance of the controller, including sinusoidal signals, step signals, and ramp signals.

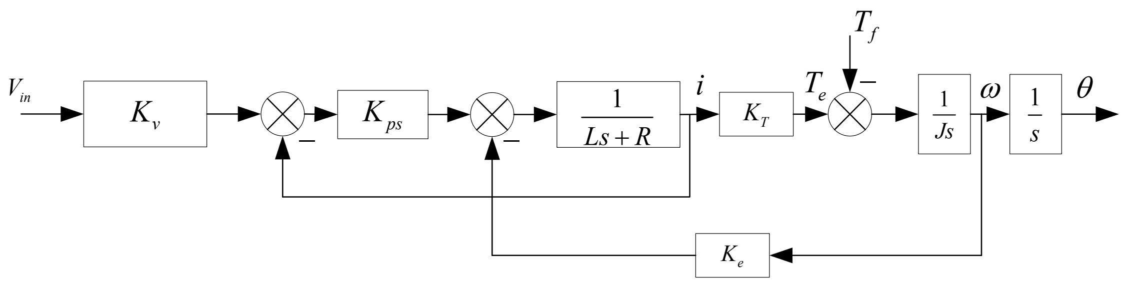

Figure 4. Turntable motor equivalent transfer function block diagram.

The equivalent transfer function can be written as:

$$G(s) = \theta(s) / R(s) = (1/s) \cdot (k_v k_{ps} / k_e) / (LJs^2 / k_T k_e + (k_{ps} + r)Js / k_T k_e + 1) \tag{7}$$

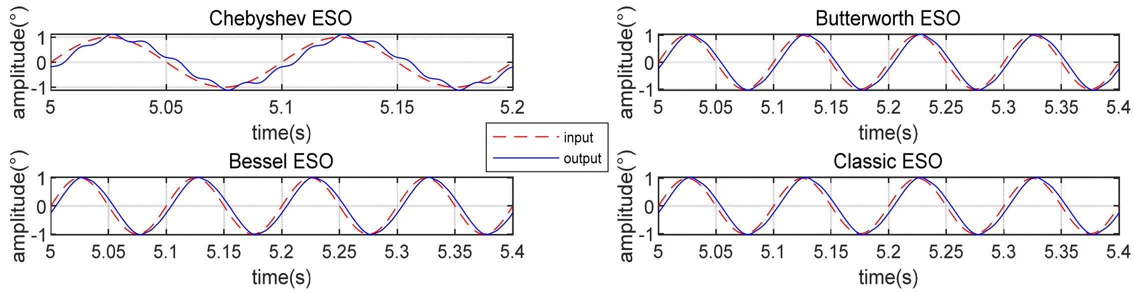

Figure 5. Comparison of 10Hz sinusoidal signal output under four methods.

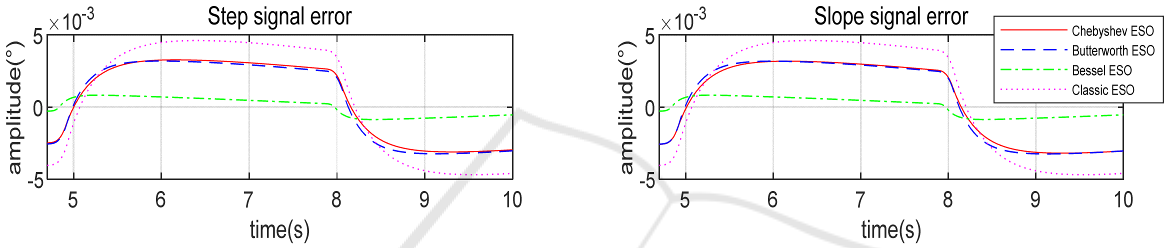

Figure 6. Comparison of output error under four methods.

We used a 10Hz sinusoidal signal as input to test the dynamic tracking performance of the system using different design methods. The standard phase error should not exceed 10ms, and the amplitude error should not exceed 10% of the input signal. Then, we can see the difference between the input and output amplitudes under the method of using the Chebyshev filter , its amplitude error is 0.138°, and its anti-disturbance capability is very bad, and the output signal has experienced drastic fluctuations, which cannot meet the indicator requirements. And the difference between the input and output amplitudes under the method of using the Butterworth filter is 0.035° and the phase difference is 3.491 ms. the difference between the input and output amplitudes under the method of using the Bessel filter is 0.033° and the phase difference is 2.405 ms.

Combined with the above results, we can get the conclusion, the Chebyshev filter method cannot make the system track the 10Hz sinusoidal signal, the Bessel filter method is the best, the Butterworth filter method is second, and the classical bandwidth method is third.

In the above step response test, we added a disturbance factor that can simulate the actual situation of the turntable motor system, such as the dead zone characteristics in the motor and the low frequency disturbance at the position output and speed output. Dead zone characteristics are -10 N•m to +10 N•m. Rate perturbation and position perturbation are 50% of the input signal amplitude and frequency is 1rad/s. It can be clearly seen that when the Bessel filter method is used, the steady-state error of the system is the smallest, the Butterworth filter method is second, the Chebyshev filter method is third, and the classic bandwidth method is the largestIf the accuracy of the system is high, we should use the Bessel filter method for LESO design. Similarly, we use the ramp signal as an input to test the system's minimum angular velocity and detect if the error meets the accuracy requirements. The ramp signal slope is 0.002° /s. From the results, the best is still Bessel method, the second is the Chebyshev, Butterworth. The classic bandwidth method has the largest steady-state error.

4 CONCLUSION

We propose the Bessel filter method, the Butterworth filter method, and the Chebyshev filter method. In the simulation results, we can find that among the above three design methods, the Bessel filter method shows good controller performance under various input signals. Among them, the Bessel filter design method has the best performance. In the future, in the design of the servo system controller, we can use the information of the controlled object model and several filter equivalent parameter design methods proposed in this paper to meet the increasing precision requirements. In the servo control system, if there is a high demand for accuracy and anti-disturbance capability, the parameter design method mentioned in this paper can be applied.

REFERENCES

GAO Zhiqiang. Scaling and bandwidth-parameterization controller-tuning [C] //Proceedings of the 2003 American Conference. Denver: IEEE, 2003, 6: 4989-4996.

Guozhang, Gao,Shipeng Zhang,Lan Gao. Research on excitation control system of marine brushless generator base on ADRC [J]. SHIP SCIENCE AND TECHNOLOGY, 2018, 40(21):116-120.

Jingqing Han. Active Disturbance Rejection Control Technology - Control Technique for Estimating Compensation Uncertain Factors [M]. National Defense Industry Press. 2009.

Jingqing Han. Active Disturbance Rejection Control Technology [J]. Frontier Science, 2007(01):24-31.

QIN Chang-mao, QI Nai-ming, ZHU Kai. Active disturbance rejection attitude control design for hypersonic vehicle [J]. Systems Engineering and Electronics, 2010, 33 (7): 1607-1610.

Wang Boyu. Intelligent Algorithm - Based Optimization Design and Application of Active Disturbance Rejection Controller [D]. Northeast Petroleum University, 2018.

Yao Xiaoyan. Research on design method of active disturbance rejection controller for electric load simulator [D]. Harbin Institute of Technology, 2018.