Design of the LADRC control system for gravimetric stabilisation platforms

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Abstract. Aiming at the problems of strong non-linearity of gravimeter stabilisation platform system, poor robustness of linear PID control algorithm and non-adaptive control system. This paper designs a LADRC-based gravimetric stabilisation platform control system design and method based on the research of PID controller and ADRC control method, and gives the anti-saturation and anti-noise design applicable to it, and the simulation experiment shows that the method is feasible.

1. Introduction

A high precision marine aviation gravimeter stabilisation platform can provide a high precision horizontal attitude for the gravimeter, ensuring that the gravimeter maintains a high precision vertical pointing under external interference, and is one of the most important instruments for reducing gravity measurement errors. The main factor that really affects the attitude accuracy of the gravimeter stabilisation platform is still the control accuracy of the control system. The appropriate control strategy and reasonable control parameters have a direct impact on the accuracy of the platform.

The gravimeter stabiliser is a very non-linear system due to the uncertainties in the mechanical resonance, electrical parameter fluctuations and torque coupled load variations. How to control the platform to the required accuracy with external disturbances and internal parameter uncertainties is one of the difficulties in the design of a stable platform control system.

Currently, the most common control strategy used by controllers within industrial control is still PID control. However, the PID control algorithm is essentially a linear control method with poor robustness. After a long period of operation of the gravimeter stabilisation platform, the system has time-varying uncertainty due to changes in the working environment and shifts in electrical parameters. When the platform parameters change, the PID requires the need to recalculate the calibrator control parameters and is not adaptive. Therefore, it is essential to find a control algorithm that can effectively suppress the controller's own internal disturbances while maintaining the accuracy of the gravimeter's level.

ADRC is a control method proposed by researcher Han Jingqing based on digital control technology¹, basically absorbing the advantages of PID controller, which has a wide application prospect in the industrial field. In recent years, with the continuous improvement of the theory of ADRC and the development of engineering applications, its influence has become more and more significant.

Despite the good control effect of the ADRC, there are too many adjustable parameters for the ADRC. In the case of a second-order controlled object, there are 11 variable parameters. Although
they can be adjusted by means of intelligent optimisation algorithms, in practice the parameters still need to be adjusted according to the actual situation, which is very unfavourable for engineering applications and is one of the reasons why ADRC has not been adopted in large numbers by industry. This is similar to the development of PID controllers, which were likewise not widely promoted until the ZN critical proportionality method was proposed. Professor Gao first proposed the concept of LADRC in 2006, converting ADRC\(^{[2-4]}\) from its original non-linear form to a linear form, with a large reduction in controller parameters and only two variable parameters remaining, driving the development of ADRC technology. Currently, most of the engineering applications of ADRC\(^{[5-17]}\) are based on the LADRC technique. The biggest difference between LADRC and ADRC is that all the non-linear parts of ADRC are simplified to a linear form. This approach greatly simplifies the structure of the ADRC, and due to the existence of ESO, the estimation of the non-linear part of the system can also be achieved, and in theory, the LADRC can achieve the same control effect of the ADRC. Therefore, this paper attempts to improve the gravimeter stabilised platform control system using the LADRC technique.

2. Design of Cascade ADRC Controller
A gravimeter stabilised platform is, in essence, a type of servo system\(^{[18]}\), so the control of the servo system is fully applicable to the stabilised platform, the working principle of which is shown in Figure 1.

![Fig. 1 Principle of control](image)

The structure of a double closed-loop PID control system, using the inner frame as an example, is shown in Figure 2.

![Fig. 2 Structure of control system](image)

Generally speaking, the control of a servo system consists of a current loop, a speed loop and a position loop, respectively, from the inside out. The current loop is built into the motor and is set by the manufacturer without the user's authority to modify it; the speed loop is used to quickly correct the influence of external disturbances on the attitude, speed up the control and reduce overshoot; the
position loop is used to improve the accuracy of the control, reduce the steady-state error and achieve a high precision control effect.

Gravimeter stabilisation platform model The ideal model of the controlled object is a servo system of second order. Similar to the PID control system, the traditional PID control method is improved using the LADRC technique and the improved model is shown in Figure 3.

Because the ideal model in the velocity loop is a second-order system, the velocity loop is controlled by second-order LADRC; the velocity loop as a whole is treated as a "black box", which can be approximated as a tracking system where the input equals the output, so the position loop is controlled by first-order LADRC.

The speed loop LESO and control rates are as follows:
\[
\begin{align*}
\dot{z}_1 &= z_2 + \beta_1 (y - z_1) \\
\dot{z}_2 &= z_3 + \beta_2 (y - z_1) + b_0 u \\
\dot{z}_3 &= \beta_3 (y - z_3) \\
u_0 &= K_p (r - z_1) - K_f z_2
\end{align*}
\]  

(1)

The position ring LESO and control rates are as follows:
\[
\begin{align*}
\dot{z}_1 &= z_2 + \beta_1 (y - z_1) + b_0 u \\
\dot{z}_2 &= \beta_2 (y - z_1) \\
u_0 &= K_p (r - z_1)
\end{align*}
\]  

(2)

This results in a first and second order LADRC tandem controller for the gravimeter stabilisation platform.

3. LADRC anti-saturation design
Input saturation must be taken into account in the design of the gravimetric stabiliser control system. As the effective operating voltage of the motor and power amplifier has a certain range, when the gravimeter stabilisation platform is faced with a large shock, the input control voltage may exceed the system's limit, which leads to a longer response time and affects the accuracy of the control system, defining this instability of the control system due to the physical constraints of the controlled system as the saturation of the controller. The most important cause of the saturation phenomenon is the actuator saturation limit, so the so-called anti-saturation design can not fundamentally solve the saturation problem of the control system, but only to alleviate it.

The saturation phenomenon can be seen as a non-linear problem of the system, and the LADRC control technique, despite being composed entirely of linear systems, is able to compensate for this non-linearity by observing it due to the presence of LESO. However, in the original design of the
LADRC control system, the response was extremely poor for the step response of the system, as shown in Figure 4.

![Fig. 4 Principle of control](image)

It can be seen that the control system does not form an effective control before the anti-saturation treatment is applied to the control system, and the control error dissipates more and more as time increases. As shown in Figure 5, analysis of the control system structure shows that it is precisely because the inputs to the LESO are not the real quantities entering the actuator that the control performance deteriorates.

![Fig. 5 First LADRC design](image)

Therefore, the anti-saturation design of the LADRC is completed by changing the input of the LESO to a real input, and the design results are shown in Figure 6.

![Fig. 6 Anti-saturation LADRC design](image)
The output after the anti-saturation design is shown in Figure 7. As can be seen, with the anti-saturation design, the system no longer oscillates and is able to follow the input signal better.

4. Noise-resistant design of LADRC based on improved TD

In practical control systems, due to various factors such as mechanical structures and electrical connections, random noise will inevitably exist during the propagation of the signal. Some studies have shown that the presence of system noise will have an impact on LESO and thus reduce the accuracy of LESO. Therefore, if the signal input to LESO can be de-noised, it can improve the control performance of LADRC to a great extent.

Firstly, one of the advantages of the cascaded LADRC design is that it can suppress noise very well, an effect achieved by using the LADRC's own characteristics. Assuming a random noise of 1 rad/s is added to the angular velocity, which, of course, would not actually exist, the step response of the system is shown in Figure 8. As can be seen, despite the addition of such a large amount of random noise to the angular velocity, the final step response of the system is still relatively good and the noise is effectively suppressed. However, the presence of noise reduces the accuracy of the LESO, as shown in Figure 9, where the control accuracy is significantly reduced by adding an external disturbance of 25°/s with a period of 10s to the system. Therefore, noise suppression is necessary.
TD is a good filtering tool that can effectively remove noise from the signal, and the filtering effect and tracking speed can be controlled by adjustable factors. This simplifies the ADRC design while taking advantage of the ADRC to optimise the control performance and accuracy of the LADRC. By adding a TD to the output of the angular velocity of the cascade LADRC, the improved control system structure is shown in Figure 10.

![Fig. 10 De-noising LADRC design](image)

While TD achieves the function of filtering, it brings some phase loss, and the better the filtering effect, the greater the phase loss. This phase loss is very detrimental to the control system and leads to a reduction in control accuracy, as shown in Figure 11, which compares the control accuracy with and without TD. As can be seen, the control system with TD not only fails to improve the control accuracy, but even decreases it, the reason for this is the phase loss. If this phase loss can be solved or mitigated on the basis of noise reduction, the control accuracy of the LADRC can be improved by TD.

![Fig. 11 Comparison of control precision in the disturbance of sine and impulse](image)
Noting that the most primitive purpose of TD is to extract the original and differential signals from the noise-containing signal, and that the differential signal has a certain predictive role, an appropriate predictive correction can be considered using the differential signal extracted by TD to obtain an improved algorithm for the tracking differentiator as follows.

\[
\begin{align*}
    x(k) &= x_0(k) + h_x(k+1) \\
    fst &= fst(x,(k) - x(k), x_2(k), r, h_0) \\
    x_1(k+1) &= x_1(k) + hx_2(k) \\
    x_2(k+1) &= x_2(k) + h \cdot fst
\end{align*}
\]  

(5)

where, \( h_1 \) is the prediction time, and extensive simulations have shown that \( h_1 \) a filter factor \( h_0 \) of 1 to 1.5 times is appropriate, with the maximum not exceeding 2 times. As shown in Fig. 12, the original signal in a sinusoidal signal containing noise is extracted with TD and modified TD, respectively. As can be seen from the partial enlargement on the right, the phase loss is significantly reduced with the improved tracking differentiator, verifying the effectiveness of the algorithm.

![Fig. 12 Comparison of control precision in the disturbance of sine and impulse](image)

(a) Overall view  
(b) Partial zoom

5. Conclusion

In this paper, the LADRC technique is applied to the control system of gravimeter stabilization platform for the problem of strong non-linearity, poor robustness of linear PID control algorithm, non-adaptive control system and too many ADRC rectification parameters, which is not conducive to engineering applications. The LADRC technology is used to apply to the control system of gravimeter stabilization platform, using LADRC technology to design a series-level controller for gravimeter stabilization platform; based on the actuator (motor and amplifier board), the LADRC anti-saturation function is designed; for the problem of noise in the system, TD is used for filtering to increase the observation accuracy of LESO; as TD filtering will bring phase loss and affect the control accuracy, the method of using TD's differential signal to compensate for the phase is designed.

Acknowledgments

This work was supported by National Natural Science Foundation (42176195) and National Natural Science Foundation (41804076). The authors would like to thank Zhang Cheng for excellent technical support and Professor Jiangning Xu for critically reviewing the manuscript.

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