Research of the feedforward control system of 3-axis stable platform based on disturbance observer

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ABSTRACT

In order to improve stability and capability of rejecting disturbance of the platform, the feedforward controller and disturbance observer (DOB) are used in angular loop of the 3-axis stabilized platform. This method can effectively avoid the conflict between stability and rapidity of system. Using the error signal as the evaluation index, the DOB can accurately track external disturbances, such as constant, periodic and random disturbance signal, eliminate model mismatches and improve the stability and robustness of the inner loop. Finally, the simulation result shows that the composite control method has better dynamic performance and smaller steady-state error than cascade lead-lag compensation.

KEYWORDS

DOB; PID; cascade lead-lag; feedforward controller; stabilized platform

1. Introduction

With the development of gyro stabilization technology (Krasnov, Odintsov, & Semenov, 2010), the stabilized platform has been widely used in the diverse fields, such as vehicle-borne, ship-borne, airborne and missile-loaded etc. Simultaneously, the requirements about static and dynamic performances of stabilized platform have become increasingly strict. For instance, in order to achieve the line of sight with the desired attitude, the carrier is required uniform motion when taking pictures. However, the carrier is unavoidably subjected to irregular, vibration and swing movement in the real terrain. Although the stable platform can effectively isolate the carrier motion, the platform is a non-linear complex control system with the mechanical structure, which would be impacted on a variety of disturbance. Therefore, with the improvement of the stability and rapidity requirements of the system, the mechanical structure and control method of the stable platform are gradually improved.

The high-performance of robust and anti-jamming control strategy was the eternal topic in control field. In some paper, a large number of methods to strength the error precision have been given. A feedforward observer to estimate the disturbance torque to enhance the stability of the system was used by the literature (Fang, Qi, & Zhong, 2010), but the method ignores the secondary perturbation. In the literature (Senevirathne, Abeykoon, & Pillai, 2016), based on the feedforward control of the disturbance model of the velocity loop, the stability and rapidity of the system is improved and the secondary disturbance is suppressed to some extent. In paper (Zhou & Jia, 2016) adopts fuzzy/PID composite control enhances system response tracking performance. The literature (Zhou & Zhao, 2013) adopts the method of using double speed loops to weaken the system internal imbalance, friction and external disturbance, which has greatly improved the stability of the platform. However, although double speed loop has good suppression of low-frequency disturbance, it is not sensitive to high-frequency disturbance. And paper (Gao, Shao, & Yang, 2014) uses compound control Auto-Disturbance Rejection Controller (ADRC), which has excellent capability in disturbance rejection, but ESO can’t estimate the aperiodic trend of error very well. In the literature (Zhou, Jia, Zhao, & Cai, 2016), by using the dual-rate-loop control method based on DOB of angular acceleration of the 3-axis system, the control system effectively suppress imbalances and frictional moments, and then the method could enhance not only the moment rigidity but immunity ability of the stable platform.

Observer-based control is an effective anti-interference control theory. This paper presents a feedforward control system based on DOB in speed control loop for a kind of 3-axis stable platform. By using DOB, the disturbance and mismatch of the model are eliminated. Furthermore, partly compensation methods are designed in the control system to predict the target position and compensate...
dynamic delay of system. By using the two methods in the compound feedforward control system, the accuracy and response speed of the stable platform are both improved.

2. System description

The basic structure model of the 3-axis platform is shown in Figure 1. Generally, the 3-axis platform consists of three gimbals, they are pitch gimbal (f), roll gimbal (r) and azimuth gimbal (a), their sensitive axes are orthogonal to each other. Mr, Mf, and Ma, respectively, represent torque of the motor which drives r-gimbal, p-gimbal and a-gimbal, their work is to keep platform steady when the platform rotates or jitters. Gx, Gy, and Gz, respectively, represent the rate gyro that is used to measure angular rate of 3-axis gimbal. The orientation forms of the platform is set as three coordinate system \( x_a y_a z_a \) (Qin, 2006). Distributing and amplifying output of Gx, Gy, Gz gyroses then fed it into Mr, Mf, Ma to control the corresponding angular motion of frame.

A certain vehicle is used as a carrier for stable platform. Based on the movement rule of the carrier, the pitching frame of this stable platform is considered as the main research object. And the stable ring of system is regarded as the start for our study. As shown in Figure 1, the roll frame is used as a platform of stable platform. When the platform is affected by the \( M_d \), an external interference in the opposite direction of the stabilization axis \( y_r \), the platform will generate a deflection angle \( \theta \), then gyro will detect the rotation angle of platform, and output a opposite angle \( \alpha \). After that the signal detector will convert \( \alpha \) into a voltage signal, feeding it into the torque device after amplification. The torque motor will produce the opposite servo torque, finally, the platform turn to the opposite direction. At the moment, the rotational speed of gyroscope outer frame is \( \omega_iG \), and the gyro moment is \( M_g \).

\[
\omega_iG = \dot{\alpha} + \dot{\theta} \\
M_g = H(\dot{\alpha} + \dot{\theta}) \\
H(\dot{\alpha} + \dot{\theta}) = -M_{cmd} = k_T k_{io} \omega_{cmd} 
\]

When \( M_g = -M_{cmd} \), the gyro will stop moving forward, that is, when \( \dot{\alpha} = 0 \), the system will reach stabilization.

\[
H\dot{\theta} = k_T k_{io} \omega_{cmd} \\
\dot{\theta} = \omega_{cmd} k_T k_{io} / H
\]

When \( k_T k_{io} / H = 1 \), the output angle of the platform is equal to the command angle, then the system performs the tracking function.

\[
\dot{\theta} = \omega_{cmd}
\]

3. System of composite control strategy

3.1. The three-loop compound method

The conventional three-closed-loop compound control system of three-axis stabilized platform is illustrated in Figure 2, it consist of a current loop, a stabilization loop and a position loop, which respectively adopt PID, PI, and P control. In the process of analysis, the couplings among frames are ignored, and the control structures of three subsystems are basically same. Therefore, the pitching frame is taken as an example to analyse and study the system performance. The detection of current loop refers to the examination of Hall elements installed inside the
drive. The rate gyroscope, which is taken as a feedback element for the stable loop, mainly applies to the isolation of carrier’s disturbance and the command of tracking loop output. The tracking loop adopts high-precision rotary transformer as feedback element. This paper uses the literature’s (Li & Zhong, 2011) three-loop compound PID control method to calculate the relevant parameters of its current loop, stable loop, and tracking loop. And the computation process is no longer repeated here.

As Figure 2 shows, $\theta_{in}$ and $\theta_{out}$ represent a system input command of angular and output angular, respectively. $\omega_{in}$ and $\omega_{out}$ symbolize the system input of angular rate and output angular rate, respectively. C-pos, C-spe and C-cur refer to tracking loop controller, stable loop controller and current loop controller respectively. $K_{PWM}$, $K_{e\omega}$, and $M_d$ represent the power amplification coefficient, motor MEF and disturbance torques respectively.

In actual operation, the situation of platform will be affected by a variety of factors, such as comprising vibration, carrier motion and other uncertain factors. In addition, during the long-term of using the platform, changes in the parameters of the stable platform system will be influenced by loads, operating environment and parts wear and so on, which have impact on parameters of the system controller (Ji, Li, Xu, Zhao, & Fang, 2011). In order to enhance the stability and rapidity of the system, the disturbance observer is used to eliminate interference. Meanwhile, the feedforward controller is added in speed loop.

### 3.2. Disturbance observer (DOB)

DOB is the most effective method to improve robustness of system on account of its simple control structure (Hirata & Murakami, 2014). The basic principle of it is to make the controlled object as a non-perturbed and non-disturbing nominal model, by introducing corresponding compensation for the model error, parameter perturbation and all other kinds of external disturbances (Yun, 2012). Firstly, according to the principle, the disturbance signal estimation has been obtained from the input and feedback signal of the system, and then it is added to the control terminal to eliminate disturbance. The low pass filter $Q(s)$ to the observed signal is added. Figure 3 shows the equivalent schematic diagram of DOB, $u$ presents the output of the PID controller, $d$ and $\xi$ present the disturbance torque and measurement noise respectively. $G_p(s)$ is the transfer function of the controlled object and $G_n(s)$ is reference model, $Q(s)$ is low pass filter of DOB.

The system transfer function is described by Figure 3, $y$ present the output of the system, its value is gained by Equation (9).

$$
y = \frac{G_p G_n}{G_n + (G_p - G_n) Q} u - \frac{G_p G_n (1 - Q)}{G_n + (G_p - G_n) Q} d - \frac{G_p G_n Q}{G_n + (G_p - G_n) Q} \xi \tag{9}
$$

When the controlled object is equivalent to the nominal model, the system output is gained by Equation (10).

$$
y = G_n(s) u - Q(s) \xi - G_n(s) (1 - Q(s)) d \tag{10}
$$

It is can be seen from above the equations, when the amplitudes of $1 - Q(s)$ and $Q(s)$ are designed as small as possible, and the last two terms of Equation (10) can be approximated to zero, then, the overall system performance is not affected by interferences and measurement noise.
Theoretically speaking, the higher orders of \( Q(s) \) is, the higher of the bandwidth will be, and it will be more sensitive to the disturbance, the observer will respond swiftly, and the effect of disturbance was restrained better. But, if the order is too high, it will result in underdamping, and even can make the system being unstable (Xiao, Wu, & Liu, 2013). Meanwhile, \( Q(s) \) is the key for the proposed DOB to accurately estimate the disturbance. Firstly, the design of \( Q(s) \) comply with the \( Q(s)G_n^{-1}(s) \) regularity, that is, the relative order of \( Q(s) \) should not be smaller than the order of \( G_n(s) \). Secondly, the bandwidth design of \( Q(s) \) should both consider the robustness of system and its ability to suppress interference.

The nominal model of \( G_p(s) \) is \( G_n(s) \), and the uncertainty of \( G_n(s) \) can be described with perturbation \( \Delta(s) \), i.e.

\[
G_p(s) = G_n(s)(1 - \Delta(s))
\]

\(
G_p(s) = \frac{1}{Js^2 + bs} = \frac{1}{(J_n + \Delta J)s^2 + (b_n + \Delta b)s}
\) (12)

In Equation (12) \( J_n \) is the equivalent moment and \( b_n \) is the equivalent underdamping coefficient. \( \Delta J \) and \( \Delta b \) are their estimation errors, and \( G_n(s) \) is given by

\[
G_n(s) = \frac{1}{J_n s^2 + b_n s}
\]

In accordance with the robust stability theory, the robust stability of the DOB sufficient condition for \( Q(s) \) is described as Equation (14).

\[
||Q(s)\Delta(s)|| \leq 1
\]

\( Q(s) \) is as the classical filter binomial coefficient type, and its form is shown as Equation (15).

\[
Q(s) = \left( 1 + \sum_{k=1}^{N-r} a_k(\tau s)^k \right)^{-1}
\]

(15)

In Equation (15), \( N \) is the order of \( Q(s) \), \( \tau \) is filter time constant, and \( r \) is the relative order of the filter. Here, let \( N = 3 \), then \( Q(s) \) is gained by Equation (16).

\[
Q(s) = \frac{3\tau s + 1}{\tau^2 s^2 + 3\tau^2 s^2 + 3\tau s + 1}
\]

(16)

The Bode diagrams of \( Q(s) \) and \( 1-Q(s) \) shows as Figure 4.

As shown in Figure 4, the condition of \( Q(s) = 1 \) and \( Q(s) = 0 \) has been reached in the low-frequency band and the high-frequency band, respectively.

Figure 5. Block diagram of feedforward control.
3.3. Feedforward controller design

The introduction of the feedforward is able to enhance the corresponding tracking characteristics of the system and have a considerable effect on suppressing the external disturbance torque of the system. The principle is illustrated in Figure 5.

As is shown in Figure 5, the system output is described by Equation (17).

\[ C(s) = \frac{[G_1(s) + G_N(s)]G_2(s)}{1 + G_1(s)G_2(s)} R(s) \]  

(17)

The equivalent system error transfer function is described by Equation (18).

\[ \Phi_e(s) = \frac{1 - G_N(s)G_2(s)}{1 + G_1(s)G_2(s)} \]  

(18)

When \( G_N(s) = 1/G_2(s) \), \( \Phi_e(s) = 0 \), compound control makes full compensation for the error. In practice, the number of denominator times of \( G_2(s) \) is higher than or equal to a numerator (Hu, 2006). Hence, it is difficult to achieve full compensation. This article uses partial compensation methods to design \( G_N(s) \). Since the high-order differential exists in the compensation process and the approximate compensation controller will bring about under compensation, the DOB is applied to observe and compensate the disturbance torque.

4. Simulation analyses

The structural diagram of the composite control system is shown in Figure 6. The simulation model of a composite

![Figure 6. Simulation model of control system model.](image)

![Figure 7. Sinusoidal response curve.](image)
control system is constructed by DOB and P controller of current loop and fed-controller of stabilization loop.

The current regulator adopts proportional control, and the control parameter is $k_{ip}$. The stable loop adopts PI correction whose proportion parameter is $k_{ωp}$ and the integral constant is $τ_{ωp}$. Position loop adopts P adjustment, and the proportion parameter is $k_{θp}$. Let $τ = 0.001$, other parameters list in Table 1.

According to the sinusoidal response test shown in Figure 6, the input sinusoidal signal $R(t) = \sin(2t)$, and the disturbance signal amplitude $d(t) = 3\sin(5t)$. The response curves of system are shown in Figure 7.

In Figure 7, Input, a, b symbolize the systematic sine input signal, the traditional cascade lead-lag compensation sine response curves, the composite sine response curves based on the DOB feedforward control respectively. Figure 7 shows that the nominal model is not able to completely contain the actual model, then the system is not able to completely suppress the disturbance. Therefore, the feedforward controller is introduced to further compensate the system disturbance.

Figure 8. DOB periodic disturbance.

Figure 9. Error of periodic disturbance.
In Figure 8, the input and the output stand for disturbance signal, the observer’s output signal respectively. It can be seen that the output of observer is exactly the same as the practical disturbance.

In Figure 9(a,b) stand for the error of traditional cascade lead-lag control response curves and the error of composite response curves based on DOB feedforward control respectively. Figure 9 illustrates that the cascade lead-lag control error is close to 0.326, and the feedforward compound control error based on DOB is 0.061, it is obviously that the control accuracy is improved.

The step response curve of the system is shown in Figure 10. The disturbance is a constant perturbation signal and the amplitude is 3.

In Figure 10, the Input, a,b are the systematic step input signal, the traditional cascade lead-lag compensation step response curves and the step response curves based on the DOB feedforward control, respectively. The feed-forward compound control based on DOB has

**Table 2.** Setting time schedule for 2% error band under unit step signal.

| Levelling control system | Cascade lead-lag | Composite control |
|--------------------------|------------------|-------------------|
| Pitch gimbal             | 5.8              | 0.25              |

**Figure 10.** Step response curve.

**Figure 11.** Observation results of external random signal.
significantly better response speed and stability accuracy than the first one. As is listed in Table 2, the setting time ($t_s$) of the system under constant perturbations is also considerably reduced.

The sinusoidal response of the random disturbance with an input variance of 5 is shown in Figures 11 and 12. Figures 8 and 11 show that the observer accurately observes the disturbance of external random signal and sinusoidal signal.

In Figure 12, the Input, a and b symbolize the systematic sine input signal, the traditional cascade lead-lag control response curves and the composite response curves based on the DOB feedforward control, respectively. Figure 12 proves that the feedforward compound control method of DOB is much stronger than conventional cascade lead-lag control method in suppressing random signal.

Figures 8 and 11 verify the effectiveness of observer to observe the different disturbance signal. Figure 7, Figure 9, Figure 10 and Figure 12 verify the ability of the latter control method to suppress various disturbance signal, and verify the robustness and rapidity of the compound control based on DOB. This will provide references for other studying of the robustness of stabilized platform.

5. Conclusion

A feed forward compound control method is applied in this paper, it is based on DOB for a three-axis stabilized platform. By studying the system model, the low-pass filter $Q(s)$ of the DOB is analysed and designed, and a system simulation model is established.

The simulation results illustrate that the method can fully observe the external disturbances, compensate for the mismatch of the nominal model and the actual model. Ultimately, both error accuracy and system response speed have been improved.

Disclosure statement

No potential conflict of interest was reported by the authors.

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