Attitude control of short-range loitering missile based on ADRC

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Abstract. ADRC (ADRC) has excellent control performance. The paper Introduces structure and discrete algorithms of the ADRC, and describes its parameter tuning rule. The ADRC control technology is applied to attitude control system design of short-range loitering missile, from the perspective of engineering applications, proposing a design method of ADRC attitude controller, specifically addressing the principle of the method and process. Simulation results show that this method has strong robustness and adaptability, strong dynamic performance and stable performance.

Introduction

The short-range loitering missile is product of the combination between UAV technology and precision-guided munitions technology, playing the more and more important roles in modern warfare, is an indispensable and important part of the current international advanced weaponry. As the core content of short-range loitering missile control system design, study of attitude control system has been a hot topic, and various control methods with their own strengths and weaknesses. Taking the short-range loitering missile for the study, the paper uses ADRC proposed and promoted by the Professor Han Jingqing. AS for Uncertain inside and outside interference, ADRC control system has strong adaptability and robustness[1][2]. By comparing the design results of ADRC control technology with the design results classic PID control design, it is proved that compared to the classical PID technology, ADRC control technology has a small overshoot, high precision, adaptability and robustness, etc. advantages. The significance of this study is to provide practical control system design for the short-range loitering missile attitude control.

ADRC theory

1) Structure and discrete algorithms of ADRC

ADRC is a non-linear controller consisting of tracking-differentiator (TD), extended state observer (ESO) and non-linear error feedback control law (NLSEF) [3]. TD arrange the transition process to track the input signal and its derivative; ESO fed back output signal and differentials of controlled object and they do differential operation; the non-linear combination control of the error-feedback value is finished in NLSEF, its output and the ESO total amount of disturbance compensate for the control, and the control signal effect act on the accused object finally. The second-order ADRC structure diagram show in Figure 1.

Fig.1 Block dianram of a second order ADRC

ADRC absorbed the essence of classic PID controller regulating by feedback error, drawing on the idea of state observer and using nonlinear combinations to construct new controller. It overcomes weakness that the traditional PID controllers are typically unable to obtain a differential signal, using tracking - differentiator to track the input signal and its differential signal, using state observer tracking output signal and its differential signal. It is the core of ADRC that the no modeling system dynamic and unknown external disturbance effects are attributed to the “general disturbance” of system to estimate and compensate, so it is not totally dependent on the controlled object mathematical model. Here are second-order ADRC common discrete control algorithm.

2) Tracking - differentiator (TD)

$$\begin{cases} x_1(k+1) = x_1(k) + h \cdot x_2(k) \\ x_2(k+1) = x_1(k) + h \cdot fst[x_1(k), x_2(k), v(k), r, h] \end{cases} \quad (1)$$

In the type:

$$fst = \begin{cases} -r \cdot sign(a) & |a| > \delta \\ -r \cdot \frac{a}{\delta} & |a| \leq \delta \end{cases} \quad \delta = r \cdot h$$

$$a = \begin{cases} x_2(k) + \frac{a_0 - \delta}{2} \cdot sign[y(k)] & |y(k)| > \delta_0 \\ x_2(k) + h \cdot y(k) & |y(k)| \leq \delta_0 \end{cases} \quad \delta_0 = \delta \cdot h.$$

$$y(k) = x_1(k) - v(k) + h \cdot x_2(k)$$

$$a_0 = \sqrt{\delta^2 + 8r \cdot |y(k)|}$$

Where: h is the integration step (filtering parameters); r determine tracking speed; *fst* is discrete-time system optimization functions.

3) ESO

$$\begin{cases} e(k) = z_1(k) - y(k) \\ z_1(k+1) = z_1(k) + T \cdot [z_2(k) - \beta_{01} \cdot e(k)] \\ z_2(k+1) = z_2(k) + T \cdot [z_3(k) - \beta_{02} \cdot fal(e(k), a_1, \delta_1) + b \cdot u(k)] \\ z_3(k+1) = z_3(k) - T \cdot \beta_{03} \cdot fal(e(k), a_2, \delta_1) \end{cases} \quad (2)$$

Where: $z_1(k)$, $z_2(k)$, respectively, the estimated state variables of object given; $z_3(k)$ is the real-time effect sum of all estimated object the uncertainty models and the external disturbance, $z_3(k) \rightarrow f(x_1, x_2, k) + w(k)$, $f(x_1, x_2, k)$ is system unmodeled dynamics quantity, $w(k)$ is unknown external perturbation.

4) NLSEF

$$\begin{cases} e_1(k) = x_1(k) - z_1(k) \\ e_2(k) = x_2(k) - z_2(k) \\ u_1(k) = \beta_1 \cdot fal(e_1(k), a_3, \delta_2) + \beta_2 \cdot fal(e_2(k), a_4, \delta_2) \\ u(k) = u_1(k) - \frac{z_3(k)}{b} \end{cases} \quad (3)$$

Where: $x_1(k)$, $x_2(k)$, respectively, the output and the differential of the transition process arranged by TD; $z_1(k)$, $z_2(k)$, $z_3(k)$, respectively, state variable of the control object by ESO ; $z_3(k)/b$ to compensate for disturbance effects.

In (2) and (3) , the $fal()$ expression function is

$$fal(e, a, \delta) = \begin{cases} \frac{e}{\delta^{a-1}} & |e| \leq \delta \\ |e|^a \cdot sign(e) & |e| > \delta \end{cases} \quad \delta > 0 \quad (4)$$

Where: e is the error value; δ , and α are corresponding ADRC parameters.

ADRC application in attitude control

1) Pitch channel transfer function

In order to make the elastomer be used as a part of the dynamic characteristics analysis, it is necessary to find an operating mechanism deflection (pneumatic rudder deflection or inference vector direction change) as input, the attitude motion parameters is the transfer function of the output[4]. On the condition of Loitering Missile movement model small perturbation assume, on the basis of the linear and curing coefficient, the perturbation equations of motion is made Laplace transform operation, the transfer function of projectile motion. Because this elastomer is axisymmetric, aerodynamic parameters of pitching and yawing motion is unanimously, so just considering one channel.

During loitering missile flight, with the change of flight speed, flight altitude, loitering missile physical heart and elastomer pressure centers, other factors and the impact of the external environment, flight dynamics elastomers also changed greatly. To make the system stable and dynamic characteristics meet the given requirements, the design of the control system of the missile has been put forward higher requirements. The traditional PID control can't meet the requirements. Elastomer longitudinal short period simplify the equations of motion are:

$$\begin{cases} \frac{d^2\Theta}{dt^2} + \frac{d\Theta}{dt} + a_1\alpha = -a_2\delta_z \\ \frac{d\Theta}{dt} - a_3\alpha = a_4\delta_z, \Theta = \theta + \alpha \end{cases} \quad (5)$$

Wherein Θ , θ , α , δ_z respectively missile attitude angle, trajectory angle, angle of attack and elevator angle. $a_1 \sim a_4$ is the power coefficient of elastomers. They are time-varying parameters. Mading Laplace transform for the above formula , elastomer longitudinal motion mathematical model is available.as it is that:

$$W_{\delta_z}^{\Theta} = \frac{K_1(T_1s+1)}{s(T^2s^2+2\xi Ts+1)} \quad (6)$$

Wherein, K_1 , T_1 , T , ξ are function of elastomers power factor $a_1 \sim a_4$, respectively, amplification factor, time constant, elastomers short cycle time constant and damping elastomer. In addition, taking into account the impact of various uncertain factors during loitering missile flight, this model is an imprecise process variable parameters.

2) ADRC parameters

ADRC control performance depends on selecting parameters, once the parameters selected, within a certain range, control performance of the actual object would not be affect[5]. The main parameters of the ADRC include TD's r , h ; ESO's $\{\alpha_1, \alpha_2, \beta_{01}, \beta_{02}, \beta_{03}, \delta_1\}$; NLSEF's parameters $\{\alpha_3, \alpha_4, \beta_1, \beta_2, \delta_0\}$.

TD need to be adjusted are tracking speed factor r and simulation step, the filter parameters h . The main parameters affecting TD is r , the greater the r , faster system response, but also increase the overshoot; h bigger, better filtering effect. But r and h is a contradiction, so the two need coordination.

Main adjustment parameters of ESO is $\{\alpha_1, \alpha_2, \beta_{01}, \beta_{02}, \beta_{03}, \delta_1\}$, wherein, $\beta_{01}, \beta_{02}, \beta_{03}$ the three parameters are the main parameters affecting the dynamic behavior of the closed loop system. First adjusting the parameters of the ESO need ensure that ESO could accurate track object state firstly, then further adjustments based on the overall control effect, Adjusting Appropriately β_{03} small

could make output curve of larger oscillation decrease. α mainly determinants of nonlinear situation, appropriate adjustments α , will greatly change the control effect. δ determines the size of the linear range of fal function. Generally, fixed values were taken at 0.5 and 0.25, a value of 0.01.

NLSEF needs adjust parameters $\{\alpha_3, \alpha_4, \beta_1, \beta_2, \delta_0\}$, however, α_3 usually value of 0.5 or 0.75, α_4 value of 1.25 or 1.5, δ_0 value of h, generally taken to be 0.01, the actual parameters require frequent adjustment on the left β_1 and β_2 . NLSEF parameters β_2 and β_1 are the equivalent of the PD controller proportional gain and differential gain, its setting is also similar to the PD controller. Increasing β_1 can effectively reduce the system static error and improve tracking accuracy, but it is possible to make the system dynamic performance deteriorates, causing the system oscillation even unstable. Increasing β_2 improves tracking accuracy in a certain extent, faster response speed of the system, thereby improving the dynamic performance of the system. In the choice of parameters, it is necessary to adjust the overall control effectiveness association set and two arguments.

Simulation

1) Stability Analysis

During the step response of the control system and stability analysis, assuming flying height $h = 300\text{m}$, flight speed $v = 35\text{m/s}$, patrol missile mass $m = 8.5\text{kg}$, given this time pitching the channel step response and the closed-loop characteristic root distribution, and thus determine the closed loop system stability of the corresponding channel, drawing the open-loop frequency characteristics of each channel, Solving stability margin[6][7]. The study found that setting the parameters r , h , α_1 , α_2 , α_3 , α_4 , δ_0 , δ_1 , etc. wouldn't have large influence on dynamic performance of the control system[8]. ADRC control parameters in the following table 1.

Table 1 Parameter setting of ADRC

TD	ESO	NLSEF
$r=10$	$\alpha_1 = 0.5$	$\alpha_3 = 0.5(0.75)$
$H=0.1$	$\alpha_2 = 0.25$	$\alpha_4 = 1.5(1.2)$
	$\beta_{01} = 80$	$\delta_0 = 0.1$
	$\beta_{02} = 250$	$\beta_1 = 15$
	$\beta_{03} = 1.8$	$\beta_2 = 15$
	$\delta_1 = 0.01$	

Given the step response curves of pitch channel in Figure 2. By comparing the PID control and ADRC at the unit step input signal, achieving 98% of stable value as the end of the transition process, the ADRC at $t = 2.8\text{s}$ end the transition process, and the end of the transition process PID control is nearly $t = 9.8\text{s}$; ADRC control is without overshoot, and PID control is with overshoot at about 8%.

Fig 2 The pitch channel response curve

Then computing system closed loop characteristic root distribution, the five characteristic root are: -35 , $-0.5126 + 3.8649i$, $-0.5126 - 3.8649i$, $-0.5126 + 3.8649i$, $-0.5126 - 3.8649i$. Apparent to all real closed loop eigenvalues are negative, indicating that the closed-loop system is stable. Open loop frequency characteristics (Bode diagram omitted) amplitude margin of inf, phase margin is 63.5° ; cut frequency of 24rad/s .

By comparing open-loop frequency characteristics of ADRC and PID control it is relatively visible that ADRC frequency domain to be significantly better than PID control[9].

2) Analysis of disturbance rejection

When verifying interference inhibition of ADRC, at $t=15s$ add external interference role amplitude $0.2nm$, a pulse width of the $5s$, PID control and response ADRC in Figure 3.

Fig 3 The experimental results

Seen from the figure, subjected to external interference the ADRC has strong immunity, but the ability of PID control in such a disturbance, the system of rapid change, far less disturbance rejection control ADRC. The parameters of the system within a certain range, observe PID control systems and self-control system in response to the discovery of immunity, ADRC can adapt to a wide range of parameter changes, and PID control can only adapt within a small range, changes slightly the system unstable.

Conclusion

ADRC attitude controller than conventional PID controller is robust attitude and adaptability, better interference suppression and vibration suppression, a higher precision attitude control and posture stability, there is a faster response speed and smaller overshoot. Simulation results show that the ADRC performance was significantly better than conventional PID attitude controller.

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