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ON ACTIVE DISTURBANCE REJECTION BASED FRAMEWORK FOR FLIGHT CONTROL: PRINCIPLE AND APPLICATIONS

M. Sun[1], Z. Gao[2], S. Du[3], and Z. Chen[1]

[1]Department of Automation and Intelligent Science, Nankai University
Tianjin 300350, China

[2]Center for Advanced Control Technologies
Cleveland State University
Cleveland, OH, USA

[3]Department of Mechanical Engineering
Tshwane University of Technology
Pretoria 0001, South Africa

Active Disturbance Rejection Control (ADRC) offers a viable framework for flight control that both inherits what is right about proportional-integral-derivative (PID) controllers that makes it a long lasting industrial solution and addresses its weaknesses. Building on this foundation, ADRC as a way of thinking and a methodology can be understood and accepted by practicing engineers. Several flight control applications are used to show flexibility and applicability of the proposed framework in tackling diverse problems in flight control. It appears that such a solution is simple to understand, easy to implement, and convenient to tune, thus making it highly user friendly and effective.

1 INTRODUCTION

Although considerable progress has been achieved in the realm of flight control in academia during the past several decades, especially after the emergence of modern model based control and intelligent control [1], PID controllers and lead-lag compensators still play dominant roles in practice since their structures are simple and their principles are easier to understand than most of other advanced controllers [2]. The standard flight control design procedure includes linearizing the flight dynamics around its trimming points based on the small perturbation assumption and then providing a fixed parameter controller according to the classical control theory. If the flight vehicle works within a rather wide envelope, this task becomes very complicated and time-consuming:

(1) dozens of operating points should be selected carefully to cover the full envelope as sufficient as possible;

(2) one fixed parameter controller with specified structure should be designed for each operating point; and

(3) the resultant controllers should be synthesized using the interpolation approach in high dimensions.

Moreover, the design process depends on the trial-and-error method and also on the expertise of the designer. Hence, the research and development (R&D) cost as well as cycle are both increasing but the reliability is decreasing. For many low-cost flight vehicles such as unmanned aerovehicles (UAV), the routine design procedure can affect their competitiveness or survivability. A fast and economical control design method is desired for flight vehicles.

Nowadays, nonlinear and robust control methods are the main techniques to address the crucial challenges of control of flight vehicles with large modeling uncertainties, strong nonlinearity, and fast time-varying dynamics [3]. Among these control methods, the feedback linearization technique based on dynamic inversion (DI) is most popular [4–7], where an inner-loop nonlinear control law is designed to partially or totally convert the flight vehicle nonlinear dynamics to a controllable chain of integrators. However, it is well-known that DI is sensitive to the modeling errors [8] because an almost exact mathematical model of the flight vehicle is needed to undergo cancelling operation and the aerodynamic data processing is a quite time-consuming procedure, which includes the interpolation of a complete set of aerodynamic coefficients and derivative tables [4], the curve fitting using the influence functions [5, 6] or neural networks (NN) [7], and so on. In practice, a model-free framework for the DI strategy is urgently needed.

Based on the feedback linearization approach, Han [9] proposed a novel philosophy — ADRC, a disturbance observer based control (DOBC) method, which does not rely on a refined dynamic model, after many years of continuous development. Active Disturbance Rejection Control has demonstrated its effectiveness in many fields [10–22]. In 2014, two review papers on ADRC were published in a special issue of *ISA Transactions* [23, 24]. Up to now, there are many Chinese scholars that are active in investigating and applying ADRC in extensive range of areas. Besides Chinese researchers, several groups outside China have also attained remarkable achievements in application of ADRC, such as Poznan University of Technology in Poland [25], CINVESTAV in Mexico [26–28], Defence Institute of Advanced Technology of India [29–34], and others. In the field of flight control, Huang *et al.* [35] proposed a decoupling control scheme based on ADRC to deal with the initial turning problem for a vertical launching air-defense missile. Such papers relating to flight control also include [17] the extensive investigations conducted by Talole group in India [29–33]. On the other hand, a considerable progress has been achieved in recent years for the closed-loop theoretical analysis, especially the convergence analysis of the disturbance observer [36–41].

This paper attempts to summarize recent achievements in active disturbance rejection flight control to provide practitioners an overview and insightful understanding of this innovative philosophy. Most of these designs are from the realistic requirements. At first, the crucial bottleneck in practical applications of modern model based control is sought from a unique user point of view except the conventional robustness consideration. Then, the key thought in ADRC is introduced on a pitch attitude control problem. Consequently, its relationship with the conventional PID controller is thoroughly revealed to show the inherent applicability of linear ADRC on a flight vehicle. Another control problem is also addressed within the framework of ADRC to illustrate the flexibility of this method. All these works are accompanied by numerical examples to show the effectiveness of linear ADRC in the flight control.

The remaining parts of the paper are organized as follows. Section 2 gives a major deficiency of modern control approach extracted from empirical experience, which was ignored in academia previously. Section 3 presents a complete design procedure for the pitch attitude control with proper explanations to introduce the crucial thought of linear ADRC. Section 4 presents an attitude decoupling control on the basis of single-input and single-output (SISO) system designs combining conventional approaches. The Concluding Remarks are summarized in the last section.

2 CRITICAL LIMITATIONS IN WIDE APPLICATIONS OF MODERN MODEL BASED CONTROL

Once we talk about the application of modern model based control on a flight vehicle, the most mentioned concept is robustness. It is well-known that the simple PID controller has strong robustness because of its weakly dependence on the refined mathematical model of a practical plant in the tuning process. On the other hand, standard model based control approaches are generally generated by polynomial or matrix computations on the basis of a plant model; therefore, the robustness problem is inborn and will accompany the controller for ever. This was also the original motivations of developing ADRC step by step in the 1990s. However, up to now, to the best of our knowledge, world widely there are only few demonstration flight vehicles that successfully employed adaptive control with parameter identification mechanisms (not just gain scheduling) or robust H_∞

control, even DI methods. The problem is that these methods encountered huge obstruction in the generalization in the quantity production phase. This phenomenon was ignored for a long time. Several factors lead to this fact:

(1) for a nonlinear controller, there is in lack of a closed-loop robustness evaluation method like the stability margin established for the linear system which is the solely acceptable industrial standard of robustness for a flight controller;

(2) from the thinking pattern perspective, one important deficiency for a complicated controller is the absence of a clear physical explanation for each component, with which the practitioners are quite familiar in the traditional PID control;

(3) moreover, the specific closed-loop performance criterion corresponding to each control component should also be claimed such that the controller tuning can be performed in a systematic manner. For example, in the PID controller, the proportional, integral, and derivative terms are the previous, current, and future information that relates to the quickness, accuracy, and stability, respectively. Therefore, these control parameters are decoupled in that each one is mainly responsible for a specific index. Nevertheless, most of model based controllers fail to meet this basic requirement since all the parameters are severely coupled together: once one parameter is tuned, other parameters should also be modified accordingly. For instance, practitioners should change 10 parameters simultaneously in the hardware-in-the-loop experiment for a robust controller like

$$G_c(s) = \frac{\sum_{i=0}^{4} b_i s^i}{s^5 + \sum_{i=0}^{4} a_i s^i}$$

until the results are satisfactory, which is quite a bore-some task and is not reliable due to these too many changes at each time. In addition, the reliable gain scheduling strategy for a high-order controller is still an open problem; and

(4) furthermore, the theoretical requirements for practitioners to master advanced controller design are beyond the simple extension of the conventional PID controller; hence, most of these methods might be rejected immediately or be disliked gradually.

These disadvantages combined together make many complicated controllers unable to be extensively employed in reality. Therefore, the possible practical utilization of a novel flight control must guarantee its similarity to the traditional PID controller and its advantage on some specific realistic problems. As an inheritor and also an extension of PID control, ADRC possesses these characteristics altogether as illustrated in the following section.

3 LINEAR ACTIVE DISTURBANCE REJECTION CONTROL DESIGN FOR THE PITCH ATTITUDE PARADIGM

It is well-known for flight control practitioners that there are severe restrictions on controlling the pitch attitude for a statically unstable flight vehicle using the PID controller. For example, the overshoot is difficult to be attenuated [42, 43] while a rather long settling time exists [17]. The thought of ADRC is firstly presented for this problem.

3.1 Brief Description of Longitudinal Flight Model and Problem Formulation

A longitudinal motion model for a generic flight vehicle is chosen as a baseline for the study and the longitudinal equations are as follows [44]:

$$\left.\begin{aligned}\dot{\gamma} &= \frac{1}{mV}\,(T\sin\alpha + L) - \frac{g}{V}\cos\gamma\,;\\ \dot{\theta} &= q\cos\phi - r\sin\phi\,;\\ \dot{q} &= \frac{I_z - I_x}{I_y}\,pr + \frac{M}{I_y}\,.\end{aligned}\right\} \tag{1}$$

when the bank angle is very small. Here, γ is the flight path angle; m is the mass of the flight vehicle; V is the ground velocity; T is the thrust; L is the lift; α is the angle of attack (AoA); g is the gravitational constant; θ and ϕ are the pitch and roll angles, respectively; p, q, and r are the roll, pitch, and yaw angular rates, respectively; I_x, I_y, and I_z are the moments of inertia for the roll, pitch, and yaw axes, respectively; and M is the pitching moment which can be decomposed as

$$M = M(q) + M(\alpha) + M(\delta_p)$$

where δ_p is the elevator deflection; and $M(q)$, $M(\alpha)$, and $M(\delta_p)$ are the pitch moment components generated by q, α, and δ_p, respectively. For the most commonly used flight vehicles, $M(\delta_p)$ is an approximate linearization related to δ_p around a specific Mach number, i. e.,

$$M(\delta_p) \approx m_{\delta_p}(\cdot)\delta_p\,.$$

Here, $m_{\delta_p}(\cdot)$ is the function with respect to Mach number, altitude, and δ_p, $m_{\delta_p}(\cdot)$ is more accurate than $M(\alpha)$ in practice, and it should be noted that $m_{\delta_p}(\cdot)$ is negative for flight vehicle. Therefore, one has:

$$\ddot{\theta} = \frac{M(q) + M(\alpha) + (I_z - I_x)pr}{I_y} \cos\phi - q\dot{\phi}\sin\phi - \dot{r}\sin\phi - r\dot{\phi}\cos\phi + \frac{m_{\delta_p}(\cdot)\cos\phi}{I_y}\delta_p \quad (2)$$

where the term $(M(q)+M(\alpha)+(I_z-I_x)pr)\cos\phi/I_y - q\dot{\phi}\sin\phi - \dot{r}\sin\phi - r\dot{\phi}\cos\phi$ is not directly related to δ_p which means that δ_p is unable to appear in an explicit way without differentiation.

In most of the flight control methods based on DI principle, the key assumption is that the values of the term $(M(q)+M(\alpha)+(I_z-I_x)pr)\cos\phi/I_y - q\dot{\phi}\sin\phi - \dot{r}\sin\phi - r\dot{\phi}\cos\phi$ of (2) is sufficiently close to its practical ones [4,7]. In general, the major uncertainty of this term comes from $M(\alpha)$ which usually depends on altitude, Mach number, and α. In fact, when these model-based approaches are put into practice, the engineers have to spend most of time on modeling rather than on controller design. Moreover, α is hard to be accurately measured, especially for the flight vehicles that operate in the low-velocity regime. Within the existing framework, the DI strategy is unable to be implemented without using complicated high-dimension interpolation methodology for the aerodynamic coefficients; therefore, other alternatives should be sought to get rid of this severe bottleneck.

3.2 Procedure of Active Disturbance Rejection Control Design for the Longitudinal Dynamics

Because q and r as well as ϕ can be measured by the onboard inertial navigation system (INS), the angular rate, $\dot{\theta}$, can be obtained from (1) in a straightforward manner. Therefore, $\dot{\theta}$ could be directly used to calculate the control signal, which can reduce the phase lag caused by using the estimated $\dot{\theta}$. According to (2), the following definition

$$\begin{aligned}
u &= \delta_{up}\,; \\
y &= \dot{\theta}\,; \\
x_1 &= y\,; \\
x_2 &= \frac{M(q) + M(\alpha) + (I_z - I_x)pr}{I_y}\cos\phi - q\dot{\phi}\sin\phi - \dot{r}\sin\phi - r\dot{\phi}\cos\phi\,; \\
K_c &= \frac{m_{\delta_p}(\cdot)\cos\phi}{I_y}\,,
\end{aligned}$$

where δ_{up} is the elevator control voltage that drives the motor to deflect corresponding angle, yields

$$\left.\begin{aligned} \dot{x}_1 &= x_2 + K_c u\,; \\ \dot{x}_2 &= w\,; \\ y &= x_1\,. \end{aligned}\right\} \tag{3}$$

Here, w is assumed to be disturbance and terminates the representation.

Because the dynamics of the elevator is much faster than the airframe of the flight vehicle, its characteristics can be neglected in the design process but should be taken into account in the later robustness evaluation. In this design, the variables with regard to the lateral-directional motion, such as the effects of variables p, r, ϕ, I_z, and I_x, are also included in x_2, which can be considered as the coupling effects. However, all these factors are neglected in the traditional design approach, which restrains control performance to be further improved. The combination of the internal dynamics and the external disturbances generates a novel state x_2 known as an extended state [9]. This extended state has no explicit physical meaning as the standard definition of a state. It should be noted that only one uncertainty exists in (3), i. e., the steady gain K_c, and it can be obtained with a high accuracy. This is the fundamental reason for its strong performance robustness as will be illustrated later. The state observer for (3) is

$$\dot{z}_1 = z_2 + l_1(y - z_1) + K_c u\,; \qquad \dot{z}_2 = l_2(y - z_1) \tag{4}$$

with the observer gain $L = [l_1, l_2]^{\mathrm{T}}$ selected appropriately, providing an estimate of the states of (3). Most importantly, the second state of the observer (z_2) approximates dynamic uncertainties (x_2). Hence, this observer is called Extended State Observer (ESO) [9]. By taking use of linear gains, this observer was denoted as Linear ESO (LESO) [45]. To simplify the tuning process, the observer gains can be parameterized as

$$L = \left[2\omega_0, \omega_0^2\right]^{\mathrm{T}}$$

where the observer bandwidth, ω_0, is the only tunable parameter.

With a well-tuned observer, one can obtain $z_2 \approx x_2$. If the control signal is

$$u = \frac{u_0 - z_2}{K_c}$$

where u_0 is the virtual control variable, the original system (2) can be approximately reformulated as

$$\ddot{\theta} = u_0\,.$$

Because the regulated output is the pitch angle, it is reasonable to employ the classical proportional-derivative (PD) control form for u_0, this is,

$$u_0 = k_e (\theta_r - \theta) - k_d \dot{\theta}$$

where θ_r is the reference for the pitch angle. To sum up, the ADRC law for pitch attitude control becomes

$$u = \frac{k_e(\theta_r - \theta) - k_d \dot{\theta} - z_2}{K_c} \tag{5}$$

which is called Linear ADRC (LADRC) [45]. It is easy to analyze the stability and robustness of LADRC in the frequency domain [17, 20, 46]. The total control effort can be split into two parts: the first part compensates for the aggregated effects of model uncertainties and the second part makes the tracking error tend to zero. The LADRC is a linear control but its design concept is totally different: it can be applied to nonlinear, time varying, uncertain process with very little model information. By adopting LESO, the operating range of linear controller can be effectively extended [47] which is beyond the traditional operating point thinking. In comparison with the standard PID controller, one can find that the difference lies in that the original integral term is replaced with an estimation term of the total uncertain effect, including internal dynamics and external disturbances, which make the plant to deviate from a chain of the canonical integrators. It is well known that the conventional error integral term generates the low frequency or the major component of the control signal in an iterative way such that evident oscillation can readily be produced. In other words, the integral feedback has an adverse effect on the closed-loop dynamic performance except its attenuation of low-frequency disturbance. In fact, the error can be considered as the consequence of the total disturbance and ADRC cancels this source straightforwardly at early stage with less phase lag to achieve better performance.

3.3 Relationship with the Conventional Proportional-Integral-Derivative Control

The LADRC is a special kind of DOBC and it will be useful to find its relationship with the conventional PID controller, which can provide an in-depth viewpoint for practitioners and theoreticians to understand it. Moreover, this connection can offer a possibility of inheriting empirical tuning knowledge because PID control is the preferred choice of most flight control engineers.

The relationship between PID control and LADRC can be established as follows. At first, the effect of ESO should be revealed. With straightforward mathematical manipulations, one has:

$$z_2 = \frac{\omega_0^2(s^2\theta - K_c u)}{s^2 + 2\omega_0 s + \omega_0^2}\,.$$

That is to say that the extended state is an estimation of the derivative of $\dot{\theta}$ except the control input. A differential signal can be obtained by using integral operations like (4) which is also an innovation of ADRC. Combining (4) with (5) yields

$$\delta_{up} = u_{\mathrm{PD}} + \frac{\omega_0^2}{s + 2\omega_0}\left(\frac{u_{\mathrm{PD}}}{s} - \frac{\dot{\theta}}{K_c}\right)$$

where s is the Laplace operator and

$$u_{\mathrm{PD}} = \frac{k_e(\theta_r - \theta) - k_d\dot{\theta}}{K_c} = K_e\,(\theta_r - \theta) - K_d\dot{\theta}$$

is the conventional PD pitch attitude controller popularly implemented in practice. As the value of K_c is negative, both K_e and K_d are also negative. The essence of LADRC is a compensator to reduce the phase lag caused by the purely integral feedback. When $\omega_0 = 0$, the LADRC degenerates to a standard PD controller. It is clear that LADRC can be looked as an augmented PID control. Therefore, many mature tuning rules for PID control can be generalized to tune the LADRC with minor adjustments. In this way, the engineering tradition can be inherited adequately for the proposed method.

3.4 Numerical Examples

Here, a typical numerical example is presented to illustrate the comparative results between LADRC and PD attitude controller. To simplify the description, only the linearized operating point is considered.

Firstly, the small perturbation theory is used to linearize the longitudinal dynamics (1). To achieve this objective, the lift should be decomposed as [44]

$$L = L(\alpha) + L(\delta_p) + L(q)$$

where $L(q)$, $L(\alpha)$, and $L(\delta_p)$ are the lift components generated by q, α, and δ_p, respectively. Then, the linear model around its equilibrium is

$$\left.\begin{aligned}
\ddot{\theta} &= m_{\delta_p}\delta_p + m_\alpha\alpha + m_q\dot{\theta}\,;\\
\dot{\gamma} &= c_\alpha\alpha + c_{\delta_p}\delta_p + c_q\dot{\theta}\,;\\
\theta &= \gamma + \alpha
\end{aligned}\right\} \qquad (6)$$

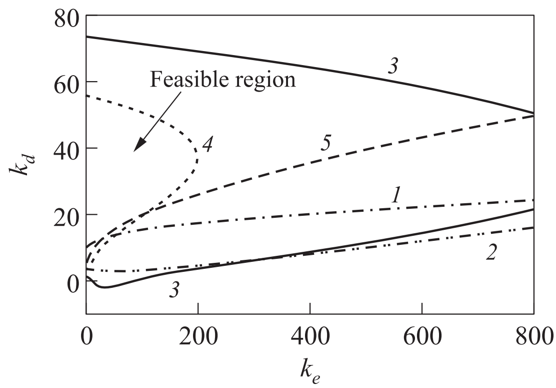

Figure 1 Feasible control parameter space with guaranteed stability margin: *1* — −10 dB; *2* — 0; *3* — 10 dB; *4* — phase margin = 45°; and *5* — phase margin = 67.5° with a unit feedback

where m_α and m_q are the pitch moment derivatives with respect to α and q, respectively; and c_α, c_{δ_p}, and c_q are the lift derivatives due to α, δ_p, and q, respectively. Equations (6) can be reformulated in the frequency domain as

$$G_p(s) = \frac{\theta(s)}{\delta_p(s)} = \frac{p(s+b)}{s(s^2 + a_1 s + a_0)}$$

where

$$p = m_{\delta_p}\,; \quad b = \frac{m_{\delta_p} c_\alpha - m_\alpha c_{\delta_p}}{m_{\delta_p}}\,; \quad a_0 = m_\alpha c_q - m_q c_\alpha - m_\alpha\,; \quad a_1 = c_\alpha - m_q\,.$$

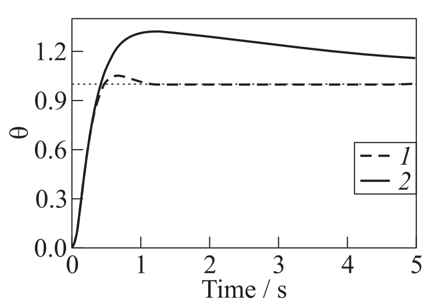

Figure 2 Linear ADRC (*1*) and PD controller (*2*) for the pitch attitude

Consider an operating point as $a_0 = -15.0640$, $a_1 = 0.3058$, $b = 0.1442$, and $p = 37.1165$ throughout the paper. This operating point is statically unstable, imposing several critical problems for the attitude control design. The elevator is modeled by a second-order dynamics as

$$G_r(s) = \frac{\delta_p(s)}{\delta_{up}(s)} = \frac{13s + 9000}{s^2 + 160s + 9000}\,.$$

Using stability margin tester [48] as shown in [20, 42] to guarantee sufficient stability margins of no less than 10 dB and 45°, select the feasible control parameters as $k_e = 60$ and $k_d = 15$ with $K_c \approx p$ according to Fig. 1. When $\omega_0 = 0$, the LADRC degenerates to a PD controller and both step responses are shown in Fig. 2. It is clear that the response from the LADRC has smaller overshoot and settling time simultaneously. Although adding an error integral term to the PD controller can reduce the settling time considerably, this action can at the same time increase the overshoot further [43]. For the statically unstable flight vehicle, the overshoot is unavoidable for an attitude controller; however, LADRC can attenuate this phenomenon as small as possible which is unable to be achieved by a conventional PID controller [43].

4 FLEXIBILITY OF ACTIVE DISTURBANCE REJECTION CONTROL APPLICATION IN FLIGHT CONTROL

4.1 Angle of Attack Control

Apart from the pitch control, AoA is also can be used as a regulated variable. In the pitch control, the available set of information is just the combination of pitch angle and its rate; therefore, the ADRC design can be conducted in a straightforward fashion. Because when controlling the AoA there is no such natural derivative relationship between variables, the ADRC design is somewhat different.

According to (6), one has:

$$\frac{q}{\delta_p} = \frac{p(s+b)}{s^2 + a_1 s + a_0}$$

and

$$G_1^{\alpha}(s) = \frac{\alpha(s)}{q(s)} = \frac{-c_{\delta_p} s + m_q c_{\delta_p} + m_{\delta_p}}{p(s+b)}\,. \tag{7}$$

Here, c_q is ignored because it is quite tiny in practice. Taking the conventional way into account, the angular rate q is indispensable in any flight control design to enhance fundamental damping characteristic of the attitude. At first, the feedback of q is used with a gain of K_d and, therefore, an inner angular rate closed-loop transfer function can be obtained as

$$\frac{q(s)}{q_r(s)} = \frac{p(s+b)}{s^2 + (a_1 + K_d p)s + (a_0 + K_d pb)}\,. \tag{8}$$

Since the damping characteristic is improved, one can assume (8) to be approximated by the first-order plant as

$$\frac{q(s)}{q_r(s)} \approx \frac{p(s+b)}{s+r} . \tag{9}$$

Combing (7) and (9) yields

$$\frac{\alpha(s)}{q_r(s)} = \frac{-c_{\delta_p} s + m_q c_{\delta_p} + m_{\delta_p}}{s+r} \tag{10}$$

where q_r is the output of a LADRC to be designed. Hence, the entire control law is

$$\delta_{up} = q_r - K_d q .$$

According to the empirical knowledge about flight mechanics, $c_{\delta_p} \ll m_{\delta_p}$ and $m_q c_{\delta_p} \ll m_{\delta_p}$. Therefore, Eq. (10) can be further simplified as

$$\frac{\alpha(s)}{q_r(s)} \approx \frac{m_{\delta_p}}{s+r} .$$

Similar to the preceding pitch attitude control design, one has

$$q_r = \frac{k_{p,\alpha}(\alpha_r - \alpha) - z_{2,\alpha}}{K}$$

where K is the tuning parameter with the default value of m_{δ_p} and

$$\left.\begin{aligned} \dot{z}_{1,\alpha} &= z_{2,\alpha} + K q_r + 2\omega_{0,\alpha}\left(\alpha - z_{1,\alpha}\right) ; \\ \dot{z}_{2,\alpha} &= \omega_{0,\alpha}^2 \left(\alpha - z_{1,\alpha}\right) . \end{aligned}\right\} \tag{11}$$

The block diagram for the AoA LADRC is shown in Fig. 3. Consider that α can be calculated by using onboard ship's INS and the first state $z_{1,\alpha}$ is the estimation of α. Because α can be obtained from velocity and attitude information,

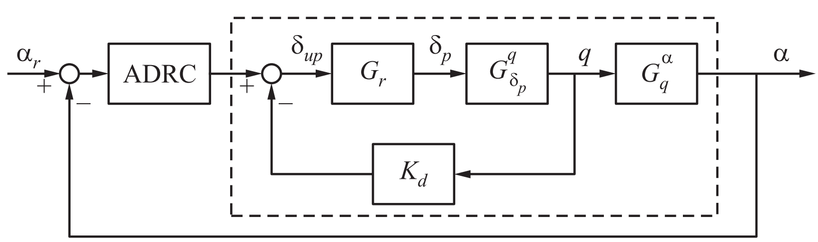

Figure 3 Block diagram for the AoA LADRC

which is rather smooth with high signal-noise-ratio, one can utilize the reduced-order observer of (11) as follows to reduce phase lag and enhance robustness:

$$\begin{aligned} \dot{z}_\alpha &= -\omega_{0,\alpha} z_\alpha - \omega_{0,\alpha}^2 \alpha - \omega_{0,\alpha} K q_r \,; \\ z_{2,\alpha} &= z_\alpha + \omega_{0,\alpha} \alpha \,. \end{aligned}$$

After straightforward mathematical manipulations, one has:

$$z_{2,\alpha} = \frac{\omega_{0,\alpha}\left(\dot{\alpha} - K q_r\right)}{s + \omega_{0,\alpha}} \,.$$

4.2 Attitude Decoupling Control with Three Single-Input and Single-Output Active Disturbance Rejection Controls

The effects of AoA control is illustrated by a decoupling control objective. Many combat fighters need to make 180 degree turn maneuver or change the roll attitude from 0° to 180° in a short time. To make the air-breathing engine operate normally and to reduce the coupling effect during this phase, this type of maneuver should accompany bank-to-turn mode in order to ensure the sideslip angle β to be as small as possible. With small AoA and sideslip angle, the small perturbation nonlinear dynamic model is:

$$\left.\begin{aligned} \dot{\alpha} &= q - p\beta - c_\alpha \alpha - c_{\delta_p} \delta_p \,; \\ \dot{\beta} &= r + p\alpha + c_\beta \beta + c_{\delta_y} \delta_y \,; \\ \dot{\phi} &= p \end{aligned}\right\} \tag{12}$$

where δ_y is the vertical tail deflection angle; and c_β and c_{δ_y} are the lateral force derivatives due to β and δ_y, respectively. According to (12), the roll angular rate p leads to strong coupling effects on both α and β. The larger the p is, the stronger the coupling influence is. Thus, an effective decoupling controller is urgently needed to attenuate this adverse effect. The conventional method uses decoupling control when combining the three channels together, which is complicated. Furthermore, there lacks of robustness evaluation criterion for a multiple-input and multiple-output (MIMO) system, like the stability margin for the SISO systems. Here, a LADRC decoupling strategy is proposed by designing three SISO LADRCs, respectively. The three regulated variables are α, β, and γ as illustrated in (12). The controller for β is similar to that of α except that the reference for β is always zero. The controller design process for ϕ is similar to the pitch attitude control and can refer to [17]. The unique advantage of this method is that the coupling effects from other channels can be considered as parts of extended states (uncertainties), respectively, with no matter what

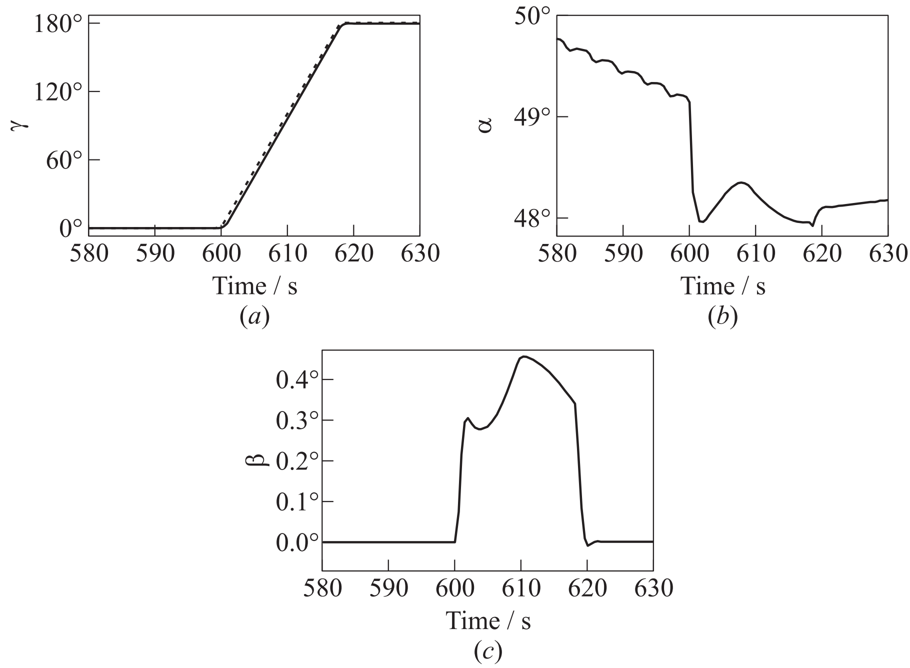

Figure 4 Roll angle (a), AoA (b), and sideslip angle (c) in the 180 degree turn process

mechanism is the source. In such a way, the traditional robustness evaluation method for SISO systems is still feasible for the MIMO control system.

For a combat fighter, the proposed three SISO LADRCs are employed to realize a 180 degree turn. The simulation results are shown in Fig. 4. It can be found that the quick ϕ turn has little effect on α and β. Therefore, this independent design is a helpful alternative in the decoupling flight control.

5 CONCLUDING REMARKS

In this paper, the authors summarized LADRC, an ESO-based unifying flight control strategy, for typical problems in practice. The limitations of the modern model based control approaches were addressed according to the user point of view. The control law with a complete linear form was derived from a nonlinear model but no dynamic model estimation is needed. The proposed method is a kind of augmented PID control. Therefore, the existing empirical knowledge, such as tuning methods and analysis in the frequency domain, can be inherited as much as possible. With this ESO, some critically poor performance could be effectively attenuated. Moreover, this philosophy exhibits sufficient flexibility to deal with distinct control problems. The highlights of the proposed approach are:

(1) no dynamic model estimation is needed;

(2) its linear form can be looked as an extension of the conventional PID control;

(3) there are explicit tuning rules; and

(4) the controller is robust.

This design process was conducted within the traditional engineering framework and it may provide helpful guidelines for practitioners.

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