

Active Disturbance Rejection Control for Delta-wing Aircraft

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Abstract—Delta Wing aircraft operating at high angles of attack may exhibit a nonlinear oscillatory motion known as the wing rock phenomenon. This instability originates from asymmetric aerodynamic vortices that produce nonlinear rolling moments, making the aircraft difficult to control using the classical linear method. This study presents the design and simulation of an Active Disturbance Rejection Control (ADRC) strategy for the roll dynamics of delta-wing aircraft. The nonlinear aerodynamic effects are treated as a generalized disturbance and estimated using an Extended State Observer (ESO). The estimated disturbance is then compensated in the control law to improve tracking performance and robustness. The classical nonlinear delta wing model used in adaptive control literature is adopted as the plant model. The observer estimates both the plant states and the lumped disturbance. A second-order reference model generates the desired bank angle trajectory, and the ADRC controller forces the plant to track this trajectory. Numerical simulations are conducted in MATLAB to investigate open-loop aircraft behaviour, disturbance estimation accuracy, command tracking performance and control effort. The ADRC controller is compared with a conventional state feedback controller. The result show that ADRC reduced the peak bank angle tracking error from 1.6° to 0.8°, reduced the peak roll rate response from 5.3 deg/s to 4.1 deg/s, decreased the overshoot from 3.75% to 1.5%, and reduced the Integral Absolute Error (IAE) from 1.0889 to 0.5309. These results demonstrated the effectiveness of ADRC for suppressing wing-rock oscillations and compensating for nonlinear aerodynamic disturbances in delta-wing aircraft dynamics.

Keywords—active disturbance rejection control, delta-wing aircraft, wing-rock instability, extended state observer, nonlinear control, disturbance estimation

I. INTRODUCTION

Aircraft with delta wing configurations are widely used in high speed and high-maneuverability flight regimes. One of the main aerodynamic challenges associated with delta wing at high angles of attack is the wing rock phenomenon. Wing rock is characterized by oscillatory rolling motion caused by asymmetric vortex shedding over the wing surfaces. These nonlinear aerodynamic

effects introduce strong nonlinearities and uncertainties into the aircraft dynamics, making the control problem particularly challenging [1–3].

The roll motion of delta-wing aircraft is mainly regulated by differential aileron deflection. The corresponding dynamic model contains linear and nonlinear aerodynamic terms, where the nonlinear terms depend on the bank angle and roll rate in a state-dependent manner. These nonlinearities complicate the control problem and make the use of conventional linear control techniques less effective. In addition, uncertainty in aerodynamic effects and the difficulty of exact modeling introduce further complications in the control design [4].

In some control applications, it is not possible to describe all nonlinearities and uncertainties of the plant accurately. Therefore, control schemes based on exact cancellation may become sensitive to modeling errors. One useful way to overcome this problem is to treat the unknown nonlinearities and disturbances as a generalized disturbance and estimate them online by means of a state observer. This philosophy is one of the main features Active Disturbance Rejection Control (ADRC). The ADRC framework does not depend on complete knowledge of the plant nonlinearities. Instead, it estimates the lumped disturbance and compensates for it in real time [5–7].

The Extended State Observer (ESO) plays a vital role in ADRC. The ESO can estimate not only the system states in real time but also the total disturbance due to nonlinear dynamics parameter uncertainty and external excitation. Thus, the ESO allows the controlled plant to be transformed approximately into a simpler nominal model [8–10].

Many researchers have investigated robust and adaptive control of wing rock motion and nonlinear flight dynamics. The benchmark example in the adaptive control literature employs a model reference adaptive control structure for the same delta-wing plant considered in this work. In that example the nonlinear plant is driven by a second-order model and the open loop instability together with the command tracking response are demonstrated in detail. In recent years ADRC have been applied successfully to

different uncertain nonlinear systems including robotic manipulators flexible joint systems, exoskeletons, electronic throttle valves, and aerospace systems. These studies indicate that observer-based disturbance rejection is an effective alternative to exact model-based control [11–13].

The system represents the roll dynamics of delta wing aircraft operating at high angle of attack. Delta wings are characterized by a highly swept leading edge, typically exceeding 70° , which provides aerodynamic advantage at high speeds. However at high angles of attack the airflow over the wing becomes highly nonlinear due to vortex formation [14–16].



Fig. 1. Wing rock phenomenon.

This is known as the wing rock phenomenon as shown in Fig. 1. The system naturally exhibits limit cycle behavior in open loop this makes it appropriate for testing robust nonlinear control strategies. In this research the control objective is to suppress the wing rock oscillations and force the roll angle to follow the desired reference trajectory, the proposed approach treats all nonlinear aerodynamic effects and parameter uncertainties as a total disturbance and estimates them in real time [17, 18].

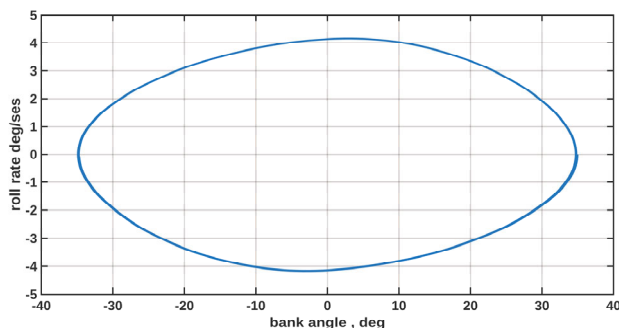


Fig. 2. Open loop phase portrait of delta wing aircraft.

The open loop in Fig. 2 shows that the aircraft does not converge to the equilibrium point instead the trajectory approaches a closed orbit in the phase plane which indicates the existence of a limit cycle. The bank angle oscillates approximately within ± 35 degrees, while the roll

rate remains bounded within few degrees per second. This means the open loop plant exhibits persistent oscillatory motion which is exactly the wing rock phenomenon. The above result confirms that the implemented model reproduces the expected nonlinear instability [19, 20].

Advanced control strategies have become increasingly important in aerospace systems due to the presence of nonlinear dynamics, disturbances, and model uncertainties. Observer-based control approaches can improve robustness and tracking performance by estimating unmeasured states and compensating for uncertainties in real time. Recent work on UAV control has demonstrated the effectiveness of differentiator- and observer-based nonlinear control strategies in enhancing system performance under uncertain operating conditions [21]. This motivates the application of ADRC for wing-rock suppression in nonlinear delta-wing aircraft.

Aircraft systems are characterized by strong nonlinear dynamics, parameter uncertainties, aerodynamic disturbances, and coupling between translational and rotational motions, making the design of high performance flight controllers particularly challenging. Robust and observer based control strategies have attracted significant attention in aerospace applications. Recent studies on quadrotor aircraft have demonstrated the effectiveness of advanced nonlinear control techniques for achieving reliable trajectory tracking under uncertain conditions [22].

A second-order sliding mode control strategy was proposed and combined with a proportional-integral observer for wing rock suppression. Their approach aimed to improve robustness against nonlinear aerodynamic disturbances while reducing chattering effects commonly associated with conventional sliding mode control [23].

In this study ADRC has been proposed for the roll angle tracking if the delta wing aircraft system including the lumped nonlinear aerodynamic disturbance. This control structure is different from the adaptive control method addressed in the benchmark example. The estimated states include the bank angle and roll rate, while the observer also estimates the total aerodynamic disturbance inherent in the delta-wing system. In addition, the controller performance is compared with a conventional state feedback controller based on the fixed gains only. The contribution of this work can be summarized as follows:

- (1) An ADRC-based control framework is developed for a nonlinear wing rock model of delta wing aircraft, where the aerodynamic nonlinearities and uncertainties are treated as a generalized disturbance and estimated online through an ESO.
- (2) A second-order reference model is incorporated within the ADRC structure to improve command tracking and provide desired loop dynamics during wing rock suppression.
- (3) The disturbance estimation capability of the ESO is investigated under both nominal operating conditions and additional bounded sinusoidal disturbances, demonstrating its ability to compensate for uncertain nonlinear aerodynamic effects.

- (4) A comprehensive performance comparison between the proposed ADRC scheme and conventional state feedback controller is conducted using multiple quantitative performance indices, including Integral of Absolute Error (IAE), Integral of Squared Error (ISE), Integral of Time-weighted Absolute Error (ITAE), Integral of Time-weighted Squared Error (ITSE), tracking error, and control effort.
- (5) The obtained results demonstrated that the ADRC framework provides superior disturbance rejection and improved tracking performance while requiring lower control effort compared with the conventional state feedback controller.

This paper is organized in four parts. The first part addresses the mathematical modeling of the delta wing aircraft roll dynamics and its ADRC-oriented form. The second part presents the design of ADRC and ESO on the plant model. The third part conducts numerical simulations to verify the effectiveness of the controller and to compare the ADRC with the state feedback structure. The fourth part highlights the conclusions from the computer simulation and outlines future work for the paper.

II. MODEL OF DELTA WING AIRCRAFT ROLL DYNAMICS

In delta wing flight dynamics, the roll motion of the aircraft can be described by the nonlinear differential equations: [1]

$$\dot{\varphi} = p \quad (1)$$

$$\dot{p} = \theta_1 \varphi + \theta_2 p + (\theta_3 |\varphi| + \theta_4 |p|)p + \theta_5 \varphi^3 + \theta_6 \delta_a \quad (2)$$

where φ is the bank angle of the aircraft, p is the roll rate, and δ_a is the differential aileron input, θ_i are unknown constant aerodynamic parameters.

TABLE I. UNKNOWN CONSTANT AERODYNAMIC PARAMETERS

Parameter Symbol	Parameter Value
θ_1	-0.018
θ_2	0.015
θ_3	-0.062
θ_4	0.009
θ_5	0.021
θ_6	0.75

The parameter values used are given in Table I, the uncertain state-dependent function $f(x)$ is represented by a constant unknown parameter vector Θ^T and the known regressor vector $\Phi(x)$ [1]:

$$f(x) = \underbrace{\frac{1}{\theta_6} (\theta_3 \quad \theta_4 \quad \theta_5)}_{\Theta^T} \underbrace{(|\varphi|p \quad |p|p\varphi^3)^T}_{\Phi(x)} = -0.0827|\varphi|p + 0.012|p|p + 0.028\varphi^3 \quad (3)$$

The system control effectiveness $\Lambda = \theta_6$ is assumed to be constant and unknown. Also unknown are the second

row coefficients (θ_1, θ_2) in A , as well as the state-dependent function $f(x)$.

The system control effectiveness is defined as:

$$b = \theta_6 \quad (4)$$

which is assumed to be constant and unknown. Hence, the roll-dynamics model can be expressed as:

$$\dot{\varphi} = p \quad (5)$$

$$\dot{p} = f(x) + b\delta_a \quad (6)$$

The command tracking problem is formulated by using a second-order reference model, which defines the desired roll angle responses. In transfer function form, the reference model is given by Lavretsky and Wise [1]:

$$\frac{\varphi_{\text{ref}}}{\varphi_{\text{cmd}}} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad (7)$$

Here, φ_{ref} is the reference roll angle, φ_{cmd} is the commanded roll angle, and (ω_n, ξ) are the desired natural frequency and the damping ratio.

One can describe the plant in state form by assigning the state variables x_1 and x_2 to the physical quantities Φ and p , respectively. Then the following equations can be obtained:

$$x_1 = \varphi \quad (8)$$

$$x_2 = p \quad (9)$$

Thus the state space representation of the nonlinear plant becomes:

$$\dot{x}_1 = x_2 \quad (10)$$

$$\dot{x}_2 = \theta_1 x_1 + \theta_2 x_2 + (\theta_3 |x_1| + \theta_4 |x_2|)x_2 + \theta_5 x_1^3 + \theta_6 u \quad (11)$$

where $u = \delta_a$. For the purpose of ADRC design, Eq. (14) is rewritten by separating the nominal input gain from the total disturbance. Accordingly, the plant is represented as

$$\dot{x}_1 = x_2 \quad (12)$$

$$\dot{x}_2 = b_0 u + f \quad (13)$$

where b_0 is a known nominal value chosen for the control design, and the total disturbance is defined by

$$f = d(x) + (b - b_0)u \quad (14)$$

with

$$d(x) = \theta_1 x_1 + \theta_2 x_2 + (\theta_3 |x_1| + \theta_4 |x_2|)x_2 + \theta_5 x_1^3 \quad (15)$$

To estimate the total disturbance, an extended state is introduced as

$$\dot{x}_3 = f \quad (16)$$

and its dynamics are assumed to satisfy

$$\dot{x}_3 = w(t) \quad (17)$$

where $w(t)$ is a bounded unknown function. Therefore, the extended-state model of the delta-wing aircraft becomes:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= b_0 u + x_3 \\ \dot{x}_3 &= w(t) \end{aligned} \quad (18)$$

where Eq. (18) comprises the three state equations defining the extended-state model. The system output is selected as:

$$y = x_1 = \varphi(t) \quad (19)$$

The performance of the proposed ADRC controller depends on the selection of the ESO bandwidth and the state error feedback gains. Increasing the observer bandwidth improves disturbance estimation and compensation but may increase sensitivity to measurement noise, while lower bandwidth values result in smoother estimation with slower disturbance rejection. Likewise, the controller gains determine the trade-off between tracking accuracy, transient response, and control effort. Therefore, the selected parameters were chosen to provide a balanced compromise between fast disturbance rejection, accurate tracking, and stable control performance.

III. ADRC DESIGN

The key in the design of ADRC is how to extend the system model such that the nonlinear aerodynamic uncertainty and disturbance are lumped into an additional state [24]. In order to apply ESO, the mathematical model of the delta wing aircraft described by Eqs. (6) and (7) is extended in the following form:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 + bu \\ \dot{x}_3 &= \frac{df(x)}{dt} \end{aligned} \quad (20)$$

where Eq. (20) represents the three equations forming the extended-state representation. The third state variable x_3 accumulates all nonlinearities, uncertainties, and external disturbance effects of the system, that is,

$$x_3 = f(x) \quad (21)$$

On the condition that the new state variable is bounded and differentiable, one can apply the extended-state concept to the above delta-wing model. According to the extended structure of the plant [25], the ESO can be synthesized as follows:

$$\begin{aligned} \dot{z}_1 &= z_2 + \beta_1(x_1 - z_1) \\ \dot{z}_2 &= z_3 + \beta_2(x_1 - z_1) + b_0 u. \\ \dot{z}_3 &= \beta_3(x_1 - z_1) \end{aligned} \quad (22)$$

where Eq. (22) includes the three equations that define the ESO structure, the observer states z_1 and z_2 estimate the actual system states x_1 and x_2 , respectively, while the observer state z_3 estimates the lumped generalized disturbance $f(x)$. The observer gains are chosen using the observer bandwidth ω_o as

$$\beta_1 = 3\omega_o, \beta_2 = 3\omega_o^2, \beta_3 = \omega_o^3 \quad (23)$$

The above choice places the observer poles at $-\omega_o$ and ensures fast convergence of observer states.

The ADRC parameters were selected according to the bandwidth parameterization method. The observer bandwidth was chosen to be sufficiently larger than the control bandwidth to ensure fast disturbance estimation while maintaining numerical stability and avoiding excessive control activity. Typically, the observer bandwidth is selected between three and ten times the control bandwidth. In this study, a ratio of $\omega_o/\omega_c = 20$ was employed after simulation-based tuning

The proposed ADRC uses the second-order ref model defined by Eqs. (10) and (11) the desired ref acceleration can be written as

$$\ddot{\phi}_{ref} = -2\zeta\omega_n r_2 - \omega_n^2 r_1 + \omega_n^2 \phi_{cmd} \quad (24)$$

Then, the virtual control law is chosen as

$$v = \ddot{\phi}_{ref} + k_1(r_1 - z_1) + k_2(r_2 - z_2) \quad (25)$$

where k_1 and k_2 are positive control gains. The final ADRC control law is

$$u = \frac{v - z_3}{b_0} \quad (26)$$

subject to actuator saturation

$$u = \text{sat}(u, u_{\max}) \quad (27)$$

The above control structure compensates the estimated disturbance z_3 and forces the plant to track the reference model dynamics. For comparison purposes, a conventional state-feedback controller is also considered, which has the form

$$u = K_x^T x + K_r r \quad (28)$$

where K_x and K_r are fixed gains selected from the benchmark example, and no disturbance estimation is used.

IV. COMPUTER SIMULATION

In Fig. 3, the nonlinear aerodynamic disturbance described by Eq. (3) has been estimated using ESO. This

figure shows the comparison between the true disturbance and the observer estimation. It is clear from the figure that the estimated state z_3 is very close to the true disturbance, this indicates that the ESO could successfully estimate the nonlinear aerodynamic effect of the delta wing aircraft.

In Fig. 4, the observer performance has been further verified by adding a bounded sinusoidal wave to the plant, again, the ESO could successfully estimate the total disturbance. One can notice that the observer follows the piecewise variation and the transition of the disturbance very closely. The importance of this result is that the ESO is not limited to estimating the nominal nonlinear function of the plant only, but can also estimate the effect of additional bounded external disturbance.

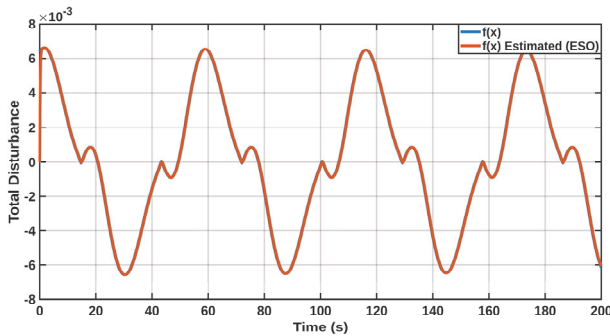


Fig. 3. Disturbance estimation using ESO.

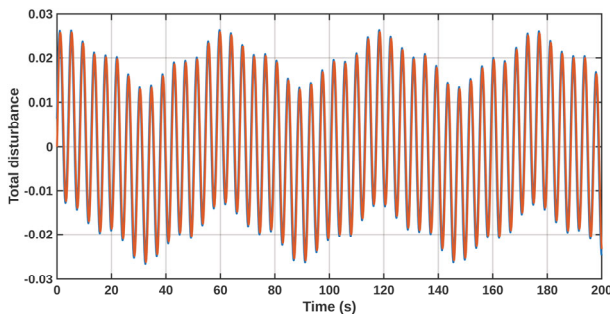


Fig. 4. Estimation of the disturbance after adding bounded sin wave.

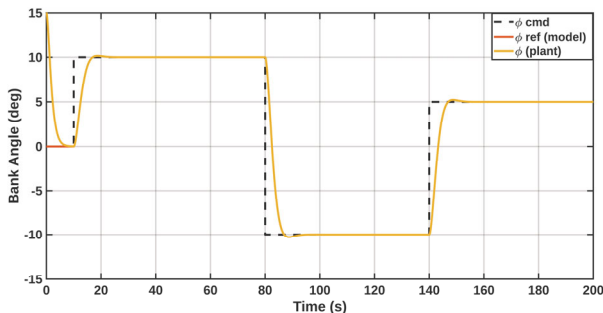


Fig. 5. Tracking performance of ADRC for delta wing aircraft bank angle.

In Fig. 5, the full ADRC structure has been implemented for Bank Angle tracking, where the dashed curve represents the command angle, the second curve represents the reference model, and the third curve represents the actual plant response. It's clear from the figure that the reference model smooths the command step signal while the actual plant tracks the reference output closely

Small transient overshoot appears around the switching instants, but they are quickly damped. This indicates that the proposed ADRC controller could force the aircraft to follow the desired bank angle behavior with good transient response and small tracking error.

In Fig. 6, the roll rate response under ADRC in this figure, the plant roll rate is compared with the derivative of the reference-model output. It's clear that the roll rate exhibits peaks mainly around the switching instants of the command signal, while it converges close to zero during constant command intervals. This is physically consistent because the aircraft requires roll motion only when changing its bank angle from one level to another. The bounded and decaying nature of the roll rate peaks indicates that the maneuver is performed smoothly without excessive oscillation.

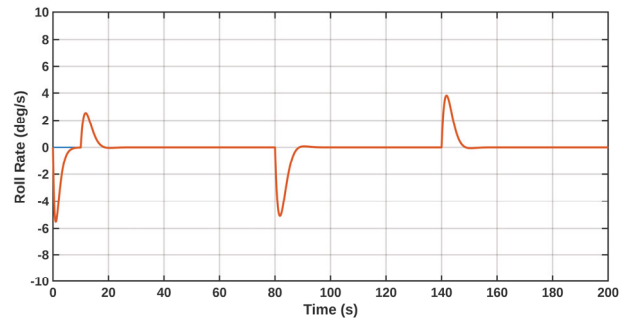


Fig. 6. Roll rate response under ADRC.

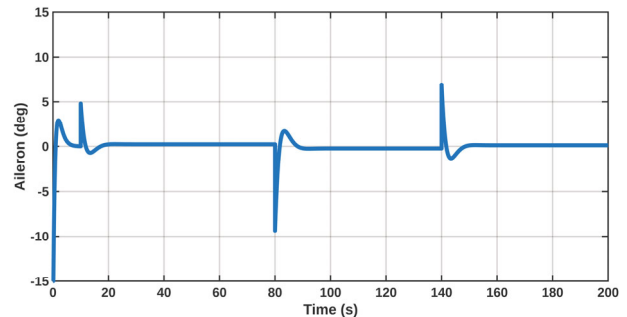


Fig. 7. Aileron input under ADRC.

In Fig. 7, aileron input under ADRC. The control input remains bounded within the actuator limit and produces pulses around the command transitions. During steady-state intervals, the control input remains zero it becomes clear that the aileron pulses generate the required roll-rate transients, which in turn produce the desired change in bank angle.

In Fig. 8, the same nonlinear delta wing plant has been controlled by a conventional state feedback controller using only fixed gains K_x and K_r , the figure shows that the controller is capable of tracking the command but not as accurately as the ADRC, and its performance is based purely on fixed feedback action and does not involve online estimation of the disturbance.

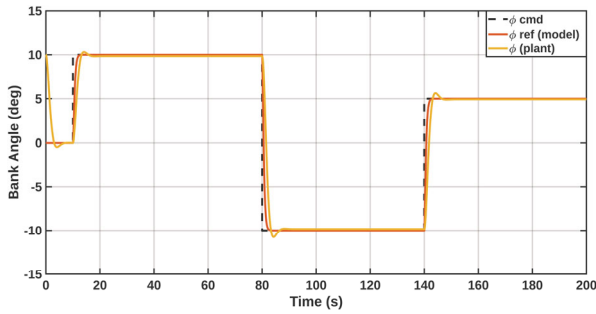


Fig. 8. Tracking performance under conventional State feedback control.

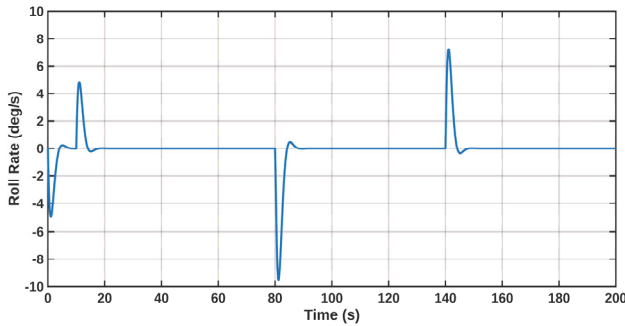


Fig. 9. Roll rate response under conventional State feedback control.

In Fig. 9, the roll rate peaks are still bounded, but they reflect the fact that the controller reacts to the plant dynamics directly without observer-based disturbance compensation compared with the ADRC roll-rate response, the state-feedback result is less structured around reference-model matching.

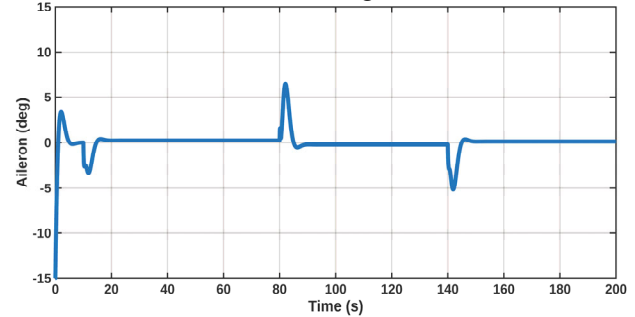


Fig. 10. Aileron input under conventional State feedback control.

In Fig. 10, the control effort remains bounded, but the lack of explicit disturbance compensation means that the controller must respond directly to the nonlinear effects through feedback action only as a result, ADRC provides a more robust control.

TABLE II. PERFORMANCE EVALUATION OF CONTROLLERS

Performance Index	ADRC	State Feedback	Improvement of ADRC
Peak tracking error of bank angle (deg)	0.8	1.6	50.00% reduction
Peak roll-rate response (deg/s)	4.1	5.3	22.64% reduction
Peak differential aileron (deg)	13.5	15.0	10.00% reduction
Rise time (s)	4.12	2.03	State feedback faster
Settling time (s)	6.28	5.24	State feedback faster
Overshoot (%)	1.50	3.75	60.00% reduction
IAE	0.5309	1.0889	51.24% reduction
ISE	0.0868	0.0693	ADRC higher by 25.25%

The quantitative comparison in Table II shows that the proposed ADRC controller provides improved tracking accuracy and smoother transient behaviour compared with the conventional state feedback controller. The peak tracking error of the bank angle was reduced from 1.6 to 0.8, corresponding to a 50% reduction. In addition, the peak roll rate response decreased from 5.3 deg/s to 4.1 deg/s, while the peak differential aileron deflection decreased from 15 to 13.5. ADRC also reduced the overshoot from 3.75% to 1.50% and decreased the IAE from 1.0889 to 0.5309. Although the state feedback controller produced shorter rise and settling times, it showed larger overshoot and higher accumulated absolute tracking error. Therefore, ADRC provides a better trade-off between tracking accuracy, actuator usage and transient smoothness.

V. CONCLUSION

In this research, the nonlinear roll dynamics of delta wing aircraft operating at high angle of attack have been investigated, the main objective was to evaluate the effectiveness of ADRC in comparison with the classical State Error Feedback (SEF) controller. The open loop

behavior of the system clearly demonstrates the existence of a limit cycle oscillation in the phase plane, which confirms the presence of the wing rock phenomenon, the phase portrait shows a closed elliptical trajectory indicating sustained oscillations caused by nonlinear aerodynamic effects, this validates that the system is inherently unstable and requires a robust nonlinear control strategy. When the SEF controller was applied the system was able to track the commanded bank angle however several limitations were observed from the simulation result. The aileron control input exhibits sharp peaks indicating high control effort and poor disturbance handling. The tracking response included noticeable overshoot and slower settling behavior. Meanwhile the ADRC based controller demonstrated significantly improved performance across all valuation aspects, the tracking performance closely followed the reference model with minimal overshoot and fast settling time, the roll rate response was smoother and better damped compared to SEF, the control input was more regulated and improved stability, the ESO successfully estimated the total disturbance with high accuracy, overall ADRC transform the nonlinear uncertain system into and approximately linear and disturbance free system through

real time estimation and compensation. The proposed ADRC strategy demonstrated effective suppression of the wing-rock phenomenon. While the present study focused on a well-established nonlinear wing-rock benchmark model with generalized disturbances estimated by the Extended State Observer, certain practical aspects, including measurement noise, parameter variations, actuator dynamics, and additional environmental disturbances, were beyond the scope of the current investigation. Furthermore, the proposed controller was validated through MATLAB/Simulink simulations. Future research will therefore focus on optimization-based parameter tuning, evaluation under more realistic disturbance scenarios, Hardware-In-the-Loop (HIL) simulation, experimental validation, and extension to full Multi-Input Multi-Output (MIMO) aircraft dynamics, including coupled roll, pitch, and yaw motions, to further demonstrate the applicability of the proposed control strategy in practical aerospace systems.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

F.M.H. is responsible for formal analysis, investigation, writing-original draft, software, and resources; A.A.D. is responsible for validation, data curation, conceptualization, and methodology; A.J.H. is responsible for project administration, supervision, visualization and writing—review and editing. All authors had approved the final version.

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