

## Article

# Enhanced Pigeon-Inspired Optimization-Based Active Disturbance Rejection Control for Carrier-Based Aircraft Landing Direct Lift Control

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## Abstract

Carrier-based aircraft landing is a critical element in generating aircraft carrier combat capability. Traditional landing control suffers from inherent drawbacks including strong trajectory–attitude coupling, high pilot workload, and insufficient disturbance rejection in complex environments. The MAGIC CARPET precision landing technology achieves decoupled manipulation via direct lift control, providing a feasible technical path to address these bottlenecks. However, existing schemes still have limitations in multi-channel dynamic decoupling performance and controller parameter tuning efficiency. This paper designs a three-channel (flap, stabilator, throttle) active disturbance rejection control landing system based on direct lift technology, with an adaptive decoupling module introduced to counteract the pitching moment coupling caused by flap deflection, so as to maintain stable attitude and velocity during trajectory adjustment. An enhanced pigeon-inspired optimization algorithm is proposed with full-process improvements in population initialization, global search operator and local search operator, and a global collaborative tuning scheme for controller parameters is constructed. Verified by multiple groups of comparative simulations and Monte Carlo statistical experiments, the proposed system outperforms comparative schemes in tracking accuracy, decoupling effect and disturbance suppression capability, and exhibits favorable robust stability under uncertain conditions. This study offers a useful reference for the design and practical implementation of direct-lift landing control systems for carrier-based aircraft.

**Keywords:** carrier-based aircraft landing technology; direct lift control; MAGIC CARPET landing; active disturbance rejection control; pigeon-inspired optimization algorithm

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## 1. Introduction

Carrier-based aircraft landing is a critical element in building aircraft carrier combat capability. Unlike land-based takeoff and landing, carrier-based landing must be conducted on the confined angled deck of an aircraft carrier. Throughout the entire process, the aircraft is subjected to severe random disturbances, including carrier air wake and six-degree-of-freedom (6-DOF) deck motion, which renders this maneuver widely recognized as the most critical and hazardous flight phase [1–3]. Traditional landing control

adjusts the trajectory indirectly via pitch attitude regulation, which entails inherent drawbacks such as strong trajectory–attitude coupling, high pilot workload, and limited disturbance rejection in complex environments. The MAGIC CARPET precision landing technology achieves decoupled manipulation based on direct lift control, providing a feasible path to break through the above bottlenecks [4–6]. This paper focuses on the design and optimization of the direct lift landing control system for carrier-based aircraft, aiming to improve landing accuracy and safety under complex sea conditions.

The development of carrier-based aircraft landing control technology has been driven by three core objectives: improving safety, reducing pilot workload, and enhancing environmental adaptability. From early fully manual visual operation to the gradual application of the Fresnel lens optical landing system (FLOLS), instrument landing system (ILS) and microwave landing system (MLS), landing reliability and operational scope have been continuously improved [7–10]. However, the core logic of traditional control — “adjusting trajectory indirectly via attitude” — has not changed fundamentally. During the final approach phase, pilots still need to coordinately operate the control stick and throttle to balance multiple coupled state variables. Moreover, an inherent phase lag exists between attitude input and trajectory response, which limits the corrective capability under sudden disturbances and thereby hinders further performance improvement.

To overcome the coupling bottleneck inherent in traditional landing control, direct lift control technology has been extensively investigated and applied in practice. Wu et al. designed a two-stage integrated direct lift landing controller based on prescribed performance nonlinear dynamic inversion, which achieved decoupling of longitudinal trajectory and attitude and verified the landing control performance of the method [11]. Zhang et al. proposed a direct-lift automatic landing system based on a fruit fly optimization algorithm (FOA) with an escape-predation mechanism, and simulation results verified its trajectory tracking capability under carrier air wake disturbance [12]. Sun et al. focused on carrier-based UAV landing control under actuator faults, and proposed a model predictive control structure based on a nonlinear extended state observer, which achieved simultaneous compensation of faults and disturbances [13]. As a robust control method that does not rely on accurate plant models, active disturbance rejection control (ADRC) is well suited to the nonlinear and multi-disturbance nature of the landing process [14]. Although existing studies have confirmed the effectiveness of direct lift control and ADRC, further improvements are still needed in terms of dynamic decoupling performance and parameter tuning efficiency [15].

The control performance of landing controllers is directly related to the effectiveness of parameter tuning. The multi-channel ADRC controller under the direct lift mode has numerous parameters to be tuned with strong coupling. Manual tuning based on engineering experience is not only time-consuming and labor-intensive, but also difficult to achieve a globally optimal trade-off among multiple objectives such as tracking accuracy, attitude stability and disturbance rejection capability. Swarm intelligence optimization algorithms, such as genetic algorithms [16] and particle swarm optimization [17], offer an effective solution to this problem. The pigeon-inspired optimization (PIO) algorithm proposed by Duan et al. features fast convergence speed and simple parameter setting, and has been widely applied in the field of landing controller parameter optimization [18]. Yang et al. introduced the Cauchy mutation mechanism into the PIO algorithm and constructed a multi-layer parameter optimization strategy for automatic landing systems [19]. He et al. proposed a multi-strategy PIO algorithm for parameter tuning of ADRC controllers for vertical takeoff and landing fixed-wing UAVs, with optimization performance superior to traditional intelligent algorithms [20]. Wu et al. adopted a PIO algorithm with a dropout mechanism to optimize landing control parameters, which effectively reduced

the dispersion range of landing points [21]. In addition, other swarm intelligence optimization algorithms have also been explored and applied in related fields [22,23].

Although abundant research achievements have been made in the field of carrier-based aircraft landing control, several core problems remain to be solved. First, the multi-channel decoupling design of direct lift landing control is insufficient, making it difficult to fully eliminate the aerodynamic coupling effect caused by flap deflection throughout the whole process. Second, the parameters of the ADRC controller are high-dimensional and strongly coupled, making it difficult for manual tuning to achieve the global optimum of comprehensive performance. Third, the basic PIO algorithm tends to converge prematurely in high-dimensional optimization, and existing enhanced variants are still insufficient to meet the parameter optimization requirements of the MAGIC CARPET mode.

The rest of this paper is organized as follows. Actuator establishes the carrier-based aircraft landing simulation framework, including the longitudinal nonlinear dynamics model of the carrier-based aircraft, the carrier air wake and deck motion disturbance model, and the fuzzy virtual pilot model. Section 3 designs the three-channel ADRC direct lift landing control system and introduces an adaptive decoupling module. Section 4 proposes an improved PIO algorithm adapted to the landing control scenarios, and constructs a global collaborative tuning scheme for controller parameters. Section 5 verifies the comprehensive performance of the system through simulation experiments. The final section summarizes the main conclusions of this paper and prospects future research directions.

## 2. Model

To establish a solid basis for the design and verification of the direct lift carrier landing control system, this paper constructs simulation models of carrier-based aircraft dynamics, environmental disturbances, and a virtual pilot for longitudinal landing. The lateral-directional motion is assumed to be stabilized by an independent control loop; thus, this work focuses exclusively on longitudinal trajectory and attitude control.

The longitudinal motion equations of the carrier-based aircraft are established as follows:

$$\left\{ \begin{array}{l} \dot{z} = V \sin \gamma \\ \dot{x} = V \cos \gamma \\ m\dot{V} = F \cos \alpha - D - mg \sin \gamma \\ mV\dot{\gamma} = F \sin \alpha + L - mg \cos \gamma \\ I_y \dot{q} = M_y \\ \dot{\theta} = q \\ \alpha = \theta - \gamma \end{array} \right. \quad (1)$$

where  $\gamma$  denotes the flight path angle;  $\alpha$  denotes the angle of attack;  $\theta$  denotes the pitch angle;  $z$  is the altitude coordinate of the aircraft in the inertial ground coordinate system;  $x$  is the longitudinal horizontal displacement in the inertial ground coordinate system;  $V$  is the true airspeed of the carrier-based aircraft;  $m$  is the total mass of the aircraft;  $F$  is the net engine thrust;  $g$  is the gravitational acceleration;  $I_y$  is the pitch moment of inertia about the body lateral axis;  $q$  is the pitch rate;  $L$ ,  $D$  and  $M_y$  represent the aerodynamic lift, aerodynamic drag, and pitch aerodynamic moment acting on the aircraft in the longitudinal plane, respectively. These aerodynamic forces and moment are expressed as:

$$\left\{ \begin{array}{l} L = 0.5\rho V^2 SC_L \\ D = 0.5\rho V^2 SC_D \\ M_y = 0.5\rho V^2 S\bar{c}C_M \end{array} \right. \quad (2)$$

where  $\rho$  is the standard sea-level atmospheric density;  $S$  is the wing reference area;  $\bar{c}$  is the mean aerodynamic chord of the wing;  $C_L$ ,  $C_D$  and  $C_M$  are the dimensionless lift, drag, and pitch moment coefficients, respectively. Their values are jointly determined by the flight state and control surface deflections.

For the landing phase, the aerodynamic coefficients are formulated as:

$$\begin{cases} C_L = C_{L0} + C_L^\alpha \alpha + C_L^{\delta_S} \delta_S + C_L^{\delta_{LEF}} \delta_{LEF} \\ C_D = C_{D0} + C_D^\alpha \alpha + C_D^{\delta_S} \delta_S + C_D^{\delta_{LEF}} \delta_{LEF} \\ C_M = C_{M0} + C_M^\alpha \alpha + C_M^{\delta_S} \delta_S + C_M^{\delta_{LEF}} \delta_{LEF} \end{cases} \quad (3)$$

where  $C_{L0}$ ,  $C_{D0}$  and  $C_{M0}$  are the baseline lift coefficient, drag coefficient, and pitch moment coefficient at zero angle of attack and zero control surface deflection, respectively; the superscripts  $\alpha$ ,  $\delta_S$  and  $\delta_{LEF}$  denote the partial derivatives of the corresponding aerodynamic coefficients with respect to the angle of attack, stabilator deflection angle, and leading-edge flap deflection angle, respectively.

Transfer function models are established for each actuator. The dynamic response of the stabilator actuator is described by a first-order inertial link:

$$\frac{\Delta \delta_S(s)}{\Delta \delta_{sc}(s)} = \frac{K_S}{s + \tau_S} \quad (4)$$

The flap actuator is also described by a first-order inertial link:

(5)

Considering the high-order lag characteristics of the engine, the throttle servo system adopts a fourth-order transfer function to characterize its dynamic response:

$$\frac{\Delta \delta_{PL}(s)}{\Delta \delta_{PLc}(s)} = \frac{a_3 s^3 + a_2 s^2 + a_1 s + a_0}{s^4 + b_3 s^3 + b_2 s^2 + b_1 s + b_0} \quad (6)$$

The specific parameter values of the three actuators are listed in Table 1.

**Table 1.** Parameters of Actuators.

| Actuator   | Parameter Value                                                                                          |
|------------|----------------------------------------------------------------------------------------------------------|
| Stabilator | $K_S = 30, \tau_S = 30$                                                                                  |
| Flap       | $K_{LEF} = 30, \tau_{LEF} = 30$                                                                          |
| Throttle   | $a_3 = 2.994, a_2 = 10.48, a_1 = 27.48, a_0 = 9.37$<br>$b_3 = 6.5, b_2 = 18.25, b_1 = 26.28, b_0 = 9.37$ |

The deflection angle and rate limits of the stabilator and flap are listed in Table 2.

**Table 2.** Actuator Limits of the Carrier-Based Aircraft.

| Actuator   | Deflection Angle Limit (deg) | Deflection Rate Limit (deg/s) |
|------------|------------------------------|-------------------------------|
| Stabilator | [−30, 30]                    | [−45, 45]                     |
| Flap       | [−30, 30]                    | [−30, 30]                     |

The simulation is carried out based on a typical carrier-based aircraft configuration. The detailed aerodynamic coefficients and key approach flight parameters are presented in Table 3 and Table 4, respectively.

**Table 3.** Aerodynamic Coefficients of the Carrier-Based Aircraft.

| Aerodynamic Parameter | Value     | Aerodynamic Parameter | Value    | Aerodynamic Parameter | Value        |
|-----------------------|-----------|-----------------------|----------|-----------------------|--------------|
| $C_{D0}$              | 0.0561444 | $C_{L0}$              | 0.363277 | $C_{M0}$              | 0.01715723   |
| $C_D^\alpha$          | 0.0170819 | $C_L^\alpha$          | 0.068653 | $C_M^\alpha$          | 0.006770368  |
| $C_D^{\delta_S}$      | 0.0055025 | $C_L^{\delta_S}$      | 0.019613 | $C_M^{\delta_S}$      | −0.005315807 |

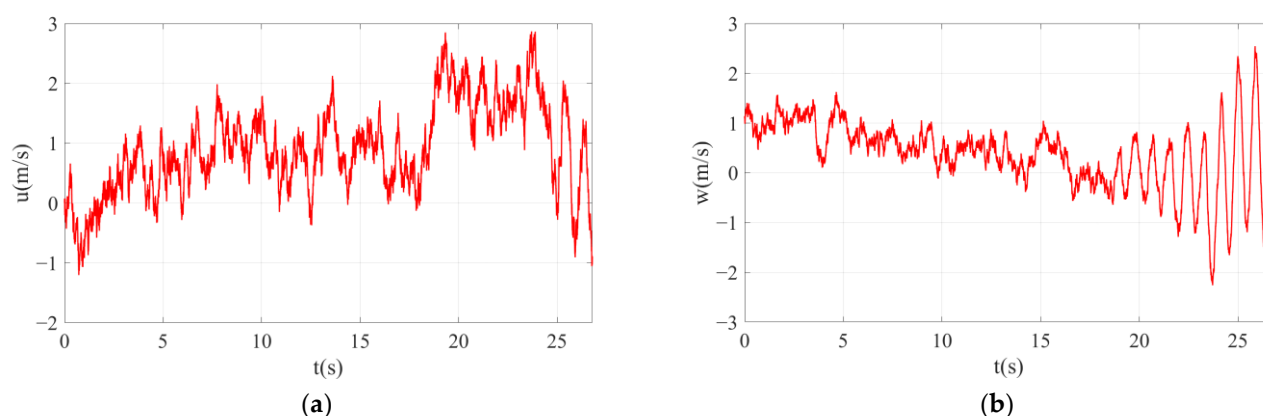
|                      |           |                      |          |                      |              |
|----------------------|-----------|----------------------|----------|----------------------|--------------|
| $C_D^{\delta_{LEF}}$ | 0.0016323 | $C_L^{\delta_{LEF}}$ | 0.019751 | $C_M^{\delta_{LEF}}$ | -0.013429127 |
|----------------------|-----------|----------------------|----------|----------------------|--------------|

**Table 4.** Key Approach Flight Parameters of the Carrier-Based Aircraft.

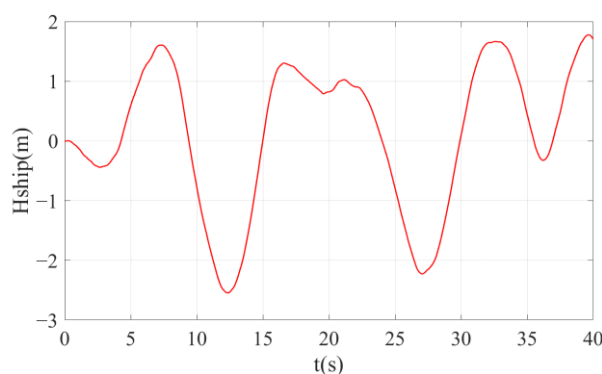
| Parameter | Value                     |
|-----------|---------------------------|
| $m$       | 21,280 kg                 |
| $b$       | 14 m                      |
| $\bar{c}$ | 4 m                       |
| $S$       | 62 m <sup>2</sup>         |
| $I_y$     | 368,908 kg·m <sup>2</sup> |

The entire landing process is subject to complex external disturbances. This paper mainly considers two typical disturbances: carrier air wake and deck motion.

The carrier air wake model is established in accordance with the U.S. military standard MIL-F-8785C, and is decomposed into four components: free atmospheric turbulence, steady disturbance component, periodic disturbance component, and local random turbulence component. The vertical and longitudinal horizontal disturbance components of the carrier air wake are shown in Figure 1.

**Figure 1.** Horizontal and vertical velocity components of carrier air wake disturbance. (a) Horizontal velocity component; (b) vertical velocity component.

The aircraft carrier undergoes random motions driven by ocean waves, among which pitch and heave directly alter the spatial position of the desired touchdown point. In this paper, the spectral modeling method is adopted: time-domain signals of the carrier pitch angle and heave displacement are generated via shaping filters, and the real-time vertical height of the desired touchdown point is derived via geometric relations. The simulation results of deck motion are shown in Figure 2.



**Figure 2.** Vertical height variation curve of carrier deck motion.

To realize closed-loop simulation of the manual landing scenario, this paper employs a virtual pilot model based on the Fresnel Lens Optical Landing System (FLOLS). Based on the altitude deviation of the carrier-based aircraft relative to the ideal glideslope and the deviation rate, the model adopts a fuzzy logic controller to simulate the pilot's manipulation decision logic and outputs the flight path angle rate control command. Meanwhile, human neuromuscular delay and control dead zone characteristics are taken into account, ensuring the command output conforms to actual pilot manipulation characteristics and providing realistic command inputs for the control system.

These models collectively form a complete human-in-the-loop simulation environment for carrier-based aircraft landing, providing a solid foundation for subsequent control system design, parameter tuning, and multi-condition performance verification.

### 3. Method

To satisfy the engineering application requirements of MAGIC CARPET precision landing, the direct-lift landing control system designed in this paper is intended to fulfill three core objectives.

First, trajectory tracking accuracy: the system is required to achieve high-precision tracking of flight path angle rate commands with zero steady-state error. It must also confine longitudinal touchdown deviations within the safe capture envelope of the arresting system and maintain the baseline angle of attack and approach speed constant throughout the landing process, thereby providing a stable aerodynamic basis for trajectory control.

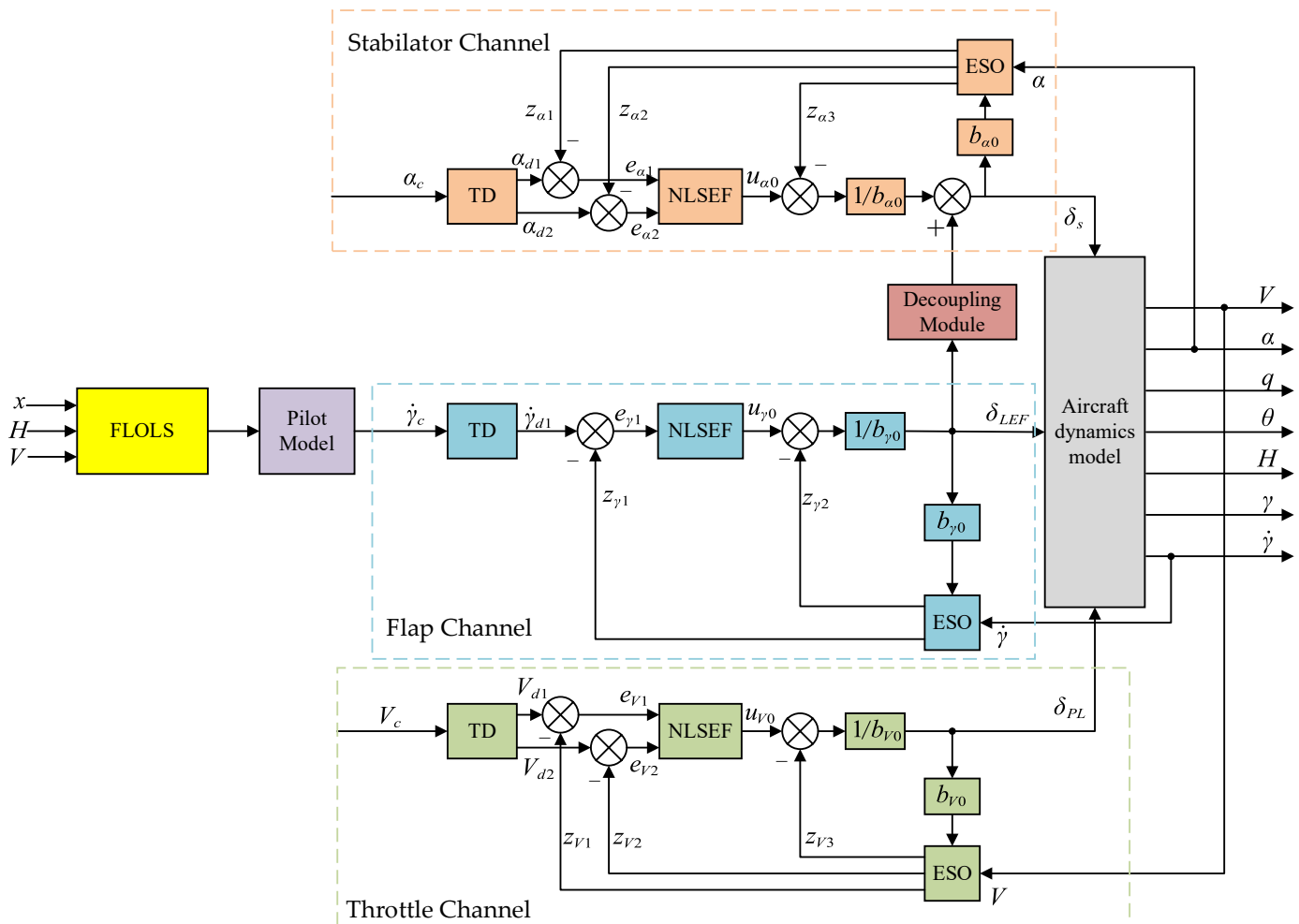
Second, control decoupling: through channelized functional division of the flap, the stabilator and the throttle, independent manipulation of trajectory control, attitude stabilization and speed maintenance is realized. The additional pitching moment coupling induced by flap deflection is counteracted, achieving the direct lift control goal of "trajectory adjustment without attitude variation".

Third, robustness: the system shall possess real-time suppression capability against external random disturbances such as carrier air wake and deck motion, and can adaptively compensate for model uncertainties including aerodynamic parameter perturbations and actuator characteristic deviations, thus maintaining stable control performance under various sea conditions.

#### 3.1. Overall Architecture of the Control System

Based on the above control requirements, this paper proposes the overall architecture of a three-channel (flap-stabilator-throttle) ADRC system, as shown in Figure 3. The system takes the FLOLS as the guidance information source, and outputs flight path angle rate manipulation commands via the virtual pilot model.

The three control channels have clear functional divisions. The flap channel serves as the main trajectory control channel: it receives flight path angle rate commands and actual feedback signals, and outputs flap deflection commands to directly adjust the flight trajectory. The stabilator channel acts as the attitude stabilization channel, with constant angle of attack as its control objective; meanwhile, feedforward decoupling compensation for flap deflection is introduced to offset the pitching moment coupling caused by flap manipulation. The throttle channel functions as the speed maintenance channel, which sustains constant approach speed by adjusting engine thrust. The three channels operate cooperatively to jointly achieve high-precision trajectory tracking as well as stable attitude and speed maintenance under the direct lift mode.



**Figure 3.** Overall structure of the direct-lift carrier landing control system.

### 3.2. Design of ADRC Controllers for Each Channel

ADRC does not require an accurate mathematical model of the controlled plant. It expands both internal and external disturbances into state variables via the Extended State Observer (ESO) for real-time estimation and feedforward compensation, thereby enhancing system robustness and disturbance rejection capability [14]. This makes ADRC particularly suitable for carrier landing control scenarios with strong disturbances and model uncertainties. In this paper, ADRC controllers of corresponding orders are designed for the controlled plants of the three control channels according to their respective dynamic characteristics.

#### 3.2.1. Design of the Flap Channel ADRC Controller

The core control objective of the flap channel is flight path angle rate tracking. Based on the carrier-based aircraft dynamic model Equation (1) established in Section 2, the flight path angle rate dynamic equation is given by:

$$mV\dot{\gamma} = F \sin \alpha + L - mg \cos \gamma \quad (7)$$

According to Equations (2) and (3), the linearized expression of aerodynamic lift  $L$  is:

$$L = 0.5\rho V^2 S(C_{L0} + C_L^\alpha \alpha + C_L^{\delta_s} \delta_s + C_L^{\delta_{LEF}} \delta_{LEF}) \quad (8)$$

Substituting Equation (8) into Equation (7) yields the dynamic equation of flight path angle rate:

$$\dot{\gamma} = \frac{0.5\rho VS(C_{L0} + C_L^\alpha \alpha + C_L^{\delta_s} \delta_s + C_L^{\delta_{LEF}} \delta_{LEF})}{m} + \frac{F \sin \alpha}{mV} - \frac{g \cos \gamma}{V} \quad (9)$$

All terms independent of the flap control input  $\delta_{LEF}$  are grouped as the system total disturbance  $f_\gamma$ , and the control gain of the flap is defined as  $b_\gamma$ , namely:

$$\begin{cases} f_\gamma = \frac{0.5\rho VS(C_{L0} + C_L^\alpha \alpha + C_L^{\delta_s} \delta_s)}{m} + \frac{F \sin \alpha}{mV} - \frac{g \cos \gamma}{V} \\ b_\gamma = \frac{0.5\rho VSC_L^{\delta_{LEF}}}{m} \end{cases} \quad (10)$$

The standard form of the controlled plant for the flap channel is finally derived as:

$$\dot{\gamma} = f_\gamma + b_\gamma \delta_{LEF} \quad (11)$$

Equation (11) demonstrates that the mapping from flap deflection angle to flight path angle rate is a proportional link. Considering the first-order dynamic characteristic of the flap actuator, the complete controlled plant of the flap channel is a first-order dynamic system. Therefore, a first-order ADRC controller is adopted. Meanwhile, aerodynamic parameter perturbations, carrier air wake disturbances and other uncertainties are all incorporated into the total disturbance  $f_\gamma$ , which is estimated and compensated by the ESO.

The Tracking Differentiator (TD) provides a smooth transition process for the flight path angle rate command from the pilot. Its discrete form is expressed as:

$$\begin{cases} \dot{\gamma}_{d1}(k+1) = \dot{\gamma}_{d1}(k) + h \cdot \dot{\gamma}_{d2}(k) \\ \dot{\gamma}_{d2}(k+1) = \dot{\gamma}_{d2}(k) + h \cdot \text{fhan}(\dot{\gamma}_{d1}(k) - \dot{\gamma}_c(k), \dot{\gamma}_{d2}(k), r_\gamma, h_{\gamma0}) \end{cases} \quad (12)$$

where  $h$  is the simulation time step;  $\dot{\gamma}_{d1}(k)$  is the tracking signal of the flight path angle rate reference command, used for subsequent error calculation;  $\dot{\gamma}_{d2}(k)$  is the differential estimation signal, which only participates in the internal TD iteration and is not used in the nonlinear error feedback;  $\dot{\gamma}_c(k)$  is the reference command;  $r_\gamma$  is the speed factor; and  $h_{\gamma0}$  is the filtering factor.  $\text{fhan}(\cdot)$  is the fastest control synthesis function, whose definition is provided in Equation (13).

$$\begin{cases} d = rh_0 \\ d_0 = h_0 d \\ y = x_1 + h_0 x_2 \\ a_0 = \sqrt{d^2 + 8r|y|} \\ a = \begin{cases} x_2 + \frac{(a_0 - d)}{2} \text{sign}(y), |y| > d_0 \\ x_2 + \frac{y}{h_0}, |y| \leq d_0 \end{cases} \\ \text{fhan} = - \begin{cases} r \text{sign}(a), |a| > d \\ r \frac{a}{d}, |a| \leq d \end{cases} \end{cases} \quad (13)$$

For the first-order controlled plant, a second-order nonlinear discrete ESO is designed to perform real-time estimation of the actual flight path angle rate and the system total disturbance. Its discrete form is given by:

$$\begin{cases} e_\gamma(k) = z_{\gamma1}(k) - \dot{\gamma}(k) \\ z_{\gamma1}(k+1) = z_{\gamma1}(k) + h \cdot (z_{\gamma2}(k) - \beta_{\gamma01} \cdot e_\gamma(k) + b_{\gamma0} \cdot \delta_{LEF}(k)) \\ z_{\gamma2}(k+1) = z_{\gamma2}(k) - h \cdot \beta_{\gamma02} \cdot \text{fal}(e_\gamma(k), \alpha_{\gamma0}, \delta_{\gamma0}) \end{cases} \quad (14)$$

where  $\dot{\gamma}(k)$  is the feedback value of the actual flight path angle rate of the carrier-based aircraft;  $\delta_{LEF}(k)$  is the flap deflection control command;  $z_{\gamma1}(k)$  is the estimated value of the flight path angle rate;  $z_{\gamma2}(k)$  is the estimated value of the system total disturbance;  $b_{\gamma0}$  is the estimated value of the control gain for the flap channel;  $\beta_{\gamma01}$  and  $\beta_{\gamma02}$  are observer gains,

which are tuned via the bandwidth method;  $\text{fal}(\cdot)$  is the nonlinear power function, whose definition is provided in Equation (15);  $\alpha_{\gamma 0}$  is the nonlinear factor;  $\delta_{\gamma 0}$  is the width of the linear segment of the fal function.

$$\text{fal}(e, a, \delta) = \begin{cases} |e|^a \text{sign}(e), & |e| > \delta \\ \frac{e}{\delta^{1-a}}, & |e| \leq \delta \end{cases} \quad (15)$$

Based on the reference signal from the TD and the state estimates from the ESO, a Nonlinear State Error Feedback (NLSEF) control law is constructed. Feedforward compensation for the total disturbance is then applied to generate the final flap deflection command.

$$\begin{cases} e_{\gamma 1}(k) = \dot{\gamma}_{d1}(k) - z_{\gamma 1}(k) \\ u_{\gamma 0}(k) = k_{\gamma} \cdot \text{fal}(e_{\gamma 1}(k), \alpha_{\gamma}, \delta_{\gamma}) \\ \delta_{LEF}(k) = \frac{u_{\gamma 0}(k) - z_{\gamma 2}(k)}{b_{\gamma 0}} \end{cases} \quad (16)$$

where  $e_{\gamma 1}(k)$  is the tracking error of the flight path angle rate;  $k_{\gamma}$  is the nonlinear proportional gain;  $\alpha_{\gamma}$  is the nonlinear factor, which is set within the range  $0 < \alpha_{\gamma} < 1$  in engineering practice;  $\delta_{LEF}(k)$  is the final output flap deflection command.

### 3.2.2. Design of the Stabilator Channel ADRC Controller

The stabilator channel takes a constant angle of attack as its control objective. Based on the carrier-based aircraft dynamic model established in Section 2, the geometric definition of the angle of attack and the basic relationship of pitch motion are given by:

$$\begin{cases} \alpha = \theta - \gamma \\ \dot{\theta} = q \end{cases} \quad (17)$$

where  $\theta$  is the pitch angle of the carrier-based aircraft,  $q$  is the pitch rate, and  $\gamma$  is the flight path angle. Taking the derivative of the angle of attack yields the basic form of the angle of attack derivative:

$$\dot{\alpha} = q - \dot{\gamma} \quad (18)$$

Substituting the flight path angle rate dynamic Equation (9) into Equation (18) and rearranging yields the complete dynamic equation of the angle of attack:

$$\dot{\alpha} = q - \frac{0.5\rho VS}{m} (C_{L0} + C_L^{\alpha} \alpha + C_L^{\delta_s} \delta_s + C_L^{\delta_{LEF}} \delta_{LEF}) - \frac{F \sin \alpha}{mV} + \frac{g \cos \gamma}{V} \quad (19)$$

All terms independent of the stabilator control input  $\delta_s$  are grouped as the system total disturbance  $f_{\alpha}$ , and the control gain of the stabilator is defined as  $b_{\alpha}$ , namely:

$$\begin{cases} f_{\alpha} = q - \frac{0.5\rho VS}{m} (C_{L0} + C_L^{\alpha} \alpha + C_L^{\delta_{LEF}} \delta_{LEF}) - \frac{F \sin \alpha}{mV} + \frac{g \cos \gamma}{V} \\ b_{\alpha} = -\frac{0.5\rho V S C_L^{\delta_s}}{m} \end{cases} \quad (20)$$

Accordingly, the standard form of the controlled plant for the stabilator channel is obtained as:

$$\dot{\alpha} = f_{\alpha} + b_{\alpha} \delta_s \quad (21)$$

Equation (21) indicates that the relationship between the angle of attack and the stabilator deflection angle exhibits first-order dynamic characteristics. Considering the first-order inertial dynamics of the stabilator actuator, the system from the stabilator deflection command output by the controller to the angle of attack is a second-order dynamic system. Therefore, a second-order ADRC controller is adopted for design. During the design

process, disturbances such as flap-induced pitching moment coupling, aerodynamic parameter perturbations, and carrier air wake disturbances are all incorporated into the total disturbance  $f_\alpha$ , which is estimated and compensated in real time by the ESO.

The TD provides a smooth transition process for the baseline landing angle of attack command. During an ideal landing process, the input angle of attack command remains constant. Its discrete form is expressed as:

$$\begin{cases} \alpha_{d1}(k+1) = \alpha_{d1}(k) + h \cdot \alpha_{d2}(k) \\ \alpha_{d2}(k+1) = \alpha_{d2}(k) + h \cdot \text{fhan}(\alpha_{d1}(k) - \alpha_c(k), \alpha_{d2}(k), r_\alpha, h_{\alpha0}) \end{cases} \quad (22)$$

where  $h$  is the simulation time step of the system;  $\alpha_{d1}(k)$  is the tracking signal of the angle of attack reference command, which is used for subsequent angle of attack tracking error calculation;  $\alpha_{d2}(k)$  is the differential estimation signal of the angle of attack reference command, which is used for subsequent differential error calculation;  $\alpha_c(k)$  is the baseline landing angle of attack reference command;  $r_\alpha$  is the speed factor of the stabilator channel TD;  $h_{\alpha0}$  is the filtering factor;  $\text{fhan}(\cdot)$  is the fastest control synthesis function, whose definition is given in Equation (13).

Based on the reference signal from the TD and the state estimation values from the ESO, a second-order nonlinear state error feedback control law is constructed to generate the stabilator deflection control command  $\delta_{S,ADRC}$  prior to the decoupling module:

$$\begin{cases} e_{\alpha1}(k) = \alpha_{d1}(k) - z_{\alpha1}(k) \\ e_{\alpha2}(k) = \alpha_{d2}(k) - z_{\alpha2}(k) \\ u_{\alpha0}(k) = k_{p\alpha} \cdot \text{fal}(e_{\alpha1}(k), \alpha_{\alpha1}, \delta_\alpha) + k_{d\alpha} \cdot \text{fal}(e_{\alpha2}(k), \alpha_{\alpha2}, \delta_\alpha) \\ \delta_{S,ADRC}(k) = \frac{u_{\alpha0}(k) - z_{\alpha3}(k)}{b_{\alpha0}} \end{cases} \quad (23)$$

where  $e_{\alpha1}(k)$  is the tracking error of the angle of attack;  $e_{\alpha2}(k)$  is the differential tracking error of the angle of attack;  $k_{p\alpha}$  is the nonlinear proportional gain;  $k_{d\alpha}$  is the nonlinear differential gain;  $\alpha_{\alpha1}$  and  $\alpha_{\alpha2}$  are nonlinear factors, which are set to satisfy  $0 < \alpha_{\alpha1} < 1 < \alpha_{\alpha2}$  in engineering practice;  $\delta_\alpha$  is the width of the linear segment of the fal function;  $\delta_{S,ADRC}(k)$  is the stabilator deflection command before passing through the decoupling module.

Since flap deflection will also cause variations in the angle of attack, a command  $\delta_{S,dec}$  output by the feedforward decoupling module for flap deflection will be introduced in the subsequent section to counteract the pitching moment coupling induced by flap deflection. The final control command input to the stabilator is given by:

$$\delta_S(k) = \delta_{S,ADRC}(k) + \delta_{S,dec}(k) \quad (24)$$

### 3.2.3. Design of the Throttle Channel ADRC Controller

The control objective of the throttle channel is to maintain a constant approach speed. Based on the carrier-based aircraft dynamic model established in Section 2, the dynamic equation of flight speed is written as:

$$m\dot{V} = F \cos \alpha - D - mg \sin \gamma \quad (25)$$

Under landing conditions, the engine operates within a steady-state low-throttle range, where the thrust exhibits a linear relationship with throttle opening, expressed as:

$$F = C_{\delta_{PL}} \delta_{PL} \quad (26)$$

where  $C_{\delta_{PL}}$  denotes the throttle thrust coefficient. Substituting Equation (26) into Equation (25) yields:

$$\dot{V} = \frac{C_{\delta_{PL}} \cos \alpha}{m} \delta_{PL} - \frac{D}{m} - g \sin \gamma \quad (27)$$

All terms independent of the throttle control input  $\delta_{PL}$  are grouped as the system total disturbance  $f_V$ , and the control gain of the throttle channel is defined as  $b_V$ , namely:

$$\begin{cases} f_V = -\frac{D}{m} - g \sin \gamma \\ b_V = \frac{C_{\delta_{PL}} \cos \alpha}{m} \end{cases} \quad (28)$$

The standard form of the controlled plant for the throttle channel is derived as:

$$\dot{V} = f_V + b_V \delta_{PL} \quad (29)$$

Equation (29) shows that the controlled plant of the throttle channel is a first-order dynamic system. Considering the first-order dynamic characteristics of the engine, a second-order ADRC controller is adopted for design. Meanwhile, aerodynamic drag perturbations, carrier air wake disturbances and other uncertainties are all incorporated into the total disturbance  $f_V$ , which is estimated and compensated in real time via the ESO.

The TD provides a smooth transition process for the baseline landing speed command. During an ideal landing process, the input speed command maintains a constant value. Its discrete form is expressed as:

$$\begin{cases} V_{d1}(k+1) = V_{d1}(k) + h \cdot V_{d2}(k) \\ V_{d2}(k+1) = V_{d2}(k) + h \cdot \text{fhan}(V_{d1}(k) - V_c(k), V_{d2}(k), r_V, h_{V0}) \end{cases} \quad (30)$$

where  $h$  is the simulation time step of the system;  $V_{d1}(k)$  is the tracking signal of the speed reference command, which is used for subsequent error calculation;  $V_{d2}(k)$  is the differential estimation signal of the reference command, which is used for subsequent differential error calculation;  $V_c(k)$  is the baseline landing speed reference command;  $r_V$  is the speed factor;  $h_{V0}$  is the filtering factor;  $\text{fhan}(\cdot)$  is the fastest control synthesis function, whose definition is given in Equation (13).

For the second-order controlled plant, a third-order nonlinear discrete extended state observer is designed to perform real-time estimation of the actual speed and the system total disturbance. Its discrete form is given by:

$$\begin{cases} e_V(k) = z_{V1}(k) - V(k) \\ \text{fe}_V = \text{fal}(e_V(k), \alpha_{V01}, \delta_{V0}), \text{fe}_{V1} = \text{fal}(e_V(k), \alpha_{V02}, \delta_{V0}) \\ z_{V1}(k+1) = z_{V1}(k) + h \cdot (z_{V2}(k) - \beta_{V01} \cdot e_V(k)) \\ z_{V2}(k+1) = z_{V2}(k) + h \cdot (z_{V3}(k) - \beta_{V02} \cdot \text{fe}_V + b_{V0} \cdot \delta_{PL}(k)) \\ z_{V3}(k+1) = z_{V3}(k) - h \cdot \beta_{V03} \cdot \text{fe}_{V1} \end{cases} \quad (31)$$

where  $V(k)$  is the feedback value of the actual speed of the carrier-based aircraft at time step  $k$ ;  $\delta_{PL}(k)$  is the throttle opening control command at time step  $k$ ;  $z_{V1}(k)$  is the estimated value of speed;  $z_{V2}(k)$  is the estimated value of the speed derivative;  $z_{V3}(k)$  is the estimated value of the system total disturbance;  $b_{V0}$  is the estimated value of the control gain for the throttle channel;  $\beta_{V01}$ ,  $\beta_{V02}$  and  $\beta_{V03}$  are observer gains, which are tuned via the bandwidth method;  $\text{fal}(\cdot)$  is the nonlinear power function, whose definition is provided in Equation (15);  $\alpha_{V01}$  and  $\alpha_{V02}$  are nonlinear factors;  $\delta_{V0}$  is the width of the linear segment of the  $\text{fal}$  function.

Based on the reference signal from the tracking differentiator and the state estimation values from the extended state observer, a nonlinear state error feedback control law is constructed, and feedforward compensation is applied to the total disturbance to finally generate the throttle opening control command:

$$\begin{cases} e_{v1}(k) = V_{d1}(k) - z_{v1}(k) \\ e_{v2}(k) = V_{d2}(k) - z_{v2}(k) \\ u_{v0}(k) = k_{pv} \cdot \text{fal}(e_{v1}(k), \alpha_{v1}, \delta_v) + k_{dv} \cdot \text{fal}(e_{v2}(k), \alpha_{v2}, \delta_v) \\ \delta_{PL}(k) = \frac{u_{v0}(k) - z_{v3}(k)}{b_{v0}} \end{cases} \quad (32)$$

where  $e_{v1}(k)$  is the speed tracking error;  $e_{v2}(k)$  is the differential tracking error of speed;  $k_{pv}$  is the nonlinear proportional gain;  $k_{dv}$  is the nonlinear differential gain;  $\alpha_{v1}$  and  $\alpha_{v2}$  are nonlinear factors, which are set to satisfy  $0 < \alpha_{v1} < 1 < \alpha_{v2}$  in engineering practice;  $\delta_v$  is the width of the linear segment of the fal function;  $\delta_{PL}(k)$  is the final output throttle opening control command.

### 3.3. Design of the Decoupling Module

Flap deflection generates a direct lift increment while introducing an additional pitching moment, which induces passive fluctuations in the angle of attack and impairs attitude stability. Therefore, a decoupling module is required to counteract this aerodynamic coupling through synchronous reverse deflection of the stabilator. This paper adopts an adaptive decoupling scheme based on a first-order low-pass filter, which performs moment compensation only for the dynamic manipulation component of the flap to avoid over-compensation of steady-state trim deflections. The detailed implementation is described as follows.

A first-order low-pass filter is used to extract the steady-state trim deflection angle of the flap in real time, retaining only extremely slow steady-state variations and filtering out dynamic manipulation components:

$$\begin{cases} \alpha = \exp(-2\pi f_{cut} \cdot h) \\ \delta_{LEF,s}(k) = \alpha \cdot \delta_{LEF,s}(k-1) + (1-\alpha) \cdot \delta_{LEF}(k) \end{cases} \quad (33)$$

where  $f_{cut}$  is the cut-off frequency of the low-pass filter;  $h$  is the simulation time step;  $k$  is the discrete time step;  $\delta_{LEF}$  is the current deflection increment of the flap;  $\delta_{LEF,s}$  is the extracted steady-state trim deflection angle of the flap.

The flap increment related only to dynamic manipulation is calculated, and this increment approaches zero under steady-state trim conditions:

$$\delta_{LEF,d}(k) = \delta_{LEF}(k) - \delta_{LEF,s}(k) \quad (34)$$

Finally, the feedforward decoupling compensation command for the stabilator is generated, which performs moment compensation only for the dynamic manipulation of the flap:

$$\delta_{S,dec}(k) = K_{dec} \cdot \delta_{LEF,d}(k) \quad (35)$$

where  $K_{dec}$  is the compensation coefficient.

Adding this compensation quantity to the stabilator control output from the ADRC yields the final deflection increment input to the stabilator:

$$\delta_S(k) = \delta_{S,ADRC}(k) + \delta_{S,dec}(k) \quad (36)$$

## 4. Optimization

The three-channel ADRC controller has high parameter dimensionality and strong inter-channel coupling, making it difficult to achieve global optimization of multiple performance indicators through empirical tuning. This section proposes an Enhanced Pigeon-Inspired Optimization (EPIO) algorithm adapted to the carrier landing control scenario, and constructs a global collaborative tuning scheme for controller parameters to achieve high-performance optimization of the control system.

#### 4.1. Basic PIO

PIO is a swarm intelligence optimization algorithm that mimics the two-stage homing navigation behavior of carrier pigeons over long distances. It consists of two iterative phases: global search and local search.

The global search phase corresponds to the map and compass operator. Taking the global best individual in the population as the navigation benchmark, the algorithm performs large-scale directional search in the entire solution space, with the individual flight velocity gradually decreasing as the iteration proceeds, so as to quickly locate the potential region of the optimal solution.

The local search phase corresponds to the landmark operator. In each iteration, individuals are sorted according to their fitness values, and the bottom 50% of individuals with poorer fitness are eliminated. The weighted position center calculated from the fitness of the remaining high-quality individuals is taken as the landmark to guide the population to converge toward the optimal region, thus completing local refined optimization.

The basic PIO algorithm offers a concise parameter structure and fast convergence. However, when applied to high-dimensional multi-parameter tuning of the landing controller, it suffers from two major limitations. First, the fixed velocity attenuation factor tends to cause rapid loss of population diversity in the late iterations. Second, the fixed-proportion elimination rule often results in premature loss of potentially high-quality solutions. As a result, it generally suffers from premature convergence and insufficient optimization accuracy, which cannot fully meet the requirements of high-precision controller parameter tuning.

#### 4.2. Design of the EPIO Algorithm

Aiming at the core defects of the basic PIO algorithm, full-process improvement is implemented across three dimensions: population initialization, global search operator, and local search operator, to construct an EPIO algorithm tailored for the carrier landing control scenario.

##### 4.2.1. Hybrid Initialization Strategy

The basic algorithm initializes the population in a purely random manner, which results in non-uniform coverage of the solution space and tends to reduce the efficiency of early-stage global search. This paper adopts a hybrid initialization strategy that combines Latin Hypercube Sampling (LHS) with random sampling. This approach provides uniform coverage of the solution space while maintaining population randomness.

Let the initial population size be  $N$ , the dimensionality of the optimization problem be  $D$ , and the lower and upper bounds of the solution space be  $lb$  and  $ub$ , respectively.

The population is divided according to the following equation: 90% of the individuals are generated via LHS, and the remaining 10% are generated via random sampling:

$$\begin{cases} N_{lhs} = \lfloor N \times 0.9 \rfloor \\ N_{rand} = N - N_{lhs} \end{cases} \quad (37)$$

The two groups of individuals are then initialized by different methods, as expressed in the following equations:

$$\begin{cases} X_{lhs} = lb + (ub - lb) \cdot lhsdesign(N_{lhs}, D) \\ X_{rand} = lb + (ub - lb) \cdot rand(N_{rand}, D) \end{cases} \quad (38)$$

where  $lhsdesign(\cdot)$  denotes the Latin hypercube sampling function.

#### 4.2.2. Adaptive Map and Compass Operator

Aiming at the problems of population homogenization in the late iteration stage and vulnerability to premature convergence caused by the fixed attenuation factor, an adaptive weight mechanism and a Gaussian perturbation mechanism are introduced.

Let the total number of iterations in the global search phase be  $T_1$ . The improved velocity and position update formulas for the  $N_c$ -th iteration ( $1 \leq N_c \leq T_1$ ) are given by:

$$\begin{cases} V_i^{N_c} = V_i^{N_c-1} \cdot e^{-R \cdot N_c} + w_1 \cdot \text{rand} \cdot (X_{gbest} - X_i^{N_c-1}) + w_2 \cdot \text{randn}(1, D) \cdot S_{perturb} \\ X_i^{N_c} = X_i^{N_c-1} + V_i^{N_c} \end{cases} \quad (39)$$

where  $V_i^{N_c}$  and  $X_i^{N_c}$  are the velocity and position of the  $i$ -th individual at the  $N_c$ -th iteration, respectively;  $X_{gbest}$  is the position of the current global best individual in the population;  $R$  is the map and compass operator parameter;  $\text{rand}$  denotes a random number uniformly distributed in the interval  $[0, 1]$ , and  $\text{randn}(\cdot)$  denotes a standard normally distributed random number;  $w_1$  is the global best guidance weight,  $w_2$  is the random perturbation weight, and  $S_{perturb}$  is the random perturbation intensity. These three parameters are adaptively adjusted along with the iteration process, and the specific rules are as follows.

In the first one-third of the iteration process ( $N_c \leq T_1/3$ ): the core objective of the algorithm is to rapidly converge to the potential optimal region. Therefore, the random perturbation is disabled and only the global best guidance is retained, namely:

$$\begin{cases} w_1 = 1.0 \\ w_2 = 0.0 \\ S_{perturb} = 0.0 \end{cases} \quad (40)$$

In the latter two-thirds of the iteration process ( $T_1/3 < N_c \leq T_1$ ): the core objective is to maintain population diversity while ensuring convergence, so as to avoid premature convergence. The weights and perturbation intensity are adjusted linearly and smoothly along with the iteration process:

$$\begin{cases} \tau = \frac{N_c - T_1/3}{2T_1/3} \\ w_1 = 1.0 - 0.7 \cdot \tau \\ w_2 = 0.0 + 0.7 \cdot \tau \\ S_{perturb} = 0.1 + 0.2 \cdot \tau \end{cases} \quad (41)$$

where  $\tau$  is the normalized progress of the latter two-thirds of the iteration process, with a value range of  $[0, 1]$ .

For dimensions whose positions exceed the upper and lower bounds of the solution space after update, their positions are constrained to the boundary values, and the velocity of the corresponding dimension is set to zero. The map and compass operator phase is thus completed.

#### 4.2.3. Hierarchical Co-Evolutionary Landmark Operator

The fixed 50% population elimination rule in the basic algorithm is discarded, and a hierarchical co-evolution strategy is proposed. The population size remains unchanged throughout the local search phase, and individuals are divided into three layers according to their fitness ranking at a ratio of 1:2:7: the elite layer, the local exploitation layer, and the global exploration layer. Differentiated update strategies are implemented for each layer to balance convergence accuracy and population diversity. The hierarchical division is updated only twice, once at the initial stage and once in the middle of the local search phase, to reduce the computational overhead of the algorithm.

(1) Elite layer

Guided by the weighted centroid of the top 10% elite individuals, this layer avoids interference from inferior individuals with the convergence direction.

First, the weighted centroid of the elite layer  $X_{center}^{elite}$  is calculated, with the reciprocal of individual fitness as the weight. This ensures that individuals with better fitness contribute more to the centroid:

$$X_{center}^{elite} = \frac{\sum_{i=1}^{N_{elite}} X_i \cdot \frac{1}{F(X_i) + e^{-8}}}{\sum_{i=1}^{N_{elite}} \frac{1}{F(X_i) + e^{-8}}} \quad (42)$$

where  $F(X_i)$  is the fitness value of the  $i$ -th elite individual, and  $e^{-8}$  is a tiny positive constant to avoid division by zero.

The position of individuals in the elite layer is updated as follows:

$$X_i^{N_c} = X_i^{N_c-1} + \text{rand}(1, D) \cdot (X_{center}^{elite} - X_i^{N_c-1}) + S_{current} \cdot \text{randn}(1, D) \quad (43)$$

where  $S_{current}$  is the adaptive random perturbation amplitude, which decays linearly with the iteration process to balance early-stage exploration and late-stage exploitation:

$$S_{current} = S_{init} - (S_{init} - S_{end}) \cdot \frac{N_c - 1}{T_2 - 1} \quad (44)$$

where  $S_{init} = (ub - lb)/20$  is the initial perturbation amplitude, and  $S_{end} = (ub - lb)/100$  is the perturbation amplitude at the end of the iteration.

## (2) Local exploitation layer

A coordinate pattern search algorithm is introduced to replace the traditional centroid guidance. It enables refined optimization for black-box problems without relying on gradient information of the objective function, and achieves high-precision local exploitation within the potential optimal region.

For the  $i$ -th individual in the local exploitation layer, its current position  $X_i^{N_c-1}$  is taken as the initial search point  $X_{current}$ . The core parameters of the pattern search are defined as follows:  $D$  is the dimensionality of the optimization problem;  $lb_j$  and  $ub_j$  are the lower and upper bounds of the  $j$ -th dimension in the feasible solution space; the initial search step size of the  $j$ -th dimension is  $step_{init,j} = (ub_j - lb_j)/10$ , and the minimum convergence step size is  $step_{min,j} = 10^{-6}$ . A dimension-wise step state matrix  $step_{state}(i, j)$  is maintained for each individual to record the current search step size of the  $j$ -th dimension for the  $i$ -th individual.

Centered on the initial point, the pattern search performs forward and reverse probing dimension by dimension in sequence. For the  $j$ -th dimension, two trial points are generated as:

$$\Pi_j = \{X_{current} \pm step_{state}(i, j) \cdot \mathbf{e}_j\} \quad (45)$$

where  $step_{state}(i, j)$  is the current search step size of the  $j$ -th dimension for the  $i$ -th individual, and  $\mathbf{e}_j$  is the unit coordinate vector of the  $j$ -th dimension. To ensure the feasibility of trial points, boundary clipping is applied to each trial point:

$$X_p = \max(\min(X_p, ub_j), lb_j), \quad \forall X_p \in \Pi_j \quad (46)$$

The fitness values of the two forward and reverse trial points in the  $j$ -th dimension are calculated sequentially, and the trial point  $X_{best,j}$  with the optimal fitness in this dimension is selected. Its fitness value  $F_{best,j}$  satisfies:

$$\begin{cases} F_{best,j} = \min\{F(X_p) | X_p \in \Pi_j\} \\ X_{best,j} = \arg \min\{F(X_p) | X_p \in \Pi_j\} \end{cases} \quad (47)$$

where  $F(\cdot)$  is the fitness function of the optimization problem. According to the fitness of the optimal trial point, the search step size is adaptively adjusted and the search starting point is updated: if a better solution is found, the search starting point is updated and the step size is maintained to expand the search range; if no better solution is found, the step size is reduced by half to refine the search granularity. The specific rules are:

$$\begin{cases} X_{current} = X_{best,j}, & F_{best,j} < F_{current} \\ step_{state}(i,j) = step_{state}(i,j) \times 0.5, & F_{best,j} \geq F_{current} \end{cases} \quad (48)$$

where  $F_{current}$  is the fitness value of the current search starting point. During the dimension-wise search, if the current step size of a dimension is smaller than its minimum step size  $step_{min,j}$ , the probing of this dimension is skipped. After traversing all dimensions, the final optimal search starting point is taken as the updated position of the individual in this iteration, i.e.,  $X_i^{N_c} = X_{current}$ .

### (3) Global exploration layer

The positions of individuals are updated through full-solution-space random sampling, which continuously injects diversity into the population and prevents the algorithm from being trapped in local optima:

$$X_i^{N_c} = lb + (ub - lb) \cdot \text{rand}(1, D) \quad (49)$$

Finally, boundary constraint processing is uniformly applied to all individuals. The historical best position of each individual and the global best position are updated, and the convergence curve data of this iteration is recorded.

### 4.2.4. Overall Algorithm Flow

The pseudocode of the algorithm is presented in Algorithm 1.

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#### Algorithm 1 Pseudocode of the EPIO

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1: Hybrid Initialization Strategy
2: for  $i = 1 : N$  do
3:   Initialize population positions by Equations (37) and (38)
4:   Calculate individual fitness
5: end for
6: Record the optimal fitness  $F_{gbest}$  and the corresponding individual  $X_{gbest}$ 
7: Adaptive Map and Compass Operator
8: for  $N_c = 1 : T_1$  do
9:   Set weight and disturbance intensity by Equations (40) and (41) in stages
10:  for  $i = 1 : N$  do
11:    Update the velocity and position of the  $i$ -th individual by Equation (39)
12:    Apply boundary constraints and record the current individual best and global best
13:  end for
14: end for
15: Hierarchical Co-evolutionary Landmark Operator
16: for  $N_c = 1 : T_2$  do
17:   if  $N_c == 1 \parallel N_c == T_2/2$  then
18:     Divide into elite layer, local exploitation layer, and global exploration layer at a ratio of 1:2:7
19:   end if
20:   for each elite layer do
21:     Update positions of the elite layer by Equations (42), (43) and (44)
22:   end for
23:   for each local exploitation layer do
24:     Perform dimension-wise exploration and update by Equations (45)–(48)
25:   end for
26:   for each global exploration layer do

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27:   Perform random update over the entire solution space by Equation (49)
28:   end for
29:   Update the current individual best and global best
30: end for
31: Result Output
32: Output the optimal position and corresponding fitness

```

---

#### 4.3. Parameter Tuning Scheme for Landing Controller Based on EPIO

The EPIO algorithm is adopted to realize global collaborative tuning of multiple parameters for the three-channel ADRC controller. To this end, the tuning parameters of the three-channel ADRC and the fitness function must first be defined.

##### 4.3.1. Design of Parameters to Be Tuned

The parameters of the three-channel ADRC controller fall into two categories: nonlinear configuration parameters and core performance parameters. To reduce the optimization dimensionality and improve tuning efficiency, the nonlinear configuration parameters that have a minor impact on system performance and have general engineering values are manually fixed. Only the core performance parameters that determine the tracking accuracy, response speed and disturbance rejection capability of the system are included in the optimization search space.

Meanwhile, the bandwidth method is applied to realize collaborative tuning of the observer gain parameters, which converts multiple groups of observer gains into a single bandwidth parameter to further compress the optimization dimensionality.

For the second-order ESO in the flap channel, the gain parameters are determined by the bandwidth  $\omega_{o\gamma}$ , satisfying the following equations:

$$\begin{cases} \beta_{\gamma 01} = 2\omega_{o\gamma} \\ \beta_{\gamma 02} = \omega_{o\gamma}^2 \end{cases} \quad (50)$$

For the third-order ESO in the stabilator channel, the gain parameters are determined by the bandwidth  $\omega_{o\alpha}$ , satisfying the following equations:

$$\begin{cases} \beta_{\alpha 01} = 3\omega_{o\alpha} \\ \beta_{\alpha 02} = 3\omega_{o\alpha}^2 \\ \beta_{\alpha 03} = \omega_{o\alpha}^3 \end{cases} \quad (51)$$

For the third-order ESO in the throttle channel, the gain parameters are determined by the bandwidth  $\omega_{oV}$ , satisfying the following equations:

$$\begin{cases} \beta_{V 01} = 3\omega_{oV} \\ \beta_{V 02} = 3\omega_{oV}^2 \\ \beta_{V 03} = \omega_{oV}^3 \end{cases} \quad (52)$$

After screening, an 11-dimensional parameter set is adopted as the optimization search space, which greatly reduces the complexity of the optimization problem while ensuring adequate coverage of control performance. The final parameters to be tuned are shown in Table 5.

**Table 5.** EPIO Tuning Parameters.

| Channel            | Tuning Parameters                                          |
|--------------------|------------------------------------------------------------|
| Flap Channel       | $\omega_{o\gamma}, b_{\gamma 0}, k_{\gamma}$               |
| Stabilator Channel | $\omega_{o\alpha}, b_{\alpha 0}, k_{p\alpha}, k_{d\alpha}$ |
| Throttle Channel   | $\omega_{oV}, b_{V 0}, k_{pV}, k_{dV}$                     |

#### 4.3.2. Design of the Fitness Function

The fitness function is constructed via the weighted fusion of the undisturbed nominal condition and the carrier air wake disturbance condition, ensuring that the tuned parameters balance both nominal tracking accuracy and disturbance rejection capability in complex environments.

##### (1) Performance index calculation under a single condition

Let the total simulation duration be  $T_s$ , and the tracking errors of each control variable are defined as follows.

Flight path angle rate tracking error:

$$e_{\dot{\gamma}}(t) = \dot{\gamma}_{ref}(t) - \dot{\gamma}(t) \quad (53)$$

where  $\dot{\gamma}_{ref}(t)$  is the flight path angle rate command, and  $\dot{\gamma}(t)$  is the actual flight path angle rate.

Angle of attack holding error:

$$e_{\alpha}(t) = \alpha_{ref}(t) - \alpha(t) \quad (54)$$

where  $\alpha_{ref}(t)$  is the fixed baseline angle of attack command, and  $\alpha(t)$  is the actual angle of attack.

Speed holding error:

$$e_V(t) = V_{ref}(t) - V(t) \quad (55)$$

where  $V_{ref}(t)$  is the fixed baseline speed command, and  $V(t)$  is the actual flight speed.

The comprehensive performance index  $J_{single}$  under a single condition is the weighted sum of the three errors, expressed as:

$$J_{single} = w_{\dot{\gamma}} \cdot \frac{1}{T_s} \int_0^{T_s} |e_{\dot{\gamma}}(t)| dt + w_{\alpha} \cdot \frac{1}{T_s} \int_0^{T_s} |e_{\alpha}(t)| dt + w_V \cdot \frac{1}{T_s} \int_0^{T_s} |e_V(t)| dt \quad (56)$$

where  $w_{\dot{\gamma}}$ ,  $w_{\alpha}$  and  $w_V$  are the weight coefficients of flight path angle rate, angle of attack and speed, respectively. The weights are set according to the priority of carrier landing control objectives.

##### (2) Overall fitness function

Let the performance index under the undisturbed nominal condition be  $J_{nom}$ , and the performance index under the carrier air wake disturbance condition be  $J_{dist}$ . The overall fitness function  $J$  is the weighted sum of the two condition indices:

$$J = w_{nom} \cdot J_{nom} + w_{dist} \cdot J_{dist} \quad (57)$$

where  $w_{nom}$  and  $w_{dist}$  are the weight coefficients of the nominal condition and the disturbance condition, respectively.

The weight coefficients are determined empirically according to the priority of carrier landing control objectives. Specifically,  $w_{\dot{\gamma}} = 0.85$ ,  $w_{\alpha} = 0.1$ ,  $w_V = 0.05$ ,  $w_{nom} = 0.75$  and  $w_{dist} = 0.25$ . The large weight on flight path angle rate ensures rapid trajectory tracking, while the substantial weight on angle of attack maintains attitude stability. The numerical gap between these two weights mainly reflects their different physical dimensions rather than a lower priority for attitude control. Airspeed receives the smallest weight because its variation during the approach is relatively tolerant. The nominal condition is weighted higher than the disturbed one, since zero steady-state error under ideal conditions is the primary requirement; additionally, the fitness under disturbance is inherently much larger, so a lower weight is used to avoid overemphasizing disturbance rejection at the expense of nominal performance.

To assess the sensitivity of the optimization results to the weighting coefficients, each weight was varied within a reasonable range while keeping the others fixed. The results

show that the controller performance remains stable when  $w_\gamma$  is between 0.75 and 0.9, when  $w_\alpha/w_v$  is between 1.5 and 3, and when  $w_{nom}/w_{dist}$  is between 2 and 4. Within these ranges, no notable degradation in tracking accuracy or attitude stability is observed. The chosen weights all lie within these bounds, indicating that the optimization outcome is not sensitive to the exact weight values.

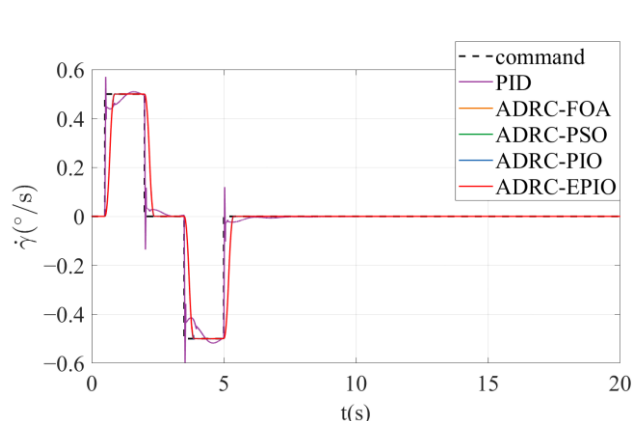
The overall fitness function serves as the objective to be minimized: a smaller value indicates better comprehensive control performance of the ADRC parameter set. Taking this function as the optimization criterion, the EPIO algorithm completes the high-performance tuning of the ADRC parameters.

## 5. Simulation Results

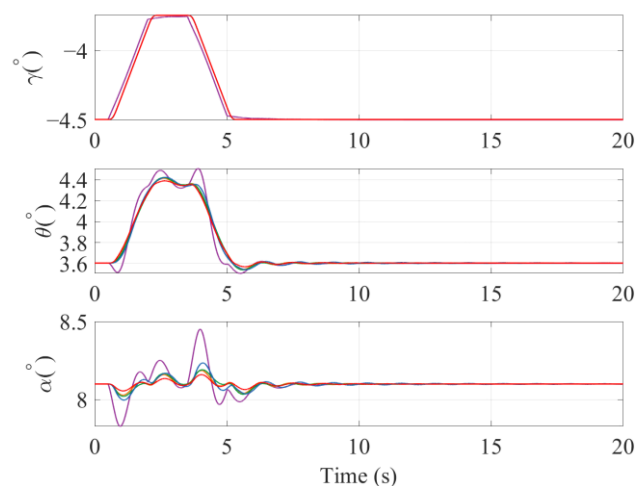
In this section, a closed-loop simulation platform is established in MATLAB/Simulink 2022a (MathWorks, Natick, MA, USA) using the models constructed in previous sections, serving as the basis for comprehensive performance evaluation of the proposed control system. Five control schemes are compared: a PID controller with EPIO tuning, ADRC with FOA, PSO, PIO, and the proposed EPIO. Four types of experiments are conducted—nominal step, disturbance step, full landing process, and Monte Carlo simulation—to evaluate tracking accuracy, decoupling, disturbance rejection, and robustness. To ensure fair comparison among stochastic optimization algorithms, all were run 10 times independently with a population size of 50 and 20 iterations, and the 5th-best fitness value was selected as the representative parameter set for subsequent simulations to mitigate the influence of random variations.

### 5.1. Comparative Test of Controller Performance Under Undisturbed Conditions

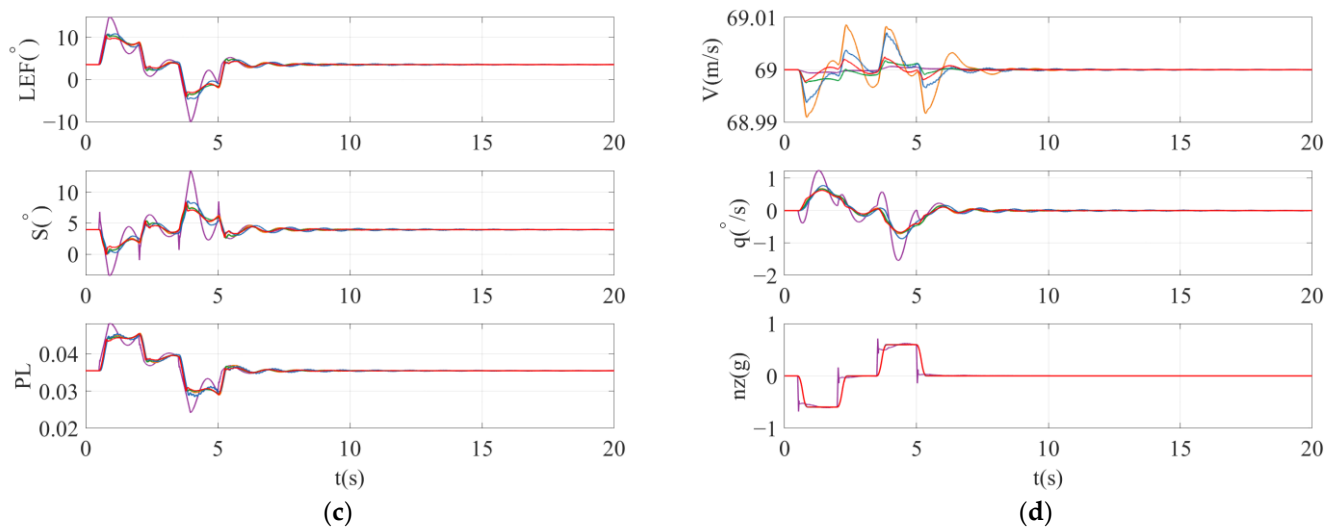
Under undisturbed conditions, a step command of flight path angle rate is applied, with the reference angle of attack ( $8.1^\circ$ ) and reference velocity (69 m/s) kept constant, to verify the nominal tracking and decoupling performance of the system. The simulation results are presented in Figure 4.



(a)



(b)

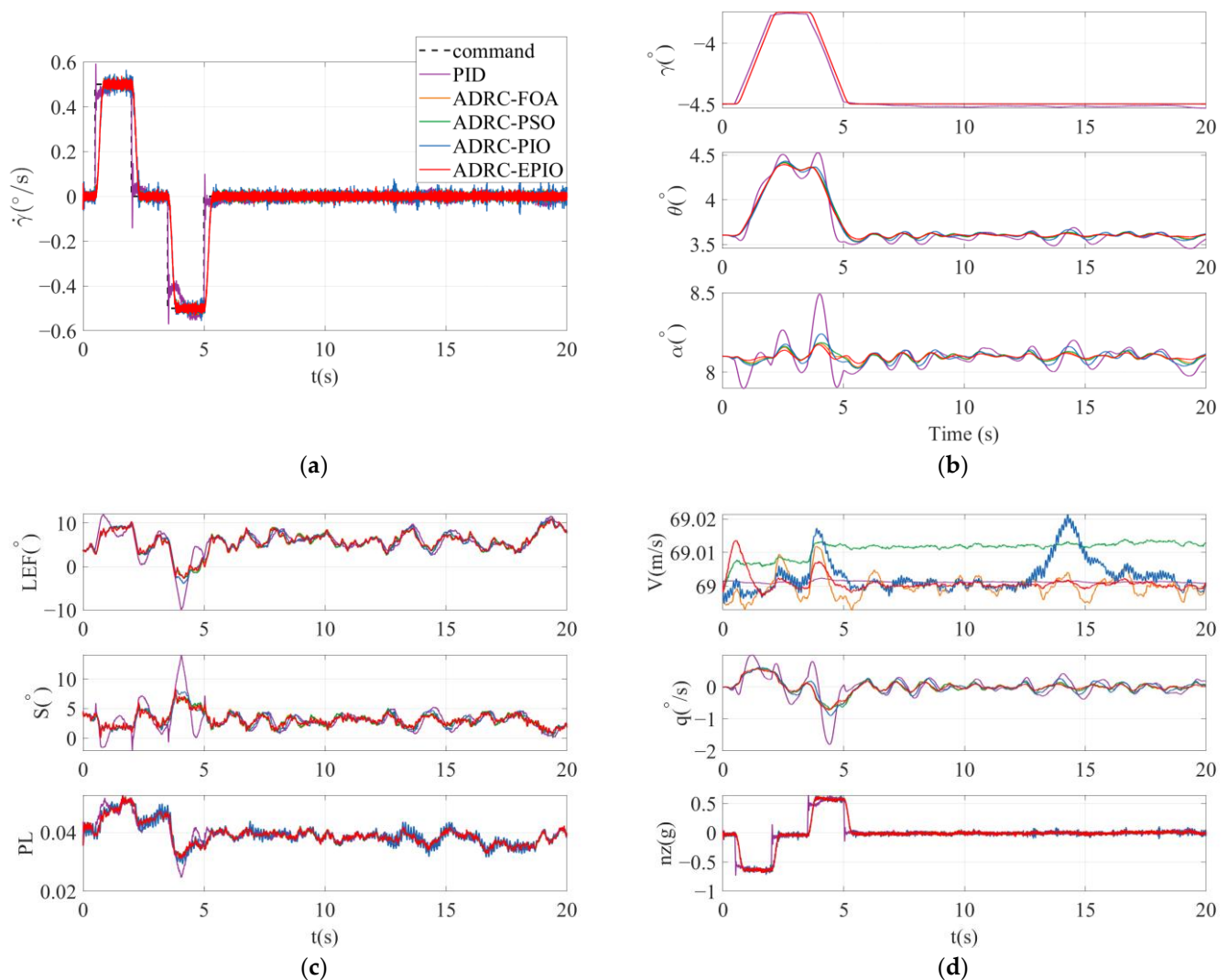


**Figure 4.** Comparison of flight responses under undisturbed conditions. (a) Flight path angle rate; (b) flight path angle, pitch angle and angle of attack; (c) deflection of leading-edge flap, stabilator and throttle command; (d) flight velocity, pitch rate and normal load factor.

The results presented in Figure 4 demonstrate that all five control schemes achieve zero steady-state error tracking of the flight path angle rate command under undisturbed conditions. However, noticeable differences exist in their dynamic responses. The PID controller exhibits a distinct overshoot with a relatively slow settling time, whereas all four ADRC-based schemes, benefiting from the transition process arranged by the Tracking Differentiator, achieve rapid and overshoot-free tracking. In terms of attitude holding, PID control results in considerable fluctuations in the angle of attack during the transient phase, while all four ADRC-based schemes maintain the angle of attack stable near the reference value throughout the process. Among the four ADRC-based schemes, the proposed ADRC-EPIO achieves a smaller fluctuation amplitude and a more rapid return to the steady-state value. All control surfaces deflect smoothly without chattering or saturation across all five schemes. Regarding velocity maintenance, PID exhibits the smallest speed deviation, while all ADRC-based schemes maintain the velocity fluctuation within 0.1 m/s, which satisfies the technical requirements for carrier landing conditions. Under undisturbed conditions, the proposed ADRC-EPIO shows improved performance in terms of tracking rapidity, attitude holding, and control smoothness compared with the other ADRC-based schemes.

## 5.2. Comparative Test of Controller Performance Under Disturbance Conditions

On the basis of the above experiments, carrier air wake disturbance is introduced to verify the disturbance rejection capability of the system. The simulation results are shown in Figure 5.



**Figure 5.** Comparison of flight responses under disturbance conditions. (a) Flight path angle rate; (b) flight path angle, pitch angle and angle of attack; (c) deflection of leading-edge flap, stabilator and throttle command; (d) flight velocity, pitch rate and normal load factor.

The results presented in Figure 5 demonstrate that, under carrier air wake disturbance, all five control schemes are capable of tracking the flight path angle rate command. The PID controller, however, exhibits an obvious overshoot in the transient phase and tends to produce low-frequency oscillations of a certain amplitude under the influence of the disturbance. In contrast, the four ADRC-based schemes achieve rapid overshoot-free tracking. In terms of attitude holding, the PID control results in relatively large fluctuations in the angle of attack, whereas the four ADRC-based schemes maintain the angle of attack stable near the reference value. Among the four ADRC-based schemes, the proposed ADRC-EPIO shows slightly smaller fluctuations in angle of attack during the transient phase. The control surface deflections of all five schemes are smooth and free from chattering or saturation. Regarding velocity maintenance, all five schemes keep the speed fluctuation within 0.1 m/s, which satisfies the technical requirements for carrier landing conditions. Overall, under disturbance conditions, the four ADRC-based schemes show improved performance over PID in terms of tracking rapidity, disturbance attenuation, and attitude holding, with the proposed ADRC-EPIO performing competitively among the ADRC-based schemes.

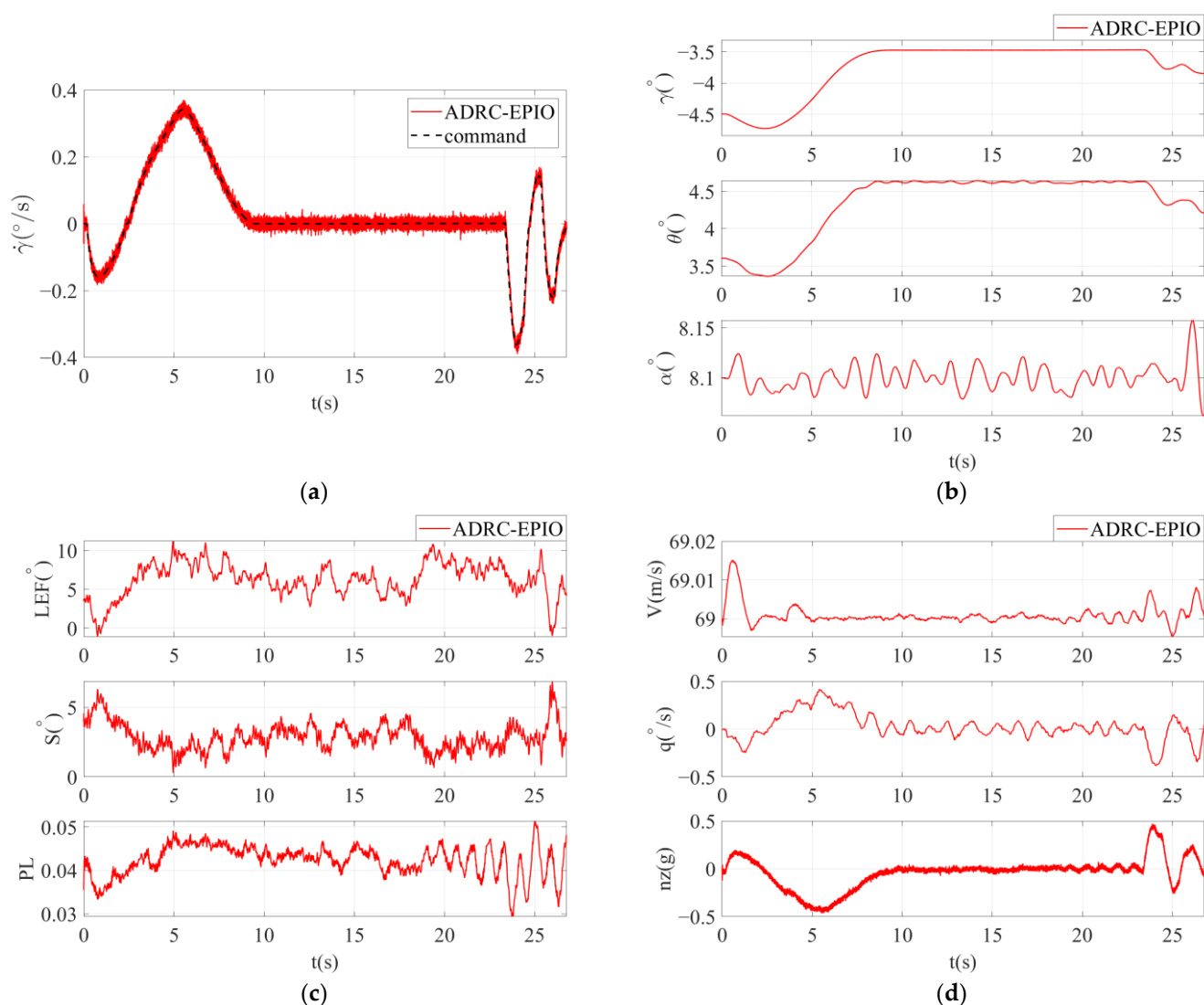
### 5.3. Simulation Verification of Full Carrier Landing Process

Four sets of landing conditions with different initial approach positions are set, with deck motion and carrier air wake disturbance superimposed throughout the process. When the altitude of the carrier-based aircraft is 15 m above the carrier deck, it tracks the ideal glideslope; when the altitude is below 15 m, it tracks the real-time glideslope, so as to verify the engineering applicability of the system. The initial conditions of the four cases are listed in Table 6.

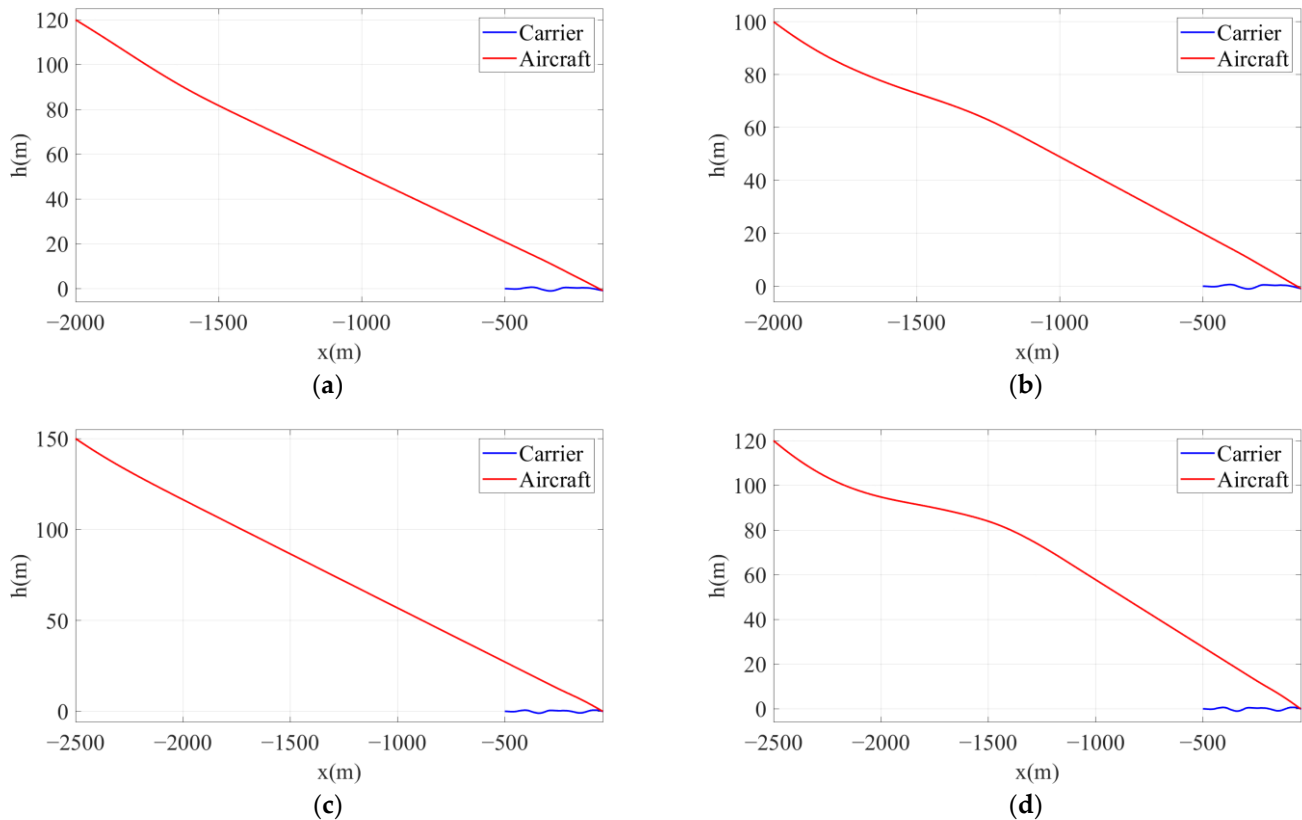
**Table 6.** Initial conditions of four cases.

| Case | $x_{ship}$ (m) | $H_{carrier}$ (m) | $x_{carrier}$ (m) |
|------|----------------|-------------------|-------------------|
| 1    | −500           | 120               | −2000             |
| 2    | −500           | 100               | −2000             |
| 3    | −500           | 150               | −2500             |
| 4    | −500           | 120               | −2500             |

The landing process response under a typical case is shown in Figure 6, the two-dimensional landing trajectories of the four cases are shown in Figure 7, and the landing performance statistics are presented in Table 7.



**Figure 6.** Comparison of flight responses during the landing process under a typical scenario. (a) Flight path angle rate; (b) flight path angle, pitch angle and angle of attack; (c) deflection of leading-edge flap, stabilator and throttle command; (d) flight velocity, pitch rate and normal load factor.



**Figure 7.** Comparison of two-dimensional longitudinal landing trajectories under four cases. (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4.

To quantitatively evaluate the landing performance of the proposed control system, a successful landing is herein defined as a touchdown point falling within a longitudinal deviation of  $\pm 10$  m from the ideal touchdown point on the carrier deck. This criterion is adopted because multiple arresting wires are distributed within this range, and an aircraft touchdown within this zone can be safely arrested.

**Table 7.** Landing time and longitudinal error under four test cases.

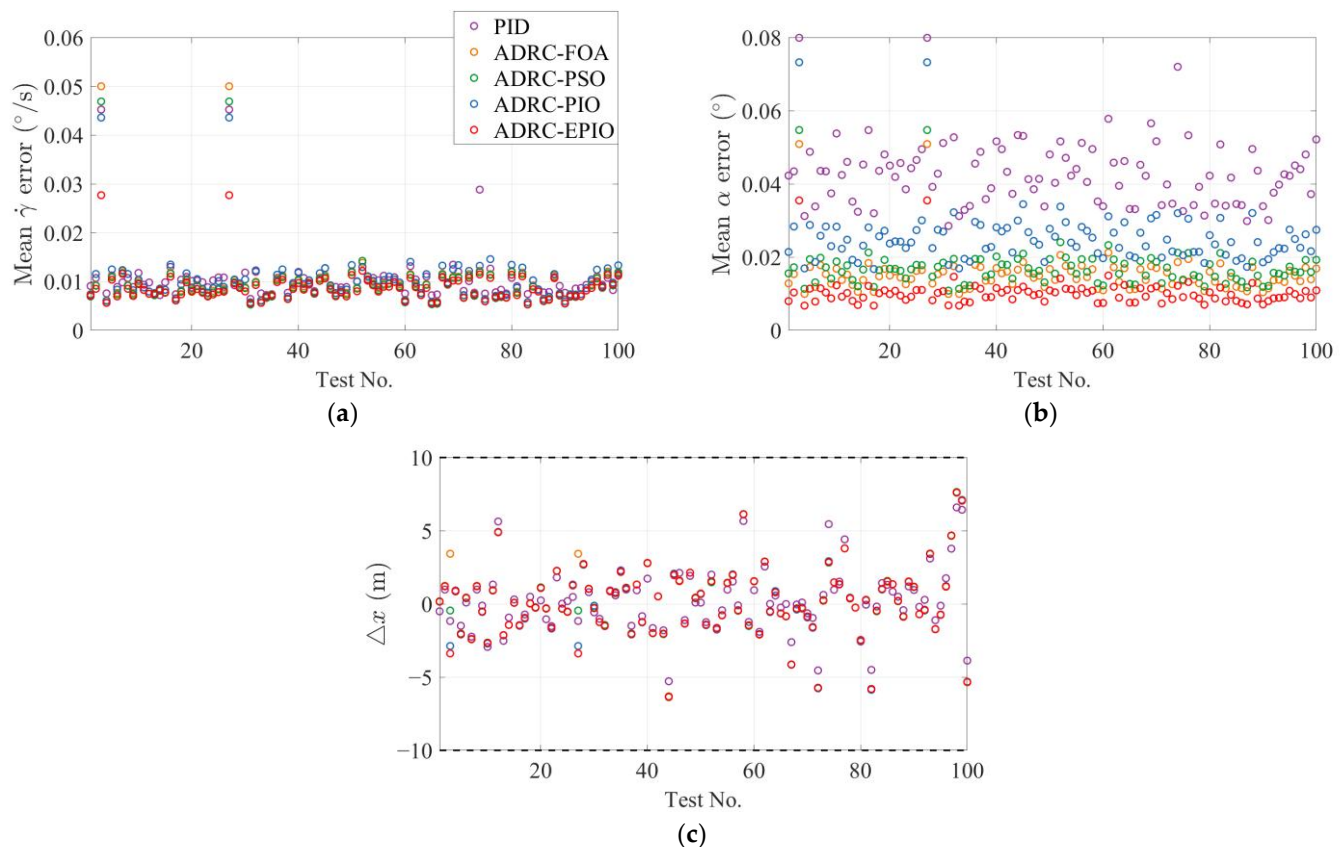
| Case | Landing Time (s) | Longitudinal Error (m) |
|------|------------------|------------------------|
| 1    | 26.76            | -1.74                  |
| 2    | 26.75            | -0.91                  |
| 3    | 35.67            | -2.07                  |
| 4    | 35.64            | -2.60                  |

The simulation results show that the proposed control system is capable of rapidly correcting the trajectory under different initial deviations. The flight path angle rate tracks the command smoothly throughout the landing process, and the angle of attack fluctuation is maintained within  $0.1^\circ$  across all four test cases. The control surface deflections remain smooth without chattering or saturation, and the velocity fluctuation is kept within 0.1 m/s. All four cases achieve successful landing, with longitudinal deviations of

−1.74 m, −0.91 m, −2.07 m, and −2.60 m, respectively, and the absolute value of the maximum deviation being 2.60 m. These results demonstrate the engineering applicability of the proposed scheme under the simulation conditions.

#### 5.4. Monte Carlo Statistical Verification and Robustness Analysis

A total of 100 independent Monte Carlo simulations are conducted with randomly set initial state deviations, deck motion amplitudes and carrier air wake disturbance gains, to statistically evaluate system performance under uncertain conditions. The comparison results are presented in Figure 8 and Table 8.



**Figure 8.** Statistical performance comparison under Monte Carlo simulations. (a) Mean flight path angle rate error; (b) mean angle of attack error; (c) longitudinal landing position error.

**Table 8.** Statistical results of Monte Carlo simulations.

| Controller | Success Rate (%) | Mean Longitudinal Error (m) | Std. Dev. of Longitudinal Error (m) | Mean Flight Path Angle Rate Error (°/s) | Std. Dev. of Flight Path Angle Rate Error (°/s) | Mean Angle of Attack Error (°) | Std. Dev. of Angle of Attack Error (°) |
|------------|------------------|-----------------------------|-------------------------------------|-----------------------------------------|-------------------------------------------------|--------------------------------|----------------------------------------|
| PID        | 100.0            | 1.493                       | 2.110                               | 0.0106                                  | 0.0056                                          | 0.0431                         | 0.0093                                 |
| ADRC-FOA   | 100.0            | 1.753                       | 2.377                               | 0.0098                                  | 0.0061                                          | 0.0153                         | 0.0057                                 |
| ADRC-PSO   | 100.0            | 1.692                       | 2.333                               | 0.0094                                  | 0.0057                                          | 0.0171                         | 0.0061                                 |
| ADRC-PIO   | 100.0            | 1.748                       | 2.379                               | 0.0102                                  | 0.0053                                          | 0.0254                         | 0.0081                                 |
| ADRC-EPIO  | 100.0            | 1.749                       | 2.382                               | 0.0088                                  | 0.0032                                          | 0.0103                         | 0.0041                                 |

The statistical results indicate that all five control schemes achieve a 100% landing success rate. The proposed ADRC-EPIO scheme yields a mean angle of attack error of only 0.0103°, which is 76.1% lower than PID (0.0431°), 32.7% lower than ADRC-FOA (0.0153°), 39.8% lower than ADRC-PSO (0.0171°), and 59.4% lower than ADRC-PIO (0.0254°),

demonstrating a significant advantage in attitude holding. The mean flight path angle rate error of ADRC-EPIO reaches  $0.0088^\circ/\text{s}$ , which is 17.0% lower than PID ( $0.0106^\circ/\text{s}$ ) and 13.7% lower than ADRC-PIO ( $0.0102^\circ/\text{s}$ ). In terms of standard deviation, ADRC-EPIO achieves  $0.0032^\circ/\text{s}$  for flight path angle rate error and  $0.0041^\circ$  for angle of attack error, both of which are the smallest among all compared schemes, indicating superior robustness and consistency.

To further substantiate these findings, statistical significance tests were performed. Table 9 reports the ANOVA  $p$ -values for overall differences among the five schemes, along with two-tailed paired  $t$ -test results between ADRC-EPIO and each competitor.

**Table 9.** Statistical significance tests for key control metrics.

| Metric                                             | ANOVA $p$ -Value | Paired Two-Tailed $t$ -Test (ADRC-EPIO vs.) |           |           |           |
|----------------------------------------------------|------------------|---------------------------------------------|-----------|-----------|-----------|
|                                                    |                  | PID                                         | ADRC-PIO  | ADRC-PSO  | ADRC-FOA  |
| Flight path angle rate error ( $^\circ/\text{s}$ ) | 0.1312           | <0.0001 *                                   | <0.0001 * | 0.0248 *  | 0.0012 *  |
| Angle of attack error ( $^\circ$ )                 | <0.0001 *        | <0.0001 *                                   | <0.0001 * | <0.0001 * | <0.0001 * |

Note: Asterisks (\*) indicate  $p < 0.05$ , the standard significance level in statistical hypothesis testing.

For angle of attack error, both ANOVA ( $p < 0.0001$ ) and all paired  $t$ -tests ( $p < 0.0001$ ) confirm highly significant differences, providing strong statistical evidence that ADRC-EPIO consistently outperforms the other schemes in maintaining angle of attack stability.

For flight path angle rate error, the ANOVA result is not significant ( $p = 0.1312$ ), suggesting that the overall mean differences among the five schemes are relatively small. This is consistent with the descriptive statistics, where the mean error differences are all below  $0.002^\circ/\text{s}$ . Nevertheless, the paired  $t$ -tests yield  $p$ -values below 0.05 for all four comparisons ( $p < 0.0001$  vs. PID and PIO,  $p = 0.0248$  vs. PSO,  $p = 0.0012$  vs. FOA), revealing a subtle but systematic advantage of EPIO under identical disturbance conditions. This advantage, together with its substantially smaller standard deviation, confirms that EPIO enhances both the accuracy and the robustness of trajectory tracking.

Overall, the Monte Carlo results demonstrate that ADRC-EPIO offers statistically reliable improvements in both mean accuracy and consistency, with the latter being particularly pronounced. The system exhibits robust stability under the tested uncertain conditions.

## 6. Conclusions

Aiming at the problems of strong trajectory–attitude coupling, high pilot workload and insufficient disturbance rejection capability in traditional carrier-based aircraft landing control, this paper designs a three-channel ADRC landing system based on direct lift technology, and proposes an EPIO algorithm to realize global collaborative tuning of controller parameters. Verified by multiple groups of simulation experiments, the main conclusions are drawn as follows:

- (1) A human–machine closed-loop simulation environment is established, which integrates the longitudinal nonlinear dynamics model of carrier-based aircraft, the carrier air wake and deck motion disturbance model, and the fuzzy virtual pilot model. Typical environmental disturbances and manual manipulation characteristics during landing are taken into account, providing a simulation basis for control system design and multi-condition performance verification.
- (2) A three-channel ADRC system composed of leading-edge flap, stabilator and throttle is developed with an adaptive decoupling module. It effectively counteracts the

pitching moment coupling induced by flap deflection, and maintains stable attitude and velocity during trajectory adjustment.

- (3) An EPIO algorithm is proposed by improving the basic PIO algorithm from three dimensions: population initialization strategy, global search operator and local search operator. It alleviates the defects of the basic algorithm such as premature convergence and insufficient optimization accuracy in high-dimensional parameter tuning, and can efficiently complete the global collaborative tuning of three-channel controller parameters.
- (4) Multi-condition simulation results demonstrate that the proposed system achieves high-accuracy zero-overshoot tracking of flight path angle rate commands under undisturbed conditions. Under disturbance conditions, the fluctuation amplitude of angle of attack is controlled within  $0.1^\circ$ , showing favorable disturbance suppression capability. The 100 independent Monte Carlo simulations yield a 100% landing success rate. The Monte Carlo results show that the proposed ADRC-EPIO achieves the smallest mean flight path angle rate error of  $0.0088^\circ/\text{s}$  and the smallest mean angle of attack error of  $0.0103^\circ$  among all compared schemes. Its standard deviations for these two metrics are also the smallest, indicating that the proposed scheme maintains consistent performance across varying conditions and exhibits improved robust stability under uncertainty.

Future research will expand lateral-directional landing control and full-channel decoupling design, introduce deck motion prediction feedforward compensation, and carry out hardware-in-the-loop simulation verification to improve the engineering applicability of the system. In addition, analytical stability analysis based on Lyapunov methods and frequency-domain robustness measures will be pursued, and Pareto-front-based multi-objective optimization approaches will be explored to better reveal the trade-offs among competing control objectives.

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