Research Article

Current-Loop Control for the Pitching Axis of Aerial Cameras via an Improved ADRC

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An improved active disturbance rejection controller (ADRC) is designed to eliminate the influences of the current-loop for the pitching axis control system of an aerial camera. The improved ADRC is composed of a tracking differentiator (TD), an improved extended state observer (ESO), an improved nonlinear state error feedback (NLSEF), and a disturbance compensation device (DCD). The TD is used to arrange transient process. The improved ESO is utilized to observe the state extended by nonlinear dynamics, model uncertainty, and external disturbances. Overtime variation of the current-loop can be predicted by the improved ESO. The improved NLSEF is adopted to restrain the residual errors of the current-loop. The DCD is used to compensate the overtime variation of the current-loop in real time. The improved ADRC is designed based on a new nonlinear function $\text{newfal}(\cdot)$. This function exhibits enhanced continuity and smoothness compared to previously available nonlinear functions. Thus, the new nonlinear function can effectively decrease the high-frequency flutter phenomenon. The improved ADRC exhibits improved control performance, and disturbances of the current-loop can be eliminated by the improved ADRC. Finally, simulation experiments are performed. Results show that the improved ADRC displayed better performance than the proportional integral (PI) control strategy and traditional ADRC.

1. Introduction

The pitching axis control system of an aerial camera adopts a servo control system with three loops, namely, current-loop, speed-loop, and position-loop. As an inner loop, the current-loop plays an important role in the pitching axis control system of an aerial camera [1, 2]. This loop should be controlled in real time to achieve good performance of the pitching axis control system. Therefore, the current-loop needs an improved control strategy. The current-loop control strategy has been extensively investigated globally, and several developments have been achieved. For example, Radwan and Mohamed [3] examined an improved vector control strategy, but the vector control strategy needs accurately known system parameters. Liu et al. [4] introduced current control strategy with an optimal variable structure that exhibits improved robustness. However, this control strategy cannot solve the jitter problem. Novak and Riener [5] examined an artificial intelligence control strategy, which does

not rely on the mathematical model of the controlled object. However, this control strategy has a complex algorithm. Liu et al. [6] examined an adaptive current control technique with constant frequency based on clocked signal. This control strategy exhibits good static performance but weak restrain capacity for external disturbance. Several studies investigated a traditional active disturbance rejection control strategy, which exhibits certain anti-interference ability. In [7], Han introduced the evolution from PID to ADRC and the advantages of ADRC. In [8–10], Guo used active disturbance rejection control (ADRC) and sliding mode control (SMC) in the stabilization of the Euler-Bernoulli beam equation, one-dimensional and multidimensional antistable wave equations with boundary input disturbance. In [11], Sira-Ramírez et al. presented an ADRC scheme for the angular velocity trajectory tracking task on a substantially perturbed, uncertain, and permanent magnet synchronous motor. An ADRC was designed to solve the trajectory tracking problem of a Delta robot with uncertain dynamical model [12]. The stabilization

problem of a class of nonlinear systems with actuator saturation is investigated via ADRC [13]. An adaptive extended state observer- (AESO-) based ADRC is proposed to deal with the uncertainties and applied to the air-fuel ratio (AFR) control of gasoline engine, which has large nonlinear uncertainties due to the unknown speed change, fuel film dynamics, and so on [14]. The absolute stability of nonlinear ADRC for single-input-single-output systems is analyzed by the circle criterion method [15]. In [16], an ADRC was applied to stabilization for lower triangular nonlinear systems with large uncertainties. Guo et al. [17] generalized the ADRC to uncertain nonlinear systems subject to external bounded stochastic disturbance described by an uncertain stochastic differential equation driven by white noise. Liu et al. [18] proposed a two-layer ADRC method with the compensation of estimated equivalent input disturbances (EID) for load frequency control (LFC) of multiarea interconnected power system. However, the high-frequency flutter phenomenon is not eliminated, and the anti-interference ability needs to be enhanced. The current-loop of the pitching axis control system of an aerial camera is controlled under weightlessness. Therefore, a small interference will result in a serious error. The control system requires an improved active disturbance rejection controller (ADRC) with strong anti-interference ability.

The improved ADRC is composed of a tracking differentiator (TD), an improved extended state observer (ESO), an improved nonlinear state error feedback (NLSEF), and a disturbance compensation device (DCD). In this study, the previously available nonlinear function of a traditional ADRC is improved to a new nonlinear function with better continuity and smoothness. Thus, the improved ADRC based on the new nonlinear function exhibits better anti-interference performance. On the one hand, the total disturbances are sufficiently estimated by the improved ESO, and the state of the system does not require direct observation. Therefore, the controllability of the system can be enhanced greatly. On the other hand, control efficiency is enhanced using the improved NLSEF to conduct nonlinear calculation of the proportion signal, differential signal, and integral signal of the error [19, 20]. Extensive studies on the improved ADRC have resulted in important progress. Qi et al. [21] constructed a continuous and smooth ESO and disturbance rejection cascade decoupling control technology. An improved ADRC has been applied in a hypersonic vehicle and in the straight course error modeling of an electromagnetically controlled gyrocompass [22]. In [23], an improved ADRC based on the nonlinear arctangent function is used to reduce the observation noise in the traditional extended state observation of a system with output measurement noise. An improved ADRC is proposed to improve the tracking performance of the electromechanical actuator [24]. In [25], an improved ADRC is used to control an autonomous underwater vehicle. In [26], an enhanced ADRC is presented for a twin-rotor multi-input multioutput system with two degrees of freedom. However, few reports have focused on the use of improved ADRC in the current-loop control system of the pitching axis of an aerial camera.

The present study proposes an improved ADRC based on a new nonlinear function $\text{newfal}(\cdot)$. Then, the controller is

applied to the current-loop control system of an aerial camera pitching axis. Simulations are conducted for cases adopting the PI control strategy, traditional ADRC, and improved ADRC. Finally, the simulation results are discussed.

2. Mathematical Model

The pitching axis of an aerial camera adopts a permanent magnet synchronous motor (PMSM) as an actuator. A control strategy of $i_d = 0$ is used in the current-loop control system, where i_d is the current of the direct axis. Therefore, the controlled object of the current-loop is i_q , where i_q is the current of the quadrature axis. The current equation of the quadrature axis in a (d, q) two-phase rotating coordinate system is given as follows:

$$\dot{i}_q = -\frac{R}{L}i_q - \frac{\psi_f}{L}\omega + \frac{1}{L}u_q, \quad (1)$$

where R is the stator phase resistance, L is the quadrature axis inductance, ψ_f is the magnetic chain produced by the rotor permanent magnet, u_q is the equivalent voltage of the quadrature axis, and ω is the angular speed of the motor rotor. The mathematical model of PMSM in a (d, q) two-phase rotating coordinate system shows that the electromagnetic torque is directly controlled by i_q . Therefore, the precise control of the electromagnetic torque can be realized by controlling the current-loop. The expression $-(\psi_f/L)\omega$ represents a coupling effect in the current equation of the quadrature axis. The current-loop is a nonlinear system under the influence of the coupling effect. Several definitions are given as follows:

$$\begin{aligned} w(t) &= -\frac{\psi_f}{L}\omega, \\ f(i_q, t) &= -\frac{R}{L}i_q, \\ b &= \frac{1}{L}, \\ u &= u_q. \end{aligned} \quad (2)$$

Then, the current equation of the quadrature axis can be expressed as follows:

$$\dot{i}_q = f(i_q, t) + w(t) + bu, \quad (3)$$

where $f(i_q, t)$ and $w(t)$ are the internal and external disturbances of the current-loop, respectively. The total disturbance of the current-loop is expressed as $a(t) = f(i_q, t) + w(t)$. Then, the current equation of quadrature axis is as follows:

$$\dot{i}_q = a(t) + bu. \quad (4)$$

Equation (4) is a typical equation used to design the improved ADRC.

3. Improved ADRC Design for the Current-Loop

3.1. Design of the New Nonlinear Function. The nonlinear function is the core of the ADRC. The following conditions

should be fully considered in designing the nonlinear function. First, the nonlinear function should exhibit good convergence around the origin. Second, the value of the nonlinear function is 0 at the origin. Third, the nonlinear function should be continuous around the origin. The traditional ADRC adopts a nonlinear function $\text{fal}(\cdot)$, which can be expressed as follows:

$$\text{fal}(e, \alpha, \delta) = \begin{cases} |e|^\alpha \text{sign}(e), & |e| > \delta \\ \frac{e}{\delta^{1-\alpha}}, & |e| \leq \delta, \end{cases} \quad \delta > 0. \quad (5)$$

The characteristics of $\text{fal}(\cdot)$ are given as follows. The value of α influences the nonlinearity degree of $\text{fal}(\cdot)$. The value of α is usually selected between 0 and 1. The nonlinear function exhibits optimal nonlinearity when $\alpha = 0$. The degree of linearity of $\text{fal}(\cdot)$ is optimal when $\alpha = 1$. The value of δ is the linear interval width of $\text{fal}(\cdot)$ and related to the error range of the system. When the input is an error signal, the system can achieve rapid stability by adjusting the parameter values of $\text{fal}(\cdot)$. $\text{fal}(\cdot)$ is a nonderivable function, although this function is continuous. If the value of δ is too small, $\text{fal}(\cdot)$ will also cause the high-frequency flutter phenomenon. The value of δ is difficult to adjust, because the control performance of $\text{fal}(\cdot)$ is sensitive to the value of δ . Thus, a new nonlinear function $\text{newfal}(\cdot)$ is designed. The proposed $\text{newfal}(\cdot)$ exhibits better convergence and continuity around the origin than $\text{fal}(\cdot)$. The expression of $\text{newfal}(\cdot)$ is calculated by the following steps.

When $|e| > \delta$, $\text{newfal}(\cdot)$ is expressed as $\text{newfal}(e, \alpha, \delta) = |e|^\alpha \text{sign}(e)$.

When $|e| \leq \delta$, the expression of $\text{newfal}(\cdot)$ is designed as an interpolation function form by multinomial and trigonometric functions and can be expressed as follows:

$$\text{newfal}(e, \alpha, \delta) = k_1 e + k_2 e^2 + k_3 \tan e. \quad (6)$$

Simulations are performed using the two nonlinear functions under $\alpha = 0.05, \delta = 0.06$. The curves of the function are shown in Figure 1.

The simulation results demonstrate that $\text{newfal}(e, \alpha, \delta)$ exhibits better continuity and derivability than $\text{fal}(e, \alpha, \delta)$. Thus, $\text{newfal}(e, \alpha, \delta)$ is not sensitive to the selection of the δ value and can avoid the high-frequency flutter phenomenon. In this study, the improved ADRC is designed based on $\text{newfal}(e, \alpha, \delta)$.

3.2. Improved ADRC Design for the Current-Loop of the Pitching Axis of an Aerial Camera. Figure 2 shows the structure of the improved ADRC of the current-loop for the pitching axis control system of an aerial camera.

Part three of the above expression is selected as $\tan e$, but not e^3 , because $\tan e$ exhibits better convergence than e^3 around the origin. Then, $\text{newfal}(e, \alpha, \delta)$ can be given as follows:

$$\text{newfal}(e, \alpha, \delta) = \begin{cases} |e|^\alpha \text{sign}(e), & |e| > \delta \\ k_1 e + k_2 e^2 + k_3 \tan e, & |e| \leq \delta, \end{cases} \quad (7)$$

where k_1, k_2 , and k_3 are the function coefficients and can be calculated by the following steps.

In the range of $|e| \leq \delta$, the following expression is given to meet the continuous and derivable conditions:

$$\begin{aligned} \text{newfal}(e, \alpha, \delta) &= \delta^\alpha, & e &= \delta, \\ \text{newfal}(e, \alpha, \delta) &= -\delta^\alpha, & e &= -\delta, \\ \text{newfal}'(e, \alpha, \delta) &= \alpha \delta^\alpha, & e &= \pm \delta. \end{aligned} \quad (8)$$

The following expression can be obtained by (7) and (8),

$$\begin{aligned} k_1 \delta + k_2 \delta^2 + k_3 \tan \delta &= \delta^\alpha, \\ -k_1 \delta + k_2 \delta^2 - k_3 \tan \delta &= -\delta^\alpha, \\ k_1 + 2k_2 \delta + k_3 \sec^2 \delta &= \alpha \delta^\alpha. \end{aligned} \quad (9)$$

The values of k_1, k_2 , and k_3 can be calculated as follows:

$$\begin{aligned} k_1 &= \frac{\delta^\alpha + \delta^\alpha \cdot \tan^2 \delta - \alpha \cdot \tan \delta \cdot \delta^\alpha}{\delta - \tan \delta + \delta \cdot \tan^2 \delta}, \\ k_2 &= 0, \\ k_3 &= \frac{\alpha \cdot \delta^{\alpha+1} - \delta^\alpha}{\delta - \tan \delta + \delta \cdot \tan^2 \delta}. \end{aligned} \quad (10)$$

Thus, the expression of $\text{newfal}(e, \alpha, \delta)$ can be obtained as follows:

$$\text{newfal}(e, \alpha, \delta) = \begin{cases} |e|^\alpha \text{sign}(e), & |e| > \delta \\ \frac{\delta^\alpha + \delta^\alpha \cdot \tan^2 \delta - \alpha \cdot \tan \delta \cdot \delta^\alpha}{\delta - \tan \delta + \delta \cdot \tan^2 \delta} e + \frac{\alpha \cdot \delta^{\alpha+1} - \delta^\alpha}{\delta - \tan \delta + \delta \cdot \tan^2 \delta} \tan e, & |e| \leq \delta. \end{cases} \quad (11)$$

3.2.1. TD. TD in the improved ADRC is used to arrange the transient process. A continuous and differentiable input signal can be obtained by TD. Therefore, drastic changes in the control signal can be avoided effectively. The TD expression of the current-loop of the pitching axis control system of an aerial camera is designed as follows:

$$\begin{aligned} fh &= f_{\text{han}}(z_{11} - i_q^*, v_2, r_0, h_0), \\ \dot{z}_{11} &= v_2, \\ \dot{v}_2 &= fh, \end{aligned} \quad (12)$$

where i_q^* is the current given the quadrature axis, z_{11} is the tracking signal for i_q^* , r_0 is the velocity factor, h_0 is the filter

FIGURE 1: Curves of newfal(·) and fal(·) when $\alpha = 0.05$, $\delta = 0.06$.

FIGURE 2: Structure of the improved ADRC of the current-loop of the pitching axis control system of an aerial camera.

factor, and r_0 and h_0 are used to arrange the speed of the transient process. $\text{fhan}(x_1, x_2, r_0, h_0)$ is an optimal control synthesis function and can be defined as

$$\text{fhan}(v_1, v_2, r_0, h_0) = - \begin{cases} r_0 \text{sign}(\alpha), & |\alpha| > \delta \\ r_0 \frac{\alpha}{\delta}, & |\alpha| \leq \delta, \end{cases} \quad (13)$$

where

$$\alpha = \begin{cases} v_2 + \frac{\alpha_0 - \delta}{2} \text{sign}(y), & |y| > \delta_0 \\ v_2 + \frac{y}{h_0}, & |y| \leq \delta_0, \end{cases} \quad (14)$$

$$\delta = r_0 h_0,$$

$$\delta_0 = \delta h_0,$$

$$y = v_1 + h_0 v_2,$$

$$\alpha_0 = \sqrt{\delta^2 + 8r_0 |y|}.$$

$v(t)$ is the input and v_1 is the output of the TD. v_1 can track $v(t)$ as fast as possible in the case of the acceleration constraint $|\ddot{v}| \leq r$. The larger the value of r_0 , the faster the tracking speed. v_2 is the differentiation of $v(t)$ when v_1 is tracking $v(t)$. h_0 is

FIGURE 3: Internal structure of the improved ESO of the current-loop of the pitching axis of the aerial camera.

used to filter out the high-frequency interferences of $v(t)$. The value of h_0 is parameterized as $h_0 = 0.01$. The greater the value of h_0 , the better the filtering effect.

3.2.2. Improved ESO. Improved ESO is the core of the improved ADRC, which is a nonlinear control technology that does not rely on the system model. Nonlinear dynamics, model uncertainty, and external disturbances are extended to a new state and observed by the improved ESO. The overtime variation of system can be predicted by the improved ESO. Therefore, the robustness of the system can be improved greatly. The expression of the improved ESO for the current-loop for the pitching axis control system of an aerial camera is designed as

$$e_1 = z_{21} - i_q,$$

$$\dot{z}_{21} = z_{22} - \beta_1 \text{newfal}(e_1, \alpha_0, \delta_1) + b_0 u(t), \quad (15)$$

$$\dot{z}_{22} = -\beta_2 \text{newfal}(e_1, \alpha_1, \delta_1),$$

where z_{21} is the tracking signal for i_q , e_1 is the tracking error, and z_{22} is the tracking signal for the total disturbance $w(t)$. If the new nonlinear function newfal(·) is selected appropriately, the state variables z_{21} and z_{22} can indicate the state variables i_q and $w(t)$, respectively. Therefore, the improved ESO for the current-loop for the pitching axis of the aerial camera can be obtained. β_1, β_2 are the gain coefficients of the improved ESO. α_0, α_1 are the nonlinear factors and satisfy the condition $0 < \alpha_1 < \alpha_0 \leq 1$. δ_1 is a filtering factor with a value of $\delta_1 = 0.01$. b_0 is the estimation of the compensation factor. The internal structure of the improved ESO of the current-loop for the pitching axis of the aerial camera is shown in Figure 3.

The stability of the improved ESO can be proved as follows. The bandwidth of the current-loop is defined as λ . The following equation can be obtained according to previous research:

$$(s + \lambda)^2 = s^2 + \beta_1 s + \beta_2. \quad (16)$$

The nonlinear parts of the improved ESO are divided into many areas to analyze the stability of the improved ESO. All areas are replaced by piecewise linear functions. The stability

of the entire area can be ensured when the stability of each area is ensured. The present study used the linear expression $z_{21} - i_q$ to replace the nonlinear function $\text{newfal}(\cdot)$ to analyze the stability of the improved ESO. Therefore, (15) can be written as

$$\begin{aligned} \dot{z}_{21} &= z_{22} - \beta_1 (z_{21} - i_q) + b_0 u(t), \\ \dot{z}_{22} &= -\beta_2 (z_{21} - i_q). \end{aligned} \quad (17)$$

Laplace transform is carried out for the above equation and the following equation can be obtained:

$$\begin{aligned} z_{21}(s) \cdot s &= z_{22}(s) - 2\lambda z_{21}(s) + 2\lambda i_q(s) + b_0 u(s), \\ z_{22}(s) \cdot s &= -\lambda^2 z_{21}(s) + \lambda^2 i_q(s). \end{aligned} \quad (18)$$

therefore, the following equation can be obtained:

$$\begin{aligned} z_{21}(s) &= \frac{\lambda^2 + 2\lambda s}{(s + \lambda)^2} \cdot i_q(s) + \frac{b_0 s}{(s + \lambda)^2} \cdot u(s), \\ z_{22}(s) &= \frac{\lambda^2 s}{(s + \lambda)^2} \cdot i_q(s) + \frac{\lambda^2 b_0}{(s + \lambda)^2} \cdot u(s). \end{aligned} \quad (19)$$

The errors of $z_{21}(s)$ and $z_{22}(s)$ can be calculated as follows:

$$\begin{aligned} e_1(s) &= z_{21}(s) - i_q(s), \\ e_2(s) &= z_{22}(s) - a(s) = z_{22}(s) - i_q(s) - b_0 u(s); \end{aligned} \quad (20)$$

then, (21) can be calculated:

$$\begin{aligned} e_1(s) &= \frac{\lambda^2 + 2\lambda s}{(s + \lambda)^2} \cdot i_q(s) + \frac{b_0 s}{(s + \lambda)^2} \cdot u(s) - i_q(s), \\ e_2(s) &= \frac{\lambda^2 s}{(s + \lambda)^2} \cdot i_q(s) + \frac{\lambda^2 b_0}{(s + \lambda)^2} \cdot u(s) - i_q(s) \cdot s \\ &\quad - b_0 u(s), \\ e_1(s) &= -\frac{s^2}{(s + \lambda)^2} \cdot i_q(s) + \frac{b_0 s}{(s + \lambda)^2} \cdot u(s), \\ e_2(s) &= -\frac{s^2 + 2\lambda s}{(s + \lambda)^2} \cdot s \cdot i_q(s) - \frac{s^2 + 2\lambda s}{(s + \lambda)^2} \cdot b_0 \cdot u(s). \end{aligned} \quad (21)$$

This article selected $i_q(t)$ and $u(t)$ as unit step input. Thus, $i_q(s) = 1/s$, and $u(s) = 1/s$. The steady-state errors can be calculated as follows:

$$\begin{aligned} e_{s1} &= \lim_{s \rightarrow 0} s \cdot e_1(s) = 0, \\ e_{s2} &= \lim_{s \rightarrow 0} s \cdot e_2(s) = 0; \end{aligned} \quad (22)$$

therefore, the improved ESO exhibits stability.

3.2.3. Improved NLSEF. Improved NLSEF is used to combine the state variables produced by tracking the TD and improved

TABLE 1: Parameters of the experimental permanent magnet synchronous motor.

Parameter	Dimension	Numerical value
Power supply voltage	VAC	400
Rated power	W	2400
Maximum nonload speed	r/min	2750
Continuous current	A	5.1
Continuous torque	N·m	6.11
Peak current	A	18
Peak torque	N·m	18
Motor pole logarithmic		16
Resistance	Ω	2.9
Inductance	mH	6.8

ESO with the error of estimated value nonlinearly. The expression of the improved NLSEF for the aerial camera pitching axis current-loop is designed as

$$\begin{aligned} e_2 &= z_{11} - z_{21}, \\ u_0 &= \beta_3 \text{newfal}(e_2, \alpha_2, \delta_2), \end{aligned} \quad (23)$$

where β_3 is the gain coefficient of the improved NLSEF, α_2 is a nonlinear factor with a value between 0 and 1, and δ_2 is a filtering factor.

3.2.4. DCD. DCD is used to compensate for the total disturbance of the current-loop for the pitching axis of the aerial camera. The total disturbance is composed of internal disturbance, external disturbance, and coupling influence. The expression of the DCD for the current-loop of the pitching axis of the aerial camera is designed as

$$u = u_0 - \frac{z_{22}}{b_0}, \quad (24)$$

where u_0 is the control signal without DCD, u is the control signal, and z_{22}/b_0 is the compensation component of total disturbance for the aerial camera pitching axis current-loop.

4. Simulation Experiments and Discussion

The improved ADRC is compared with the traditional ADRC and PI control strategy to accurately evaluate its performance. A PMSM is selected as the executing agency of the system. Table 1 shows the PMSM parameters, Table 2 presents the traditional ADRC parameters, and Table 3 presents the improved ADRC parameters.

Simulations are performed in the current-loop control system of the pitching axis of an aerial camera in the following three cases.

First, simulations are performed to verify the response speed and steady-state performance of the improved ADRC. A current of 1 A is applied on the rotor for nonload starting. Figure 4 shows the motor response curves under the PI control strategy, traditional ADRC, and improved ADRC.

TABLE 2: Parameters of the traditional ADRC.

Component of improved ADRC	Parameter name	Symbol	Numerical value
TD	Velocity factor	r_0	10
	Filter factor	h_0	0.02
Traditional ESO	Nonlinear factor	α_0	1
	Nonlinear factor	α_1	0.5
	Linear interval width	δ_1	0.01
	Gain coefficient	β_1	60
	Gain coefficient	β_2	1200
Traditional NLSEF	Nonlinear factor	α_2	0.5
	Filter factor	δ_2	0.01
	Gain coefficient	β_3	75
DCD	Compensation coefficient	b_0	1

TABLE 3: Parameters of the improved ADRC.

Component of improved ADRC	Parameter	Symbol	Numerical value
TD	Velocity factor	r_0	200
	Filter factor	h_0	0.01
Improved ESO	Nonlinear factor	α_0	0.5
	Nonlinear factor	α_1	0.25
	Linear interval width	δ_1	0.01
	Gain coefficient	β_1	30
	Gain coefficient	β_2	300
Improved NLSEF	Nonlinear factor	α_2	0.75
	Filter factor	δ_2	0
	Gain coefficient	β_3	1000
DCD	Compensation coefficient	b_0	2.485

The control strategy based on improved ADRC exhibits shorter response time and smaller overshoot amount than the PI control strategy and the traditional ADRC control strategy. The simulation results show that the overshoot amount of the control strategy based on improved ADRC is 14.2822% and 9.4183% lower than those of the PI and traditional ADRC control strategies, respectively. The response time of the control strategy based on the improved ADRC is 1.5392 and 0.6459 s shorter than those of the PI and traditional ADRC control strategies, respectively. The current-loop parameters of the overshoot amount and the response times for the three strategies are shown in Table 4.

Second, simulations are performed to verify the anti-interference ability of the improved ADRC. As an external disturbance, a step signal of 1 A is applied on the motor for 3 s. The current response curves are shown in Figure 5. The simulation results show that the improved ADRC control strategy exhibits smaller response curve fluctuation, shorter

FIGURE 4: Response curves of current-loop for nonload starting under the PI control strategy, traditional ADRC, and improved ADRC control strategy.

TABLE 4: Parameters of the overshoot amount and the response time for nonload starting under the PI control strategy, traditional ADRC, and improved ADRC control strategy.

Control strategy	Response time/s	Overshoot amount
PI	7.0056	16.6352%
Traditional ADRC	0.8623	5.7653%
Improved ADRC	0.4564	2.3470%

TABLE 5: Parameters of the overshoot amount and recovery time under the PI control strategy, traditional ADRC, and improved ADRC control strategy for an external disturbance applying.

Control strategy	Response time/s	Overshoot amount
PI	6.7281	40.2103%
Traditional ADRC	0.4935	7.3252%
Improved ADRC	0.4758	4.7341%

recovery time, and smaller load disturbance influence than the PI and traditional ADRC control strategies. The simulation results show that the overshoot amount of the improved ADRC control strategy is 7.5911% and 36.4762% lower than those of the traditional ADRC and PI control strategies. The recovery time of the improved ADRC control strategy is 1.4877 and 6.9423 s shorter than those of the traditional ADRC and PI control strategies. Table 5 presents the current-loop parameters of the overshoot amount and recovery time.

Finally, simulations are performed to verify the indicator ability of the improved ADRC. A sinusoidal signal input is applied to the current-loop control system. The current output curves for the traditional ADRC and improved ADRC control strategies are shown in Figure 6. According to the simulation results, the improved ADRC control strategy

FIGURE 5: Response curves of current-loop for an external disturbance applying under the PI control strategy, traditional ADRC, and improved ADRC control strategy.

FIGURE 6: Response curves of the current-loop under the traditional ADRC and improved ADRC control strategies for a sinusoidal signal input.

exhibits better indicator ability than the traditional ADRC control strategy.

Simulations are also performed to verify the performance of z_{22} tracking the disturbance, and the results are shown in Figure 7. Figure 7 shows that z_{22} can track the disturbance in real time when a unit step disturbance is applied on the current-loop at the time 3 s.

5. Conclusions

An improved ADRC of the current-loop of the pitching axis control system of an aerial camera is proposed. The

FIGURE 7: Response curves of z_{22} and the disturbance.

new nonlinear function can effectively decrease the high-frequency flutter phenomenon, because it exhibits better continuity and smoothness than the previously available nonlinear functions. Therefore, the improved ADRC designed based on the new nonlinear function exhibits better control performances than the PI control strategy and the traditional ADRC. The nondifferentiable and discontinuous characteristics of the nonlinear function of NLSEF are overcome by the improved ADRC. Simulations are performed, and the results indicate that the system with improved ADRC control strategy exhibits better dynamic performance, static performance, and robustness than the system with PI control strategy and traditional ADRC control strategy. Extending the proposed design technique to the improved ADRC of the position-loop is an interesting topic, and this technique is the focus of our future study.

Competing Interests

The authors declare no conflict of interests regarding the publication of this paper.

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