

Article

Research on Variable Pitch Propeller Control Technology of eVTOL Based on ADRC

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Abstract

To address heading instability in electric vertical take-off and landing (eVTOL) aircraft at low speeds and large pitch angles, a rotational speed feedback compensation control scheme based on Active Disturbance Rejection Control (ADRC) is proposed for variable-pitch propellers. This scheme integrates propeller speed into the heading control inner loop and employs a state observer to process the measured speed. Simulation results demonstrate that under dynamic propeller speed variations of 0.5%, 1%, and 2%, the proposed compensation scheme reduces yaw angle oscillation amplitudes by 22.2%, 30.6%, and 37.8%, and yaw angular velocity fluctuations by 32.5%, 43.4%, and 33.3%, respectively, compared to a basic speed feedback scheme, showcasing significantly superior robustness. Experimental bench tests further validate that the proposed strategy enhances overall propeller force efficiency from 2.479 kg/kW to 3.05 kg/kW at 120 km/h cruise, resulting in a power saving of 0.48 kW and extending the cruising range by 8.5 km. The stability and energy efficiency of the proposed method are rigorously validated through both simulation and experimental testing.



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1. Introduction

Research into vertical takeoff and landing (VTOL) aircraft began as early as the 1950s, coinciding with the maturation of helicopter technology. However, due to limitations in battery and electronic control systems at the time, the application of eVTOL technology remained in its infancy [1]. Over the past two decades, significant advancements in battery energy density, flight control systems, and manufacturing techniques have propelled eVTOL technology into practical use. During this period, numerous innovative companies and research teams have dedicated efforts to eVTOL development, attracting substantial investment and fostering a highly competitive global market [2]. In the early 2010s, a range of aerospace companies and startups began actively developing eVTOL prototypes, including Airbus's Vahana, Bell's Nexus, and Joby Aviation's S4 [3]. The key advantage of eVTOL lies in its ability to take off and land vertically, eliminating the need for long runways. Additionally, its electric propulsion system minimizes noise and emissions, making it an ideal candidate for urban air mobility solutions, particularly in densely populated cities

facing traffic congestion and environmental challenges. Today, eVTOL technology has progressed from theoretical research to actual flight testing. A notable innovation in this field is the adoption of variable-pitch propeller technology, which enables precise control of lift and thrust, significantly enhancing flight control accuracy and efficiency [4].

Despite its potential, several challenges remain for eVTOL development. The most critical bottleneck is battery technology. Although lithium battery performance has improved significantly in recent years, energy density and weight continue to limit eVTOL capabilities. Breakthroughs in next-generation battery technologies, such as solid-state or lithium-sulfur batteries, are likely necessary to enable longer flight times and greater payload capacities [5].

Another major challenge lies in flight control and automation. To ensure the safe operation of eVTOL aircraft in urban airspace, flight control systems must be exceptionally precise and reliable. Furthermore, advancements in autonomous flight technology will be vital for widespread adoption. Fully autonomous navigation and operation are expected to define the future of eVTOL aircraft. eVTOL designs typically feature multi-rotor or tilt-rotor configurations to achieve both vertical takeoff/landing and efficient horizontal flight [6,7]. Variable-pitch propellers play a central role by adjusting the blade angle of each rotor, thereby controlling the magnitude and direction of thrust to ensure precise flight control [8]. Furthermore, precise pitch control is also critical for optimizing performance characteristics such as maneuverability and acoustic stealth, as blade pitch angle significantly influences rotor aerodynamic and signature properties [9]. In eVTOL aircraft, variable-pitch propellers are employed to adjust the angle of the rotor blades, thereby controlling both thrust and lift [10]. By altering the blade's angle of attack, the aircraft can execute smooth vertical takeoffs and landings, hovering, and turning maneuvers. The precise adjustment of the blade angle is essential for maintaining flight stability, particularly in complex urban airspace environments where the aircraft must navigate external disturbances such as air turbulence and fluctuations in wind speed [11].

However, achieving this precise control is challenging due to the inherent nonlinearities of the propulsion system (e.g., aerodynamic hysteresis, complex fluid–structure interactions) and exposure to unpredictable external disturbances [12]. Traditional control methods, such as PID control and Model Reference Adaptive Control (MRAC), have been widely applied but exhibit significant limitations in this context. While simple and robust, PID controllers struggle with nonlinear systems and require meticulous parameter tuning to maintain performance across the entire flight envelope. MRAC, though capable of adaptation, can suffer from robustness issues and computational complexity when confronted with rapid and high-magnitude disturbances, which are prevalent in urban airspace.

In response to these challenges, various intelligent control algorithms have been explored. For instance, adaptive PID algorithms (e.g., using Recursive Least Squares (RLS) [13]) rely on accurate system modeling, which is difficult to achieve in practice. Neural network-based controllers [14] can improve performance but often require extensive training data and may overlook critical control loops. Fuzzy PID algorithms [15] enhance stability but are often optimized for specific input types like step signals. Compared to these methods, Active Disturbance Rejection Control (ADRC) offers a fundamentally different and more robust paradigm. It does not require an accurate mathematical model of the plant, nor does it need extensive training or pre-defined fuzzy rules. Instead, ADRC treats all model uncertainties and external disturbances as a generalized “total disturbance,” which is estimated in real-time and actively compensated for. This model-agnostic approach makes it uniquely suited for handling the complex and variable conditions of eVTOL flight.

We introduce the ADRC algorithm. The ADRC algorithm is designed based on the pre-planning of the system transition process, extracting tracking and differentiating

signals according to the characteristics of the controlled object. It estimates the system state from the system outputs and control inputs, utilizing error values to determine control quantities. These quantities are combined with the estimation of system perturbations to calculate the final control output [16,17]. The self-immune controller within the ADRC framework neutralizes various uncertain external disturbances by applying control actions, thereby achieving precise control. Eliminating the effects of these disturbances is a key consideration in control system design. There are two main control principles: the absolute invariance principle, which emphasizes measuring and suppressing external disturbances, and the internal mode principle, which focuses on understanding and modeling external disturbances [18]. What distinguishes the self-resistant control algorithm from traditional methods is its treatment of unknown factors and internal/external perturbations as unified unknown disturbances [19]. By observing data, the algorithm estimates and compensates for these disturbances without requiring direct measurement or prior knowledge of their characteristics. This approach overcomes the limitations of traditional control principles and represents an innovative achievement in the era of digital control. It combines the essence of modern control theory with the core concept of PID control, while skillfully utilizing nonlinear effects to enhance control performance. As such, it represents an emerging and practical control technology [20].

The core of ADRC is the Extended State Observer (ESO), which actively estimates both the system states and the “total disturbance” in real time [21]. This estimate is then canceled out in the control law, effectively linearizing the system and making it inherently robust against perturbations. For eVTOL variable-pitch control, this capability is crucial. It allows the aircraft to maintain stable performance against aerodynamic uncertainties, gusty winds, and model inaccuracies, without the need for constant re-tuning of controller parameters. This addresses the specific limitations of the methods previously discussed.

Jingqing Han introduced the ADRC algorithm, a novel nonlinear control method that integrates the advantages of both modern control theory and classical regulation theory [22]. Its most notable feature is the ability to categorize all uncertainties as “unknown disturbances,” which are then estimated and compensated for using input-output data. This capability allows ADRC to handle nonlinearities and model uncertainties within the control system, thereby improving dynamic performance in terms of both speed and accuracy. ADRC can be seen as an enhanced version of PID control, particularly when paired with the Extended State Observer (ESO) for real-time disturbance estimation, significantly improving the robustness of traditional PID control under external disturbances. The superior performance of ADRC in nonlinear UAV systems underscores its robustness and practicality, making it particularly suitable for nonlinear UAVs and systems with substantial uncertainties [23]. In scenarios where wind resistance and modeling errors are present, ADRC can maintain stable attitude control and achieve high trajectory tracking accuracy. Garg proposed a fusion control strategy combining Accelerated Finite-Time Sliding Mode Control (AFTSMC) with ADRC for attitude and trajectory control in quadrotor UAVs [24]. The integration of AFTSMC further enhances the response speed and control accuracy of ADRC, particularly in complex flight environments. To demonstrate the superiority of ADRC in controlling eVTOL variable-pitch propellers, we conducted a comparative analysis between the speed inner-loop feedback and speed feedback compensation control schemes. Our analysis highlights ADRC’s advantages in variable-pitch propeller speed control, particularly regarding precision, robustness, and adaptability to complex disturbances.

While existing studies have effectively demonstrated ADRC’s robustness for general disturbance rejection in eVTOL platforms [14,21,23], they predominantly operate under the assumption of a fixed or unperturbed propulsion system speed. This work advances the field by specifically addressing a critical yet overlooked scenario: active propeller speed

reduction for energy-efficient cruise flight. We propose a novel rotational speed feedback compensation scheme that is deeply integrated into the ADRC framework. This approach uniquely enables the ADRC controller to maintain precise yaw stability despite the intentional and dynamic variation of propeller speed—a significant source of system disturbance and model uncertainty that is not compensated for in conventional ADRC implementations. Thus, our contribution moves beyond applying ADRC merely for disturbance rejection; it leverages and extends the ADRC philosophy to enable and safeguard a new energy-optimal flight mode for variable-pitch eVTOL aircraft.

It is important to note that the scope of this study focuses on the control methodology under axial and low-advance-ratio flight conditions. The development and validation of the control algorithm are conducted based on this well-defined operational regime to establish a clear foundational benchmark.

The structure of this paper is organized as follows: Section 2 introduces the ADRC algorithm. Section 3 delves into the coordinated control of variable pitch and variable speed, presenting simulation results derived from the application of the ADRC method. Section 4 validates these findings through bench experiments. Finally, Section 5 provides a summary of the research conclusions on variable-pitch control using ADRC.

2. Simulation Model of ADRC Algorithm

The ADRC architecture consists of three key components: the Tracking Differentiator (TD), the Extended State Observer (ESO), and the Nonlinear State Error Feedback Control Law (NLSEF). Each component plays a unique role within the control system and operates relatively independently of the others. The NLSEF enhances control performance by adopting a nonlinear combination approach. Self-immune controllers, which are integral to this architecture, can effectively handle complex control tasks and improve overall system performance.

The dynamics of an eVTOL aircraft are inherently high-order and nonlinear, involving complex couplings between translational and rotational motions. However, for the specific problem of yaw control via a variable-pitch propeller, the dominant dynamics can be effectively captured by a second-order system model focusing on the yaw channel. This second-order system can be expressed as follows:

$$\ddot{y} = f(y, \dot{y}, w(t), t) + bu \quad (1)$$

where $w(t)$ is the external disturbance, $f(y, \dot{y}, w(t), t)$ is the total disturbance including both internal and external disturbances, y represents the output of the pitch paddle system, i.e., the real heading angle, and $\dot{y}$ represents the real heading angular velocity. In order to facilitate the analysis and observe the relativity, the variables x_1 and x_2 are used to represent the two real-time states of the system (x_1 represents the real-time heading angle and x_2 represents the real-time heading angular velocity): $x_1 = y$, $x_2 = \dot{y}$, then Formula (1) can be converted into a state formula:

$$\begin{cases} y = x_1 \\ \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x_1, x_2, w(t), t) + bu \end{cases} \quad (2)$$

The key idea of ADRC is to estimate the disturbance $f(x_1, x_2, w(t), t)$ in real time and cancel it out in time, turning Formula (1) into a linear integrator series standard type shaped like Formula (3), which makes the control simple.

$$\ddot{y} = u_0 \quad (3)$$

2.1. Tracking Differentiator(TD)

The Tracking Differentiator (TD) can be used to estimate the derivatives of a signal, enabling both tracking and prediction of the signal. Tracking differentiators are typically employed to process non-smooth signals or in scenarios with significant noise interference. The principle of a tracking differentiator is to estimate the derivative based on the sampled values of a known signal while suppressing high-frequency noise through filtering.

The input of TD has only one data, and the output has two data, which are x_1 and x_2 . In order to accommodate the needs of numerical computation, the discrete system of the following formula:

$$\begin{cases} x_1(k+1) = x_1(k) + hx_2(k) \\ x_2(k+1) = x_2(k) - r_0u(k) \end{cases} \quad (4)$$

A speediest integrated function is derived $fhan(x_1, x_2, r_0, h_0)$:

$$fhan = -r[a/d - \text{sign}(a)]s_a - r_0\text{sign}(a) \quad (5)$$

where $s_a = [\text{sign}(a+b) - \text{sign}(a-d)]/2$, $a = (a_0 + y - a_2)s_y + a_2$, $s_y = [\text{sign}(y+d) - \text{sign}(y-d)]/2$, $a_2 = a_0 + \text{sign}(y)(a_1 - d)/2$, $a_1 = \sqrt{d(d+8|y|)}$, $y = x_1 + a_0$, $a_0 = h_0x_2$, $d = r_0h_0^2$, x_1 is the system state and r_0, h_0 are the function control parameters. The discrete most velocity feedback system utilizing this function is as follows:

$$\begin{cases} x_1(k+1) = x_1(k) + hx_2(k) \\ x_2(k+1) = x_2(k) + hf h \\ fh = fhan(x_1(k) - v(k), x_2(k), r_0, h_0) \end{cases} \quad (6)$$

It is realized that x_1 follows the input signal v quickly and without overshooting, while x_2 acts as an approximate differential of v to track the differential signal of the process.

2.2. Expansion State Observer (ESO)

In the eVTOL pitch paddle control process, the core of ESO is to expand a new state variable from the external total perturbation such as side wind disturbance, total pitch mutation, because the direct disturbance of the external total perturbation acting on the pitch paddle to the yaw system is the angular acceleration, but the angular acceleration is a non-systematic state variable that can be mutated, so the core work of this expanded state observer is to estimate the next cycle of the original state variables angle and angular velocity while estimating the disturbing angular acceleration of the external action at this time. For the second-order controlled object shown in Formula (1), $w(t)$ is the external disturbance action, and $f(y, \dot{y}, w(t), t)$ represents the total perturbation of the external and internal disturbances, and the total perturbation is physically visualized in the system by giving the system an additional angular acceleration:

$$a(t) = f(x_1, x_2, w(t), t) \quad (7)$$

The angular acceleration of the pitch paddle system is represented by $x_3(t)$, which is a function of time and represents the real-time value of the angular acceleration value of the system:

$$x_3(t) = a(t) = f(x_1, x_2, w(t), t) \quad (8)$$

Formula (8) is added to the original system Formula (2), i.e., the information on the rate of change in the expanded angular acceleration is added, and the original system becomes a linear system:

$$\begin{cases} y = x_1 \\ \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 + bu \\ \dot{x}_3 = f(x_1, x_2, w(t), t) = w_0(t) \end{cases} \quad (9)$$

A nonlinear state observer is built for this linear system:

$$\begin{cases} \varepsilon_1 = z_1 - y \\ \dot{z}_1 = z_2 - \beta_{01}\varepsilon_1 \\ \dot{z}_2 = z_3 - \beta_{02}fal\left(\varepsilon_1, \frac{1}{2}, \delta\right) + bu \\ \dot{z}_3 = -\beta_{03}fal\left(\varepsilon_1, \frac{1}{4}, \delta\right) \end{cases} \quad (10)$$

where $fal(\varepsilon, a, \delta)$ is a nonlinear function:

$$fal(x, a, \delta) = \begin{cases} \frac{x}{\delta(1-a)}, & |x| \leq \delta \\ \text{sign}(x)|x|^a, & |x| > \delta \end{cases} \quad (11)$$

In this way, the heading angle, heading angular velocity, and heading angular acceleration $z_i(t)$ estimated by the expansion observer can be made to track the heading command and angular acceleration command $x_i(t)$ of the system with a large adaptive range when b is known or close.

$$\begin{cases} \varepsilon_1 = z_1(k) - y(k) \\ z_1(k+1) = z_1(k) + h[z_2(k) - \beta_{01}\varepsilon_1] \\ z_2(k+1) = z_2(k) + h[z_3(k) - \beta_{02}fal\left(\varepsilon_1, \frac{1}{2}, \delta\right) + bu] \\ z_3(k+1) = z_3(k) - h\beta_{03}fal\left(\varepsilon_1, \frac{1}{4}, \delta\right) \end{cases} \quad (12)$$

2.3. Nonlinear State Error Feedback Control Law (NLSEF)

The basic idea of the Nonlinear State Error Feedback Control Law (NLSEF) is to design a nonlinear feedback controller based on the error signals of the system. This controller is capable of compensating in real time for factors such as unmodeled dynamics, external disturbances, and parameter variations, thereby enabling the system to better adapt to changes in the external environment.

In the NLSEF, integral information can be disregarded because the state observer estimates and removes system perturbations. The nonlinear state error feedback control law can be expressed as Formulas (13) and (14).

$$u_0 = \beta_1 fal(e_1, a_1, \delta) + \beta_2 fal(e_2, a_2, \delta) \quad (13)$$

where $fal(\varepsilon, a, \delta)$ is the same as Formula (11) and $0 < a_1 < 1 < a_2$ is good.

$$u_0 = fhan(e_1, ce_2, r, h_1) \quad (14)$$

where c is the damping factor and h_1 is the accuracy factor.

2.4. Complete Algorithm

Differential tracking and transition process arrangement:

$$\begin{cases} x_1(k+1) = x_1(k) + hx_2(k) \\ x_2(k+1) = x_2(k) + hf \\ fh = fhan(x_1(k) - v(k), x_2(k), r_0, h_0) \end{cases} \quad (15)$$

Expansion state observation:

$$\begin{cases} \varepsilon_1 = z_1(k) - y(k) \\ z_1(k+1) = z_1(k) + h[z_2(k) - \beta_{01}\varepsilon_1] \\ z_2(k+1) = z_2(k) + h[z_3(k) - \beta_{02}fal(\varepsilon_1, \frac{1}{2}, \delta) + bu] \\ z_3(k+1) = z_3(k) - h\beta_{03}fal(\varepsilon_1, \frac{1}{4}, \delta) \end{cases} \quad (16)$$

Nonlinear combinations:

$$\begin{cases} u_0 = \beta_1 fal(e_1, a_1, \delta) + \beta_2 fal(e_2, a_2, \delta) \\ e_1 = v_1 - z_1 \\ e_2 = v_2 - z_2 \end{cases} \quad (17)$$

Disturbance compensation forms control quantity:

$$u = \frac{u_0 - z_3}{b_0} \quad (18)$$

$r_0, \beta_{01}, \beta_{02}, \beta_{03}, \beta_1, \beta_2, a_1, a_2, \delta, b_0$ are the parameter of the controller, the value of a_1, a_2 are $0 < a_1 < 1 < a_2$, generally $5h \leq \delta \leq 10h$.

To make the extended state observer work effectively, the b_0 must be estimated to approximately replace the b value. The difference between the estimated value b and the actual value b can be treated as a disturbance. The command information processing module tracking-differentiator, the actual system extended state observer, the nonlinear state error feedback control law like the proportional differentiation link, and the key output signal generation link are built in the simulation environment to form the overall model of the nonlinear active disturbance rejection control system.

3. Variable Pitch Variable Speed Coordinated Control Technology of Variable Pitch Propeller

The ADRC algorithm used in this paper This paper uses the $fal()$ function as a nonlinear combinatorial function and the parameters that need to be tuned are $r_0, h_0, \beta_1, \beta_2, a_1, a_2, \beta_{01}, \beta_{02}, \beta_{03}, \delta, b_0$. Because the serial ADRC is used, the parameters of the inner loop ADRC and outer loop ADRC need to be adjusted separately. For the propeller model at 4400 rmp, the parameters of the inner and outer loops corresponding to the optimal control are finally adjusted as shown in Table 1.

Table 1. Serial ADRC parameters.

	TD		NNLSEF				ESO			Gain	
parameters	r_0	h_0	β_1	β_2	a_1	a_2	β_{01}	β_{02}	β_{03}	δ	b_0
inner loop	1000	1	10	0.75	1	1	5	20	100	0.1	0.95
outer loop	2000	0.5	130	0.2	1	1	170	1000	1	0.1	2

3.1. Yaw Response Analysis

This section details the controller parameter adjustment process using a single eVTOL propeller model at 4400 rpm, with the resulting step response plotted. The analysis then proceeds with propeller speed variations to 3965 rpm and 3529 rpm, plotting their respective step response curves.

As illustrated in Figure 1, it is evident that system instability increases as the rotational speed decreases. The following sections will propose a solution to address this issue.

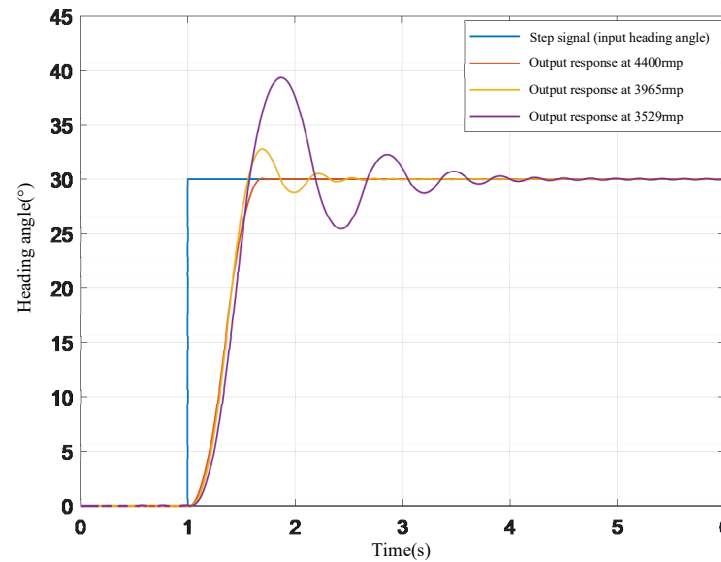


Figure 1. Single-rotor step response for 30° yaw command at three rotational speeds (4400, 3965, and 3529 rpm).

3.2. Speed Inner Loop Feedback Anti-Interference Improvement

When the variable pitch propeller is reduced from high speed to low speed, the actual control model also changes, and the optimal parameters at high speed are not the optimal parameters at low speed. One control method is to add the speed information to the controller in the control quantity generation link, no longer use the fixed value b_0 , and replace it with the dynamic parameters that change with the speed. It can be understood that $u_0 - z_3$ is the angular acceleration action that the controller wants the object to make. $(u_0 - z_3) \times I$ represents the anti-torque generated by the propeller, and $(u_0 - z_3) \times I/L$ represents the tension generated by the propeller. According to the formula, a reasonable pitch angle can be calculated, which can be converted into the angle of the steering gear, and the high-level time of the steering gear control signal can be calculated to complete a control cycle. The output of the nonlinear state error feedback control rate of the inner loop of the cascade ADRC is the theoretical expected anti-torque value. After subtracting the state variables output by the inner loop extended state observer, the real anti-torque input is obtained, and the input of the controlled object is the pitch angle. Therefore, the value plays the role of converting the expected thrust value of the propeller and the pitch angle.

$$(x_3 - Z_{13}) \cdot b_0 = \delta_{ped} \quad (19)$$

where x_3 is the output of the inner-loop nonlinear state error feedback control law, Z_{13} is the extended quantity of the inner-loop extended state observer, b_0 is the output link parameter of the control quantity, and δ_{ped} is the pitch angle of the actual input.

$$(x_3 - Z_{13}) \cdot I_Z = I_{input} \quad (20)$$

where I_Z is the moment of inertia of the body along the Z-axis of the body coordinate system, I_{input} is the Z-axis anti-torque input through the pitch angle, and the expression of I_{input} is as follows:

$$I_{input} = F_T \cdot L \quad (21)$$

where L is the vertical distance from the propeller shaft to the center of gravity on the horizontal plane, which is a constant; F_T is the pulling force of the propeller, and its expression is as follows:

$$\begin{cases} F_T = R \cdot p \cdot w \cdot \Omega_T^2 \cdot Air \cdot Exp \\ p = 0.5 \cdot R \cdot \pi \cdot \tan \delta_{ped} \end{cases} \quad (22)$$

Among them, R refers to the rotation diameter, w refers to the blade width, Ω_T^2 refers to the rotation speed of the propeller, Air refers to a standard atmosphere, and Exp refers to the empirical parameters (Dimensionless parameter 0.25).

Combining Formulas (19) to (22) can be obtained:

$$\delta_{ped} = \frac{180}{\pi} \cdot \arctan \left((x_3 - Z_{13}) \cdot \frac{1}{\Omega_T^2} \cdot \frac{2 \cdot I_Z}{R^2 \cdot w \cdot Air \cdot Exp \cdot L} \right) \quad (23)$$

In the above formula, let:

$$b_1 = \frac{2 \cdot I_Z}{R^2 \cdot w \cdot Air \cdot Exp \cdot L} \quad (24)$$

The simultaneous Formulas (23) and (24) can be obtained:

$$\delta_{ped} = 57.3 \cdot \arctan \left((x_3 - Z_{13}) \cdot \frac{b_1}{\Omega_T^2} \right) \quad (25)$$

where b_1 is the parameter to be adjusted, and Ω_T is the propeller speed information.

3.3. Speed Inner Loop Feedback Compensation Anti-Disturbance Improvement

In Formula (25), Ω_T represents the value directly measured by the speed sensor. Typically, values measured by sensors exhibit a certain degree of lag. To enhance the control accuracy of the propeller, it is necessary to predict the precise speed of the propeller during pitch angle control. The proposed solution is to compensate for the error caused by time delay using an extended observer before substituting the propeller speed information Ω_T into Formula (25). The formula is as follows:

$$\begin{cases} \delta_{ped} = 57.3 \cdot \arctan \left((x_3 - Z_{13}) \cdot \frac{b_1}{\Omega_1(k+1)^2} \right) \\ \Omega_1(k+1) = \Omega_1(k) + h[\Omega_2(k) - \beta_{01}\Delta\Omega] \\ \Omega_2(k+1) = \Omega_2(k) - h\beta_{02}fal\left(\Delta\Omega, \frac{1}{2}, \delta\right) \\ \Delta\Omega = \Omega_1(k) - y(k) \end{cases} \quad (26)$$

The Main ESO is a higher-order observer that estimates the states and the total disturbance acting on the airframe's yaw dynamics.

The Rotational Speed Observer is a simpler, second-order observer focused solely on estimating the state of the propulsion system. Its purpose is explicitly to compensate for sensor dynamics and lag, providing a phase-advanced prediction of the speed signal.

3.4. Comparative Analysis of Two Control Methods for Yaw Stability Under Propeller Speed Fluctuation

3.4.1. Comparison of Yaw Stability Under 0.5% Propeller Speed Variation

As shown in Figure 2a,b, when the propeller rotational speed is 3529 rpm with dynamic speed variations of 0.5%, the yaw angle swing amplitude of the yaw control system based on rotational speed feedback is ± 0.18 degrees, and the yaw angular velocity output range is ± 0.4 degrees/second. In contrast, the yaw angle swing amplitude of the yaw control system based on rotational speed feedback compensation is ± 0.14 degrees, corresponding to 77.8% of the pre-improvement value with the yaw angular velocity output range at ± 0.27 degrees/second (67.5% of the pre-improvement value). These results clearly demonstrate that the control performance with rotational speed feedback compensation is significantly better than that without compensation.

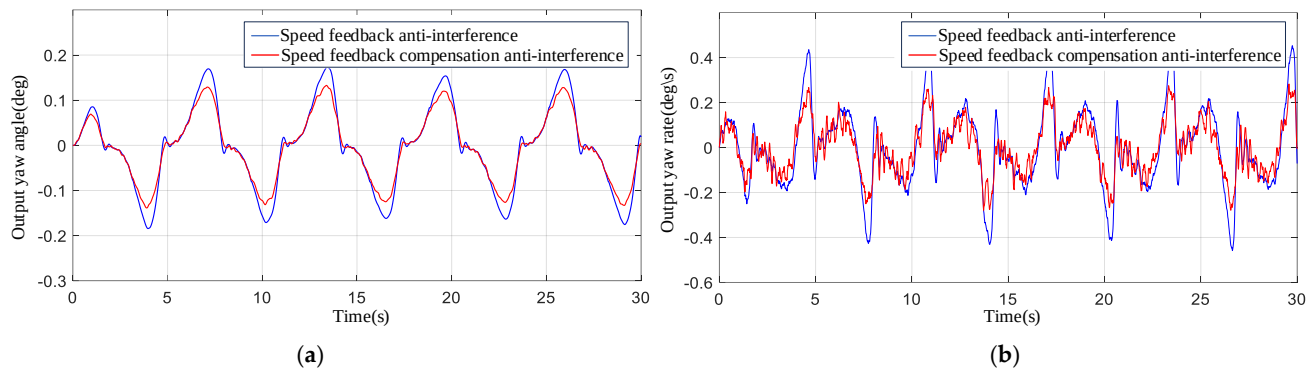


Figure 2. (a) Effect of 3529 rpm propeller: 0.5% change in rotational speed on airframe yaw angular. (b) Effect of 3529 rpm propeller: 0.5% change in rotational speed on airframe yaw angular velocity.

3.4.2. Comparison of Yaw Stability Under 1% Propeller Speed Variation

As shown in Figure 3a,b, when the propeller operates at 3529 rpm with 1% dynamic speed variation, the yaw angle swing amplitude of the yaw control system based on rotational speed feedback is ± 0.245 degrees, and the yaw angular velocity output range is ± 0.53 degrees/second. In contrast, the yaw angle swing amplitude of the yaw control system based on rotational speed feedback compensation is ± 0.17 degrees, representing a reduction to 69.39% of the pre-improvement level, and the yaw angular velocity output range is ± 0.3 degrees/second, representing a reduction to 56.6% of the pre-improvement level. These results clearly demonstrate that the control performance with rotational speed feedback compensation is significantly better than that without compensation.

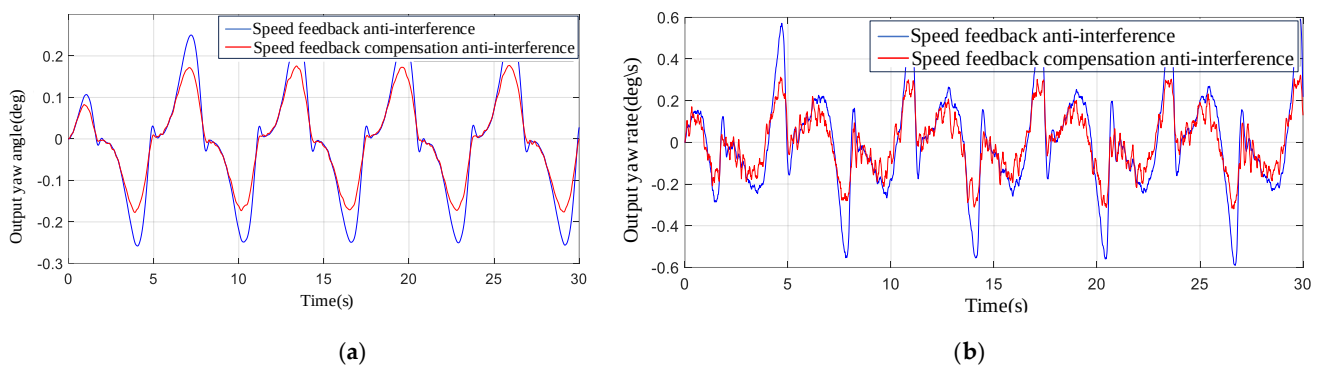


Figure 3. (a) Effect of 3529 rpm propeller: 1% change in rotational speed on airframe yaw angular. (b) Effect of 3529 rpm propeller: 1% change in rotational speed on airframe yaw angular velocity.

3.4.3. Comparison of Yaw Stability Under 2% Propeller Speed Variation

As shown in Figure 4a,b, when the rotor speed of the propeller is 3529 rpm and the rotor speed changes dynamically by 2%, the yaw angle swing amplitude of the yaw control system based on rotor speed feedback is ± 0.37 degrees, and the yaw angular velocity output range is ± 0.6 degrees/second. In contrast, the yaw angle swing amplitude of the yaw control system based on rotational speed feedback compensation is ± 0.23 degrees, representing a reduction to 62.2% of the pre-improvement level, and the yaw angular velocity output range is ± 0.4 degrees/second, representing a reduction to 66.7% of the pre-improvement level. These results clearly demonstrate that the control performance with rotational speed feedback compensation is significantly better than that without compensation.

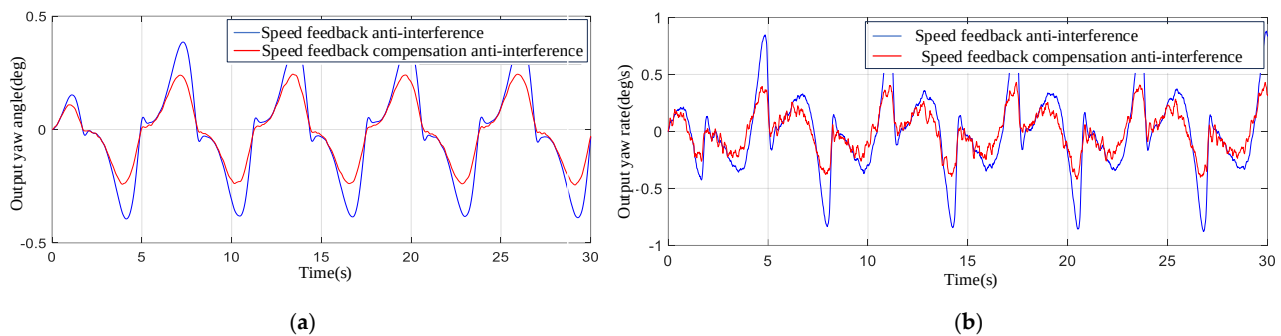


Figure 4. (a) Effect of 3529 rpm propeller: 2% change in rotational speed on airframe yaw angular. (b) Effect of 3529 rpm propeller: 2% change in rotational speed on airframe yaw angular velocity.

Summarizing the findings from the above three subsections and comparing the curve analysis, it is evident that the control performance based on rotational speed inner-loop feedback compensation is superior to that of heading control with only rotational speed inner-loop feedback. Specifically, the yaw angular rate is less affected by fluctuations in rotor rotational speed, and the yaw angle oscillation amplitude is also smaller. Furthermore, curve comparisons reveal, the control scheme with rotational speed feedback compensation is more sensitive to disturbances caused by main propeller rotational speed fluctuations. Figure 5 illustrates the yaw angle oscillation amplitude under the two control laws when the propeller speed fluctuates from 0.5% to 5%.

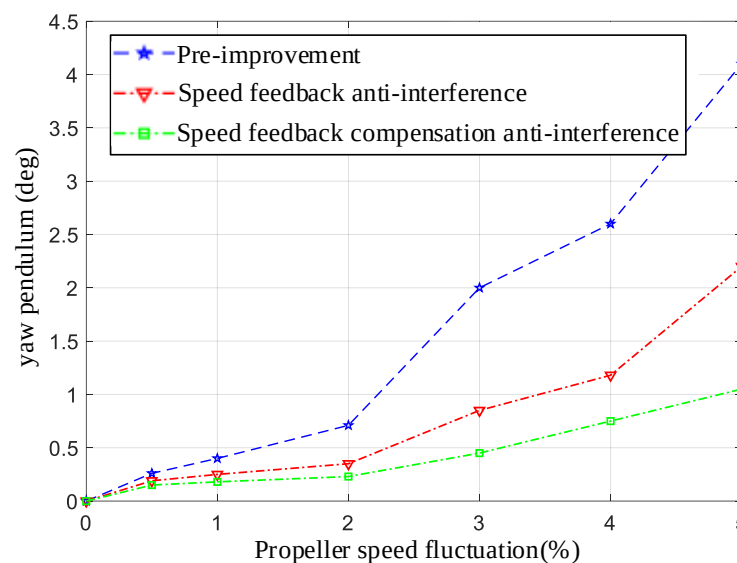


Figure 5. Effect of propeller speed fluctuation on yaw angle error.

4. Pitch Propeller Test Verification

To further investigate the control instability caused by reducing the rotational speed, a test rig was constructed based on the eVTOL variable-pitch propeller system, as shown in Figure 6 below.



Figure 6. (a) Three-dimensional assembly of the variable pitch propeller. (b) Variable pitch propeller 1:1 test bench.

During a mission cycle, the variation in the variable-pitch propeller speed before improvement is illustrated in Figure 7a. The propeller speed increases from zero to the rated speed before takeoff, remains constant at the rated speed during flight, and decreases to zero after landing, completing a full flight cycle.

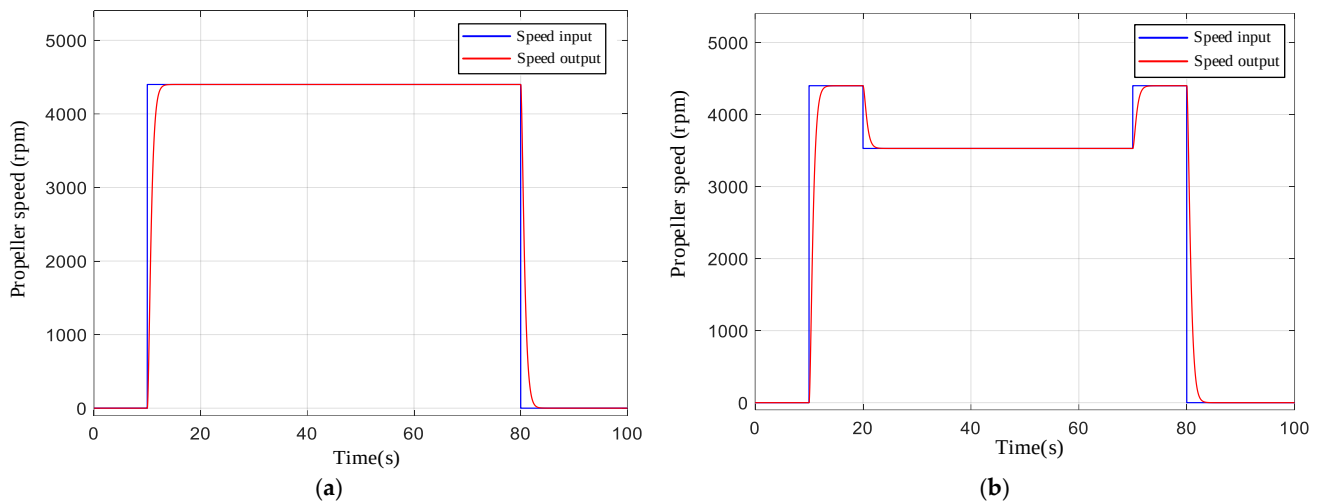


Figure 7. (a) Change in propeller speed before improvement. (b) Change in propeller speed after improvement.

The variation in the improved propeller speed is illustrated in Figure 7b. The propeller speed increases to the rated speed of 4400 rpm before takeoff, decreases to 3529 rpm once the eVTOL enters the 120 km/h cruise mode, and increases back to 4400 rpm when the eVTOL exits the cruise flight mode.

As the flight speed increases, the propeller power no longer increases but remains near 0.75 kW. This is because, before the improvement, the propeller pitch angle decreased with increasing flight speed, causing the propeller to operate in a low lift-to-drag ratio region with low force efficiency. After the improvement, during the economic cruise phase, the pitch angle is maintained at approximately 8.2 degrees, ensuring operation in a high lift-to-drag ratio region with high force efficiency.

For a total of 41 rotational speed sampling points in Figure 8, 41 tests were conducted on the propeller to obtain the input power data at different flight speeds. The results demonstrate that the improved variable-speed, variable-pitch scheme consumes less energy compared to the pre-improved fixed rotational speed, variable-pitch angle scheme.

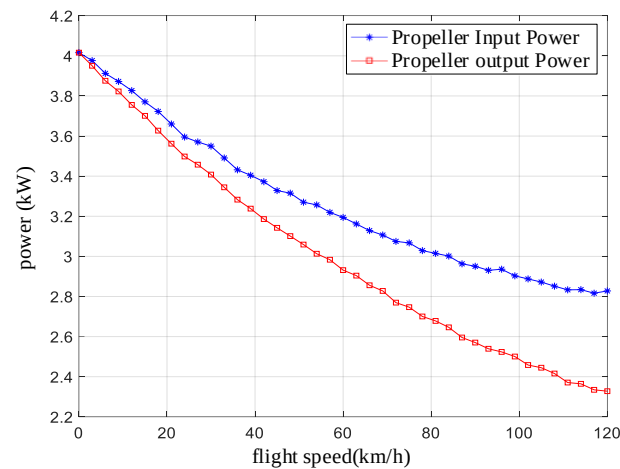


Figure 8. Comparison of propeller power before and after improvement.

Figure 9 shows a comparison of the propeller force efficiency before and after the improvement. It is evident that the force efficiency of the improved motorized propeller is consistently higher than that of the pre-improvement design.

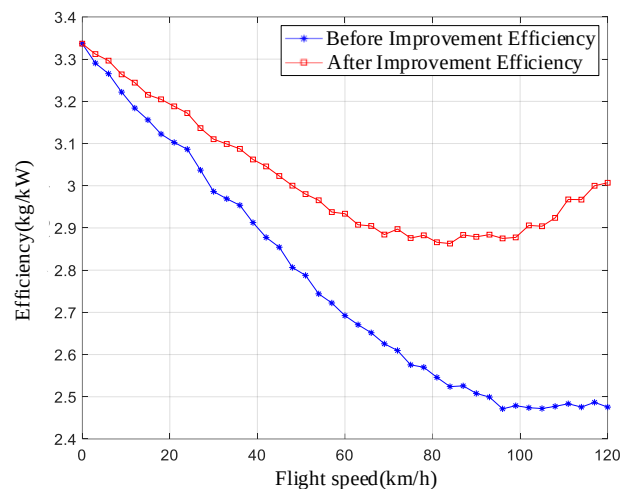


Figure 9. Comparison of propeller force efficiency before and after improvement.

Taking the economic cruising speed of 120 km/h as an example, the power required to generate a given thrust was reduced by 23% after the improvement. Quantitatively, this translates to an increase in the thrust-to-power ratio from 2.48 to 3.05 N/W (or, equivalently, from 2.48 to 3.05 kg/kW), meaning the same 1 kW of power can generate an additional 0.57 kg of thrust. Consequently, at 120 km/h, the improved propeller saves 0.48 kW of power, enabling the eVTOL to cruise for an additional 4.27 min and travel an additional 8.53 km, thereby increasing its operational radius by 4.26 km.

5. Conclusions

Based on current eVTOL application requirements and an investigation of the current status of eVTOL technology, an improved control scheme for the variable-pitch propeller is proposed. This scheme involves real-time measurement of data such as propeller rotational

speed, which is fed back to the self-immunity controller for pitch angle control. To address potential heading instability issues in eVTOL vehicles, this paper proposes two control schemes for the variable-pitch propeller: an anti-disturbance control design based on rotational speed feedback and an anti-disturbance control design based on rotational speed feedback compensation. Simulation results demonstrate that the speed feedback-based anti-disturbance control improves yaw stability by approximately 50% compared to the control without speed feedback, while the speed feedback-compensated anti-disturbance control further improves yaw stability by approximately 45% compared to the speed feedback anti-disturbance control. These results clearly indicate that the speed feedback-compensated control offers significantly higher stability. Additionally, a ground test bed was established to verify the improved energy efficiency of the variable-pitch propeller system. The results show that the improved variable-pitch propeller exhibits higher power efficiency compared to the pre-improved design, with a power saving of 0.48 kW during 120 km/h cruise flight. The propeller model and experimental validation employed in this study, while effectively validating the core control concept under hover and static conditions, serve as a crucial first step. However, as rightly highlighted during the review process, the critical next step for the applicability of this technology is validation under edgewise flight conditions. Therefore, our immediate future work will be experimentally focused: we will conduct wind tunnel testing to rigorously validate the controller's performance under precisely controlled edgewise flow. This essential work will directly address the aerodynamic complexities of forward flight, such as rotor stall and uneven blade loading, and is a mandatory requirement for transitioning this control strategy from a promising concept to a deployable solution for eVTOL vehicles.

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Abbreviations

The following abbreviations are used in this manuscript:

eVTOL	Electric Vertical Take-Off and Landing
ADRC	Active Disturbance Rejection Control
RLS	Recursive Least Squares
ESO	Extended State Observer
AFTSMC	Accelerated Finite-Time Sliding Mode Control
TD	Tracking Differentiator
NLSEF	Nonlinear State Error Feedback Control Law

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