

Article

Control Strategy for Powered Flight Following Tail Rotor Failure in Helicopters

Xinming Feng ¹, Haiming Tian ², Rui Zu ¹, Yi Luo ¹ and Jianbo Li ^{1,*}

¹ National Key Laboratory of Helicopter Aeromechanics/Helicopter Research Institute, Nanjing University of Aeronautics and Astronautics, Nanjing 210001, China; xmfeng101@nuaa.edu.cn (X.F.); zurui19@nuaa.edu.cn (R.Z.); lylyly@nuaa.edu.cn (Y.L.)

² China Flight Test Establishment, Xi'an 710089, China; jj986708804@gmail.com

* Correspondence: lj101@nuaa.edu.cn

Abstract

Tail rotor failure represents a critical emergency in helicopter flight operations. Conventional recovery mandates an immediate engine shutdown and transition to autorotation, significantly compromising both mission survivability and operational flexibility. To achieve stable powered flight, this paper establishes a yaw stability strategy integrating vertical tail side-force control with active main rotor torque suppression. This strategy employs controlled sideslip to generate a yaw-restoring moment from the vertical tail and an increased descent rate to reduce rotor power requirement. These two effects act in concert to counteract the rotor torque. Trim analysis of a representative helicopter in a tail rotor failure condition validates the strategy. Two yaw control architectures are developed for the failure operation: (1) a cascade loop comprising yaw angle, yaw rate, lateral velocity, and roll angle, and (2) the latter omitting lateral velocity. Comparative simulations demonstrate that although Loop (1) yields slower yaw convergence than Loop (2), it delivers enhanced stability. Furthermore, an emergency control trajectory tailored for moderate forward velocity is proposed. The trajectory initiates with a controlled descent-rate increase to arrest yaw divergence. The forward velocity is then augmented to mitigate sideslip, and the descent rate is gradually reduced, ensuring adequate altitude clearance over the landing zone. This study provides a strategy for enabling powered flight under tail rotor failure conditions.

Keywords: flight control; control strategy; tail rotor failure; flight simulation

1. Introduction

The tail rotor provides essential anti-torque to counteract the main rotor torque. Failure induces a disruptive torque imbalance, presenting a critical hazard to flight safety. Statistical analyses indicate that tail rotor failures account for approximately 30% of all helicopter accidents [1,2]. This figure remains consistent with data from 1980–1985 (32%) [3], suggesting that the accident rate associated with tail rotor failure has persisted with no significant mitigation over the past four decades.

The existing literature primarily classifies tail rotor failures into two categories: Tail Rotor Control Failure (TRCF) and Tail Rotor Drive Failure (TRDF) [4,5]. In the TRCF state, mechanical lockup renders the tail rotor moment unmanageable, albeit with retained aerodynamic damping. TRDF entails a total loss of tail rotor authority, triggering an immediate and severe yaw response. Due to its inherent susceptibility to catastrophic loss of control, TRDF is universally acknowledged as the most critical failure mode [6].



Academic Editor: Zheng Chen

Received: 3 July 2026

Revised: 31 July 2026

Accepted: 1 August 2026

Published: 3 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Consequently, its potential for severe consequences has driven extensive research efforts in recent years.

Andrea [7] proposes “In-Depth Feature Selection,” a methodology that facilitates early fault warnings by exclusively leveraging extant onboard signals, thereby obviating the need for additional sensor hardware. Paola [8] proposes a hybrid approach integrating physics-based simulations with machine learning to enable proximal alerting for Loss of Tail Rotor Effectiveness (LTE). These methodologies provide proximal alerts to pilots and flight control systems prior to tail rotor failure, thereby significantly reducing the response time required for emergency mitigation. Addressing TRCF during hovering flight, Sulakshan [9] formulated fault-tolerant control laws for a small-scale helicopter, thereby ensuring stability following failure onset. Yan [2] examined emergency recovery strategies for a mechanically locked tail rotor under both high and low collective pitch conditions using optimal control theory. The findings reveal that powered-landing attempts with the tail rotor locked at low collective are predisposed to precipitating severe yaw divergence, thereby exacerbating the risk of control departure. Garcia [10] proposed an airframe spin control strategy for TRDF that demonstrates the feasibility of powered survival. However, its stringent demands on actuator dynamic response, coupled with the physiological tolerance limits of pilots exposed to sustained rotation, render it impractical for direct implementation on manned helicopters. Notably, this strategy exhibits strong conceptual congruence with the uniform passive Fault-Tolerant Control (FTC) scheme proposed by Ke [11] for quadrotors under rotor failure. Both methodologies relax stringent stability constraints on noncritical states, specifically the yaw angle, to prioritize the expansion of survivability envelopes. Through the Software Enabled Control (SEC) initiative, researchers at Georgia Tech [12] rigorously validated failure-mode control methodologies for helicopters. This effort culminated in a comprehensive flight demonstration showcasing the synergistic integration of fault detection, control reconfiguration, vision-based navigation, and envelope protection. The results demonstrate that enhanced fault tolerance is indispensable for improving UAS reliability.

For manned helicopters, the emergency procedure for TRDF mandates the immediate engine shutdown to induce main rotor autorotation [2,4,5,9,10,13,14]. Extensive research has been conducted on helicopter control methodologies during the autorotative state. Yomchinda [15] proposed a three-dimensional trajectory planner for an autorotative landing that integrates an augmented Dubins curve framework with acceleration constraints and a descent rate profile. Based on flight-test data, Jump [16] devised a τ theory-based real-time trajectory planner for manned autorotation, which was also useful for unmanned helicopter autonomous landing [17]. Saetti [18] proposed a control scheme for the autorotative flare maneuver, which integrates τ theory-based rapid trajectory generation with Nonlinear Dynamic Inversion (NDI) for robust tracking. Fattizzo [19,20] developed a hybrid framework coupling offline trajectory optimization with online closed-loop control. Using quadratic polynomials for smooth flare profiling and NDI for robust attitude control, the approach achieves fully autonomous safe landing.

Collectively, TRDF mitigation approaches comprise two approaches. The first approach prioritizes retained power, deliberately relaxing stringent yaw stability requirements to permit sustained uncontrolled yaw, while maintaining longitudinal, lateral, and vertical controllability. The second approach mandates engine shutdown to initiate autorotation, thereby nullifying the main rotor torque, albeit at the expense of total power loss and the inevitability of continuous descent. Notably, both approaches share a fundamental design tenet: relaxing stringent control authority over select non-critical states to prioritize helicopter survivability. However, the former is physiologically intolerable for manned rotorcraft, while the latter not only imposes severe reachability constraints on the emergency landing site [21,22] but also precludes any possibility of sustained flight.

To endow a manned helicopter with sustained flight capability under TRDF conditions, this paper establishes an “altitude-for-controllability” trade-off strategy. A controlled descent is initiated to attenuate main rotor torque, while a regulated sideslip angle is imposed to harness the yaw moment generated by the vertical tail in the free stream. This approach restores yaw stability and regains yaw control authority, thereby safeguarding flight safety without necessitating engine shutdown. Operational applicability of this strategy hinges on two critical prerequisites. First, the helicopter must sustain a minimum forward velocity threshold. Otherwise, inadequate inflow over the vertical tail at low speed precludes generation of the necessary stabilizing yaw moment to counteract main rotor torque. Second, sufficient initial altitude is required to allow for the limited duration of the controlled descent. Compared to conventional engine shutdown or uncontrolled yaw divergence, the planned altitude sacrifice enhances overall safety margins. While Ref. [3] investigated this approach, it did not provide a specific implementation for yaw stabilization control. To address this, a dedicated yaw control loop is formulated.

The remainder of this paper is organized as follows. First, a nonlinear flight dynamics model of a representative helicopter is developed and validated by trim analysis. Second, trim analysis is performed following TRDF, upon which the “altitude-for-controllability” control strategy is formulated. To evaluate the impact of the feedback loop topology on yaw stability, two distinct closed-loop yaw control architectures are formulated. Comparative simulations of the transient responses then identify the better configuration for manned helicopters. Subsequently, a post-TRDF flight trajectory is predefined, and the selected control architecture is implemented to track this trajectory. Finally, conclusions are provided.

2. Helicopter Flight Dynamics Model

2.1. Model

The Z11 helicopter serves as the research platform, for which a nonlinear flight dynamics model is developed using a component-buildup modeling framework, incorporating the aerodynamic characteristics of key components including the main rotor, tail rotor, fuselage, horizontal stabilizer, and vertical tail. Key model parameters are presented in Table 1, with a comprehensive listing provided in Ref. [23]. Aerodynamic forces and moments generated by each constituent component are first transformed from local component frames to the body-fixed reference frame via standard rotational transformations, then vectorially summed to determine the net body-axis forces and moments. Integrating the aggregate loads into the six-degree-of-freedom (6-DOF) rigid-body equations of motion yields the complete nonlinear helicopter dynamics model. The mathematical model is formulated as follows.

Table 1. Helicopter model parameters.

Parameters	Value	Parameters	Value
Weight m	2000 kg	Rotor speed Ω	40.42 rad/s
Rotor radius R	5.345 m	Blade number n_b	3
Blade twist θ_t	−0.2094 rad	Blade chord c	0.35 m
Solidity σ	0.06253	Direction of rotation	clockwise
Vertical tail areas S_v	1.021 m ²	Horizontal tail areas S_h	1.265 m ²
Fuselage areas S_{fus}	2.7625 m ²	Fuselage length L_{fus}	11.24 m

Let $\boldsymbol{\theta} = [\phi, \theta, \psi]^T$ denote the attitude angles, $\mathbf{V}_b = [u, v, w]^T$ the body-axis velocities, and $\boldsymbol{\omega} = [p, q, r]^T$ the angular rates. The 6-DOF equations of motion are then expressed as follows:

$$\begin{aligned}\dot{\boldsymbol{\theta}} &= \mathbf{R}\boldsymbol{\omega} \\ \dot{\boldsymbol{\omega}} &= \mathbf{I}^{-1}(\mathbf{M} - \boldsymbol{\omega} \times \mathbf{I}\boldsymbol{\omega}) \\ \dot{\mathbf{V}} &= \mathbf{S}\mathbf{V}_b \\ \mathbf{V}_b &= -\boldsymbol{\omega} \times \mathbf{V} + \mathbf{F}/m\end{aligned}\quad (1)$$

In Equation (1), $\mathbf{F}$ and $\mathbf{M}$ represent the aggregate aerodynamic force and moment vectors, respectively, obtained by synthesizing the contributions from individual components. $\mathbf{I}$ denotes the inertia matrix, m the total mass, and $\mathbf{V} = [V_x, V_y, V_z]^T$ the velocity vector expressed in the earth-axis frame. The remaining parameters are defined as follows:

$$\begin{aligned}\mathbf{R} &= \begin{bmatrix} 1 & \sin \phi \tan \theta & \cos \phi \tan \theta \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi / \cos \theta & \cos \phi / \cos \theta \end{bmatrix} \\ \mathbf{S} &= \begin{bmatrix} -\sin \theta & \cos \theta \sin \phi & \cos \theta \cos \phi \end{bmatrix}^T\end{aligned}\quad (2)$$

Let $\mathbf{x} = [\mathbf{V}_b^T, \boldsymbol{\omega}^T, \boldsymbol{\theta}^T]^T$ denote the state vector and $\boldsymbol{\delta} = [\delta_0, \delta_b, \delta_c, \delta_{0t}]^T$ the control input vector, where δ_0 , δ_b , δ_c , and δ_{0t} represent the collective, longitudinal cyclic, lateral cyclic, and pedal control, respectively. Coupled with $\mathbf{F}$ and $\mathbf{M}$, the nonlinear helicopter flight dynamics model can be expressed as follows:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \boldsymbol{\delta}) \quad (3)$$

It is noteworthy that the yaw restoring moment generated by the baseline vertical tail is insufficient to counteract the main rotor torque following TRDF. Consequently, a modified configuration with the vertical tail planform area scaled by a factor of 1.5 is established as the primary configuration for subsequent control analysis. The baseline configuration is utilized exclusively for initial model validation.

To account for structural modifications induced by variations in vertical tail area, the helicopter inertial properties were corrected. Referencing empirical data from [24,25], which indicate that the vertical tail typically constitutes 0.3–1.5% of the gross weight, a 47% increase in structural mass was implemented based on the weight–size relationship ($W \propto S^{0.9 \sim 1}$) [25,26]. This adjustment added 0.7% to the total aircraft weight and shifted the center of gravity (CG) aft by 5 cm, resulting in an 11% increase in the yaw moment of inertia.

2.1.1. Rotor Model

The main rotor model is formulated based on blade element theory, with total thrust and resultant hub moments obtained via radial integration along the blade span [27]. The Pitt-Peters dynamic inflow model [28] is employed for inflow characterization, and rotor flapping dynamics are accounted for to capture the dynamic characteristics of the rotor.

The rotor flapping motion is expressed as follows:

$$\begin{cases} \ddot{\mathbf{a}}_p + \mathbf{D}_p \dot{\mathbf{a}}_p + \mathbf{K}_p \mathbf{a}_p = \mathbf{f}_p \\ \beta(\zeta) = a_{0p} - a_{1p} \cos(\zeta) - b_{1p} \sin(\zeta) \end{cases} \quad (4)$$

In Equation (4), $\mathbf{a}_p = [a_0, a_1, b_1]^T$ denotes the vector of rotor flapping angles. $\mathbf{D}_p$, $\mathbf{K}_p$, and $\mathbf{f}_p$ denote the damping, stiffness, and hinge moment matrices, respectively. $\beta(\zeta)$ denotes the rotor flapping angle, and ζ is the azimuth angle.

The rotor inflow model employs a first-order dynamic inflow formulation:

$$\mathbf{M}_0 \dot{\boldsymbol{\lambda}} + \mathbf{L}_0^{-1} \boldsymbol{\lambda} = \mathbf{C} \quad (5)$$

In Equation (5), $\boldsymbol{\lambda} = [v_0, v_s, v_c]^T$ denotes the rotor-induced velocity, and $\mathbf{C} = [C_T, C_L, C_M]^T$ denotes the rotor aerodynamic coefficient, derived by blade element theory. $\mathbf{M}_0$ and $\mathbf{L}_0$ are third-order matrices characterizing the inflow time delay and induced velocity distribution, respectively, and are expressed as follows:

$$\mathbf{M}_0 = \begin{bmatrix} \frac{128}{75\pi} & 0 & 0 \\ 0 & -\frac{16}{45\pi} & 0 \\ 0 & 0 & -\frac{16}{45\pi} \end{bmatrix} \quad (6)$$

$$\mathbf{L}_0 = \frac{1}{v_m} \begin{bmatrix} \frac{1}{2} & 0 & \frac{15\pi}{64} \sqrt{\frac{1-\cos\eta}{1+\cos\eta}} \\ 0 & -\frac{4}{1+\cos\eta} & 0 \\ \frac{15\pi}{64} \sqrt{\frac{1-\cos\eta}{1+\cos\eta}} & 0 & -\frac{4\cos\eta}{1+\cos\eta} \end{bmatrix} \quad (7)$$

In Equation (7), v_m denotes the mass flow parameter, and η denotes the wake deflection angle. Analogous to the main rotor model, the tail rotor utilizes a uniform inflow assumption and details are omitted for brevity.

2.1.2. Airframe Aerodynamic Modeling

Aerodynamic databases [23] for the fuselage, horizontal stabilizer, and vertical tail are populated using empirical wind-tunnel data. Tabulated force and moment coefficients across arbitrary angles of attack α and sideslip β are subsequently evaluated by interpolation. Taking the fuselage as an example, the aerodynamic force $[D_{fus}, Y_{fus}, L_{fus}]^T$ and moment $[l_{fus}, m_{fus}, n_{fus}]^T$ are expressed as functions of the dynamic pressure $Q = 0.5\rho v^2$, reference area S_{fus} , and reference length L_{fus} as follows:

$$\begin{cases} D_{fus} = QS_{fus}C_D(\alpha, \beta) \\ Y_{fus} = QS_{fus}C_Y(\alpha, \beta) \\ L_{fus} = QS_{fus}C_L(\alpha, \beta) \\ l_{fus} = QS_{fus}L_{fus}C_l(\alpha, \beta) \\ m_{fus} = QS_{fus}L_{fus}C_m(\alpha, \beta) \\ n_{fus} = QS_{fus}L_{fus}C_n(\alpha, \beta) \end{cases} \quad (8)$$

2.2. Model Validation

This section performs trim computations for the subject helicopter, with results compared against the benchmark data from Ref. [23] to validate the model. Figure 1 compares the trim values for collective pitch, longitudinal cyclic, lateral cyclic, and pedal control across various forward flight velocities, while Figure 2 illustrates the corresponding attitude angles. The close agreement between the simulation results obtained herein and previously published benchmark data demonstrates the accuracy of the developed nonlinear flight dynamics model.

Notably, a deviation in roll attitude is observed at higher forward velocities (>40 m/s); this discrepancy is primarily attributed to the simplified modeling of aerodynamic interferences, specifically main rotor–horizontal tail and tail rotor–vertical tail interference. Since the subsequent simulations are confined to the velocity regime of 25–40 m/s, this error does not significantly compromise the validity of the conclusions.

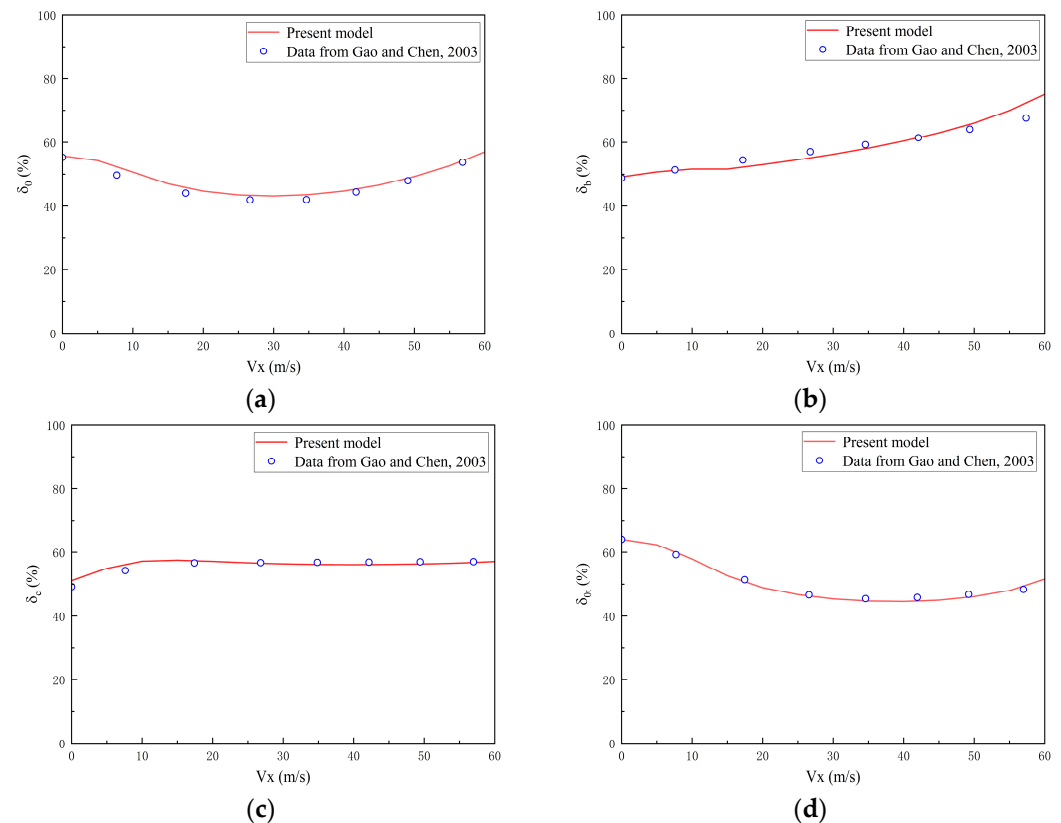


Figure 1. Trim validation [23]: (a) Collective pitch; (b) Longitudinal cyclic; (c) Lateral cyclic; (d) Pedal control.

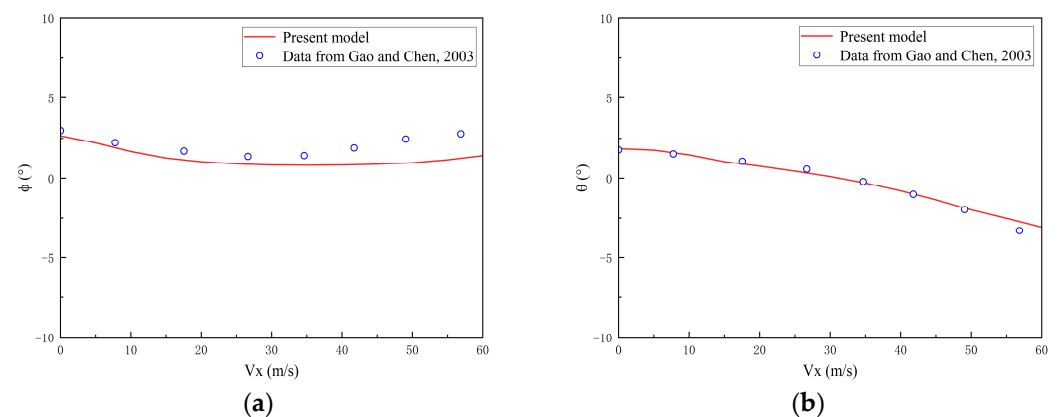


Figure 2. Trim validation of attitude angles [23]: (a) Roll angle; (b) Pitch angle.

3. Control Following TRDF

This section addresses the control challenge posed by TRDF. A worst-case scenario, instantaneous total tail rotor thrust loss, is postulated. Consequently, pedal inputs yield no corrective yaw moment. Under this condition, the total aerodynamic force F_s and moment M_s are contributed solely by the main rotor (F_r and M_r), fuselage (F_{fus} and M_r), horizontal stabilizer (F_h and M_h), and vertical tail (F_v and M_v).

$$\begin{cases} F_s = F_r + F_{fus} + F_h + F_v \\ M_s = M_r + M_{fus} + M_h + M_v \end{cases} \quad (9)$$

Substituting Equation (1), the post-failure helicopter flight dynamics model is formulated as follows:

$$\dot{x} = f_s(x, \delta_s) \quad (10)$$

In Equation (10), $\delta_s = [\delta_0, \delta_b, \delta_c]^T$ represents the modified control input vector, which accounts for the complete loss of direct yaw control authority.

3.1. Yaw Control Strategy

TRDF triggers the complete loss of tail rotor thrust, thereby perturbing the yaw moment balance of the helicopter. Although the vertical tail generates a restorative yawing moment during sideslip, its effectiveness is inherently constrained at moderate to low velocities. Consequently, a new equilibrium can only be attained by mitigating the main rotor reactive torque while exploiting the restorative moment generated by the vertical tail at nonzero sideslip angle. This torque reduction is effectively realized by main rotor collective pitch reduction. As demonstrated by Matthew [3], while this strategy successfully attenuates rotor torque, it entails a substantial increase in the rate of descent. Accordingly, a hybrid control strategy for post-TRDF flight is proposed herein. This strategy trades an elevated descent rate for attenuated main rotor torque while simultaneously exploiting the sideslip angle to generate the requisite restorative yawing moment. Based on this strategy, a trim analysis of the post-TRDF helicopter model is conducted. The resulting variations of the sideslip angle β and roll angle ϕ with forward velocity, parameterized across different descent rates, are presented in Figure 3.

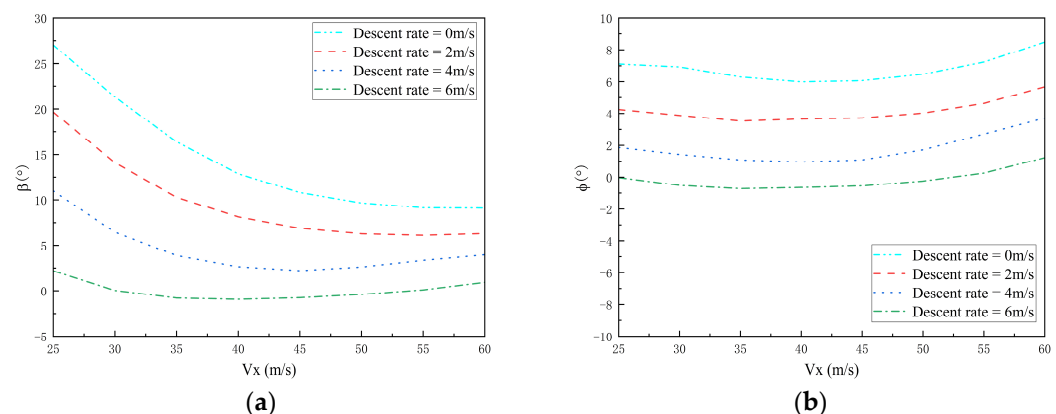


Figure 3. Trim results following TRDF: (a) sideslip angle; (b) roll angle.

As shown in Figure 3a, the sideslip angle exhibits a non-monotonic variation with forward velocity, characterized by an initial decrease followed by a subsequent increase. This trend is governed by the requirement for increased rotor thrust at a higher velocity to overcome parasitic drag, thereby elevating the main rotor torque. While the vertical tail's aerodynamic authority improves with forward velocity, the main rotor torque increases more rapidly than the available restoring moment generated by the vertical tail, driving the observed divergence. In contrast, an increased descent rate substantially suppresses the sideslip angle, thereby confirming the effectiveness of the proposed torque-mitigation strategy.

As shown in Figure 3b, a reduction in the descent rate induces a substantial increase in the roll angle, a trend that correlates strongly with the variations observed in the sideslip angle. Specifically, a lower descent rate leads to higher main rotor torque, which in turn demands a larger sideslip angle to generate the requisite restoring yaw moment. The increased sideslip elevates the fuselage lateral velocity, thereby augmenting the aerodynamic side force. To counteract this lateral load, a larger steady roll angle is required to tilt the main rotor thrust vector, thereby generating the requisite lateral thrust component to restore lateral force equilibrium.

The trim analysis reveals that the sideslip angle and roll angle constitute the key state variables governing post-TRDF helicopter stability. Consequently, the subsequent design of the yaw stability control loop will center on the regulation of these two critical parameters.

Critically, while a theoretical trim equilibrium may exist at a given velocity, its existence does not guarantee operational safety following TRDF onset [3]. This discrepancy arises from the violent yaw transient induced by instantaneous tail rotor thrust loss. Ultimately, equilibrium restoration is dictated not by static trim availability but by the post-failure response latency and the helicopter's inherent yaw stability. Consequently, a critical velocity boundary inherently exists: flight below this value drives irrecoverable divergence of the post-failure transient, irrespective of trim feasibility. The derivation of this threshold can be cast as an optimal control problem, with the numerical solution framework detailed in Refs. [29,30].

3.2. Yaw Control Architecture

With the control strategy established, the subsequent step involves developing a tailored control architecture. Owing to the impracticality of direct sideslip angle measurement, lateral velocity serves as the surrogate for closed-loop control. Consequently, building upon the trim analysis findings, this section develops two distinct yaw stability control loops predicated on lateral velocity and roll angle feedback, respectively. A cascaded control architecture is adopted, wherein the roll angle control loop constitutes the inner loop, integrated with the yaw angle control loop serving as the outer loop. Both approaches employ the roll angle as the primary control variable; their sole distinction lies in whether lateral velocity feedback is incorporated. The yaw control architecture is illustrated in Figure 4, wherein all controllers are implemented using PID control. For the remaining control channels, control architectures from Ref. [18] are adopted. The controller parameters were tuned sequentially from the inner to the outer loop under the principle of maximizing response speed and minimizing overshoot [31,32]. Furthermore, the tuning of the yaw-channel parameters following failure prioritizes stability over rapid response. Given that the primary emphasis of this work is on the formulation of the novel control strategy, a rigorous stability proof pertaining to the controller is not provided herein.

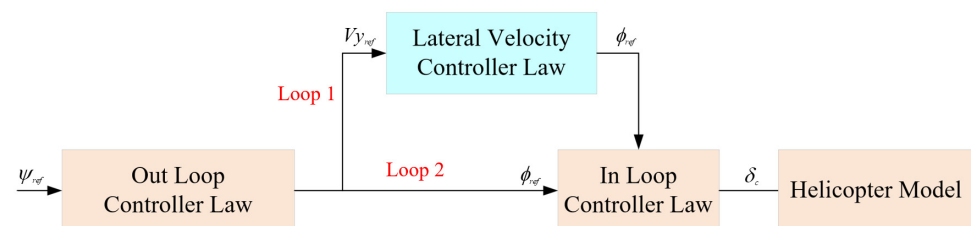


Figure 4. Yaw control architecture.

4. Simulation

4.1. Comparison of the Two Control Architectures

Based on the two implementations of the yaw control architecture specified in Section 3.2, this section carries out a comparative simulation study to characterize and compare their yaw stabilization behaviors following TRDF. The simulation employs the nonlinear helicopter model delineated in Section 3, conducted under the following initial conditions and failure scenario:

- (1) Initial conditions: Prior to TRDF, the helicopter is in trimmed, level flight with a longitudinal velocity of 30 m/s. The failure is triggered at 10 s.
- (2) Response latency: A 2 s switching delay [5] is introduced post-TRDF to emulate the system response time required for control law activation.

- (3) Control commands: Post-TRDF, the longitudinal velocity command is held constant at 30 m/s, while the vertical velocity command is set to a 5 m/s descent. A zero-yaw attitude hold mode is engaged. The simulation assumes the helicopter remains at a safe altitude.

As shown in Figure 5e,f, following TRDF onset at 10 s, the helicopter undergoes severe uncommanded yaw. After the 2 s switching delay, both control architectures successfully suppress the divergent yaw motion and ultimately regulate the yaw angle to a zero steady-state value. Specifically, omitting lateral velocity feedback (Loop 2 in Figure 4) results in a first zero-crossing of the yaw angle at 17 s, albeit with pronounced yaw rate oscillations. Conversely, incorporating lateral velocity feedback (Loop 1 in Figure 4) delays the zero-crossing to approximately 20 s, yet yields markedly faster subsequent convergence.

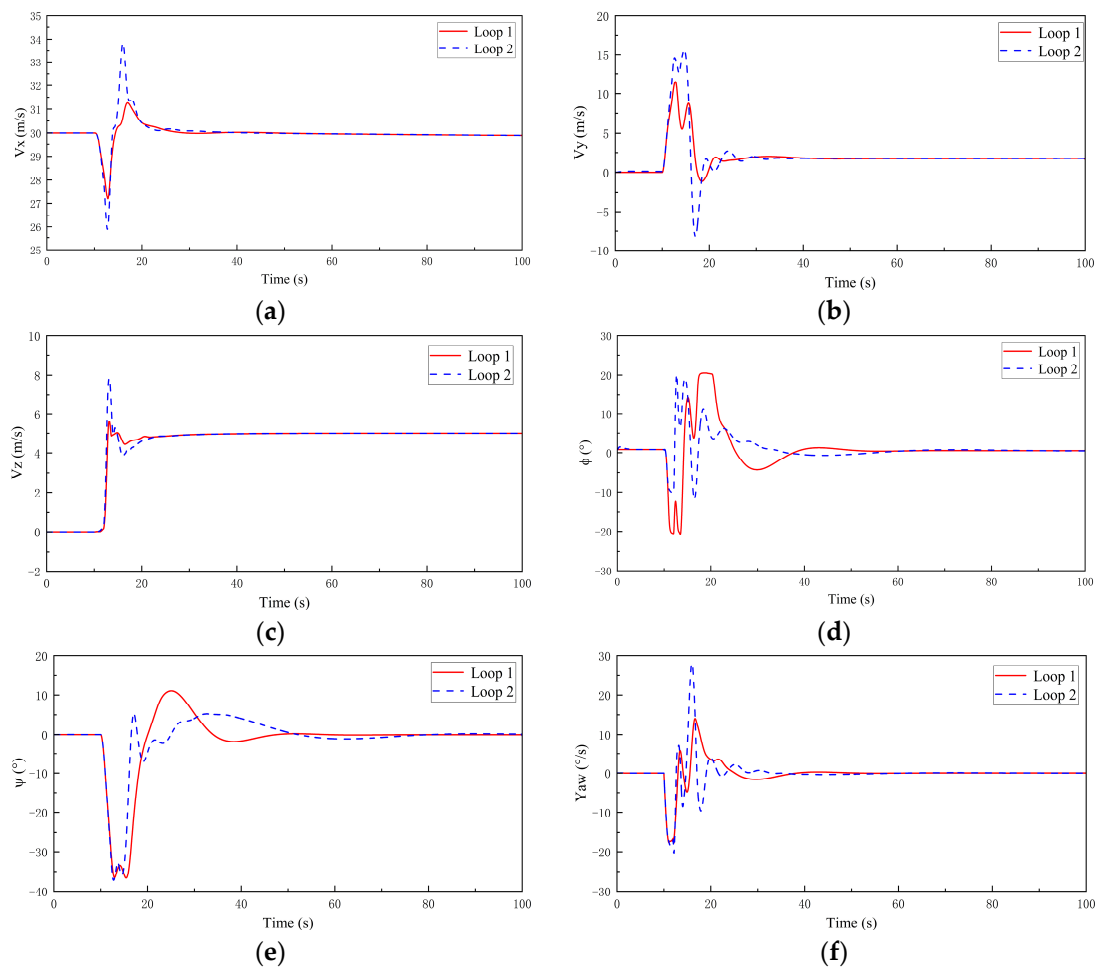


Figure 5. Comparative simulation of two control variants: (a) Longitudinal velocity; (b) Lateral velocity; (c) Vertical velocity; (d) Roll angle; (e) Yaw angle; (f) Yaw rate.

As shown in Figure 5b, the incorporation of lateral velocity feedback, serving as a proxy for sideslip angle, accelerates lateral velocity convergence, albeit at the penalty of a slower roll angle response (Figure 5d). This behavior is attributable to the rapid stabilization of lateral velocity, which expedites sideslip convergence and promotes prompt yawing moment equilibration. Hence, the control architecture (Loop 1 in Figure 4) trades roll-axis responsiveness for increased yaw damping and stability. Furthermore, Figure 5a,c demonstrates that both longitudinal and vertical velocity are consistently well regulated, with the responses under the two architectures closely matched. This precludes interference from these axes during the comparative analysis of the yaw response.

According to a survey study [33], pilots exhibit a perception threshold of $0.14^\circ/\text{s}^2$ for sustained yaw and $0.5^\circ/\text{s}^2$ for sustained roll. During short-duration stimuli (1–5 s), these thresholds increase to $1.5^\circ/\text{s}^2$ and $2.04^\circ/\text{s}^2$, respectively. Notably, the perceptual threshold for yaw is significantly lower than that for roll under both sustained and transient conditions. This suggests that pilots are markedly more sensitive to yaw disturbances, rendering them more susceptible to disorientation induced by uncommanded yaw. Given that pronounced yaw oscillations can readily induce pilot spatial disorientation and precipitate loss-of-control incidents [1,33,34], whereas degraded roll-axis responsiveness poses a comparatively marginal risk to flight safety, Loop 1 in Figure 4, which incorporates lateral velocity feedback, is adopted for subsequent investigations.

4.2. Effect of Descent Rate on Yaw Control Post-TRDF

Variations in the descent rate modulate the main rotor-induced velocity, substantially alter the main rotor torque, and ultimately dictate the net yawing moment. Accordingly, simulations of yaw-axis response are conducted across a range of descent rates to evaluate the effect of this parameter on yaw regulation following TRDF. Consistent with the simulation setup in Section 4.1, the initial conditions and failure scenario remain identical, with the vertical velocity command being the sole varied parameter. The commanded vertical velocities are set to 0, 2, 4, and 6 m/s.

As shown in Figure 6d, an increased descent rate significantly suppresses the uncommanded yaw induced by TRDF and markedly accelerates the convergence of the yaw angle. Concurrently, the steady-state lateral velocity magnitude required for yaw stabilization diminishes significantly, indicating that the sideslip angle is maintained at a lower equilibrium value (Figure 6a). However, this benefit incurs the penalty of increased altitude loss (Figure 6c). Notably, the benefit of increasing the descent rate diminishes significantly, exhibiting a clear saturation effect. As shown in Figure 6d, increasing the descent rate from 4 m/s to 6 m/s reduces the yaw settling time by only 4 s (from 49 s to 45 s), while the corresponding altitude loss grows substantially from 140 m to 183 m. This identifies a distinct inflection point in the trade-off between altitude expenditure and yaw stabilization. In summary, a suitable descent rate can be identified for a given helicopter configuration and forward velocity, representing a practical compromise between dynamic stability and altitude safety. This specific rate minimizes altitude loss while ensuring the most rapid yaw stabilization following TRDF, thereby maximizing the safety margin for emergency contingency procedures. Based on the comparative simulation results, a descent rate of 4 m/s is adopted for subsequent analyses at a forward velocity of 30 m/s, providing a balance between dynamic stability and altitude safety.

4.3. Strategy Validation via Trajectory Simulation

Once the forward velocity and yaw motion reach steady state, the prevailing descent rate induces persistent altitude loss. Consequently, rapid descent mitigation is imperative to preserve the minimum safe altitude margin. As shown in Figure 3, under constant forward velocity conditions, a reduction in descent rate leads to a marked increase in sideslip angle. As the sideslip angle approaches the stall threshold of the vertical tail, the restoring moment diminishes abruptly, thereby exacerbating yaw instability and adversely affecting stability and control. Consequently, mitigating the descent rate necessitates a concurrent increase in forward airspeed to preserve favorable inflow conditions, thereby mitigating the risk of vertical tail stall during maneuvering. To address the limitation of neglecting environmental effects, an atmospheric turbulence model [35] has been introduced into the simulation framework in this section. A detailed formulation of this model is provided in Appendix A. Following extensive simulations, the command inputs are defined as follows:

- (1) Yaw stabilization phase: The control input is maintained consistent with Section 4.2, with the descent rate held constant at 4 m/s.
- (2) Post-stabilization phase: Upon completion of yaw stabilization, the helicopter undergoes a longitudinal acceleration of 0.5 m/s^2 until the forward airspeed reaches 40 m/s. Concurrently, a vertical acceleration of -0.3 m/s^2 is applied to arrest the descent rate until it reaches zero.

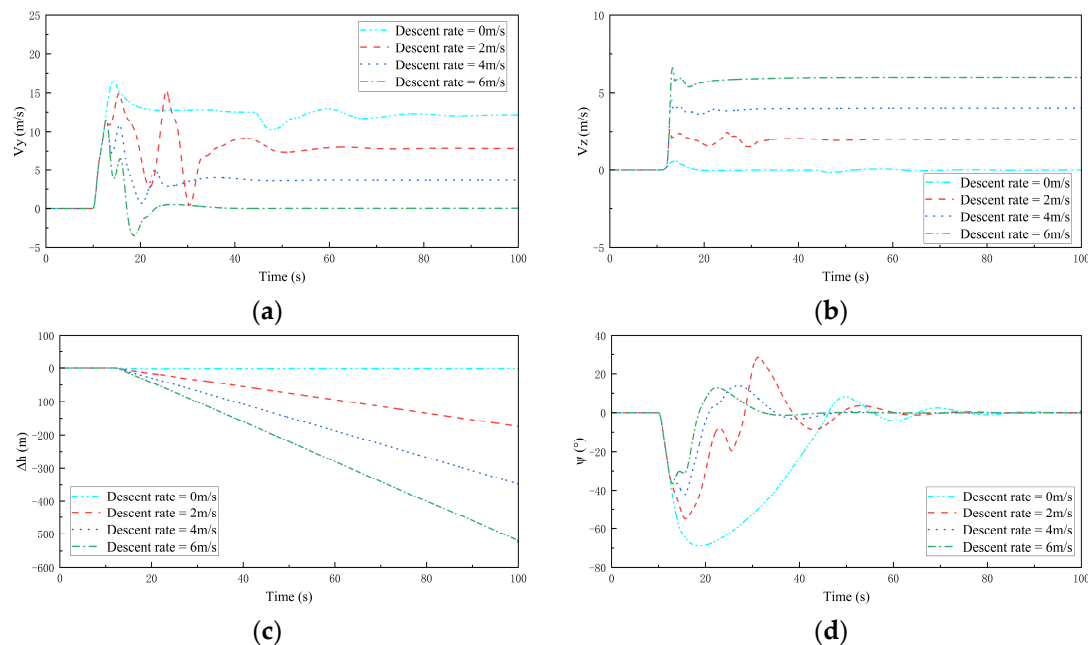


Figure 6. Comparison of control performance under varying vertical velocities following TRDF: (a) Lateral velocity; (b) Vertical velocity; (c) Altitude variation; (d) Yaw angle.

As shown in Figure 7a,b, following the establishment of yaw stability ($\sim 45 \text{ s}$), both the longitudinal and vertical velocities promptly respond to the commands and accelerate along the prescribed trajectories. Comparative simulations conducted with and without atmospheric turbulence exhibited only small discrepancies in altitude loss (Figure 7c). The simulated altitude loss of 161 m is marginally higher than the 152.4 m (500 ft) minimum safe altitude mandated by 14 CFR § 91.119, which remains within practical operational tolerances for emergency procedures. However, Figure 7d (No Turbulence) indicates significant yaw oscillations during the transition. These oscillations arise because the rise in longitudinal velocity elevates aerodynamic drag, while the reduction in descent rate augments the rotor-induced velocity. Collectively, these effects induce a surge in required rotor torque, disrupting the yaw-moment equilibrium and triggering the observed directional oscillations. Nevertheless, the predictability of this oscillation mitigates perceived risk. A phased implementation of longitudinal acceleration and descent rate attenuation can effectively mitigate such yaw oscillations; it inherently incurs additional altitude loss. Consequently, this mitigation strategy is viable provided sufficient altitude reserves are available. As shown in Figure 7d (With Atmospheric Turbulence), persistent yaw oscillations are evident. Beyond inherent system dynamics, these oscillations are primarily attributable to turbulence-induced perturbations (Figure 8) to the vertical tail, which disrupt the already marginally stable equilibrium. This phenomenon underscores the limited disturbance-rejection capability of the conventional PID controller during tail-rotor failure scenarios. As the primary focus of this study is on the proposed control strategy, no enhancements were made to the controller.

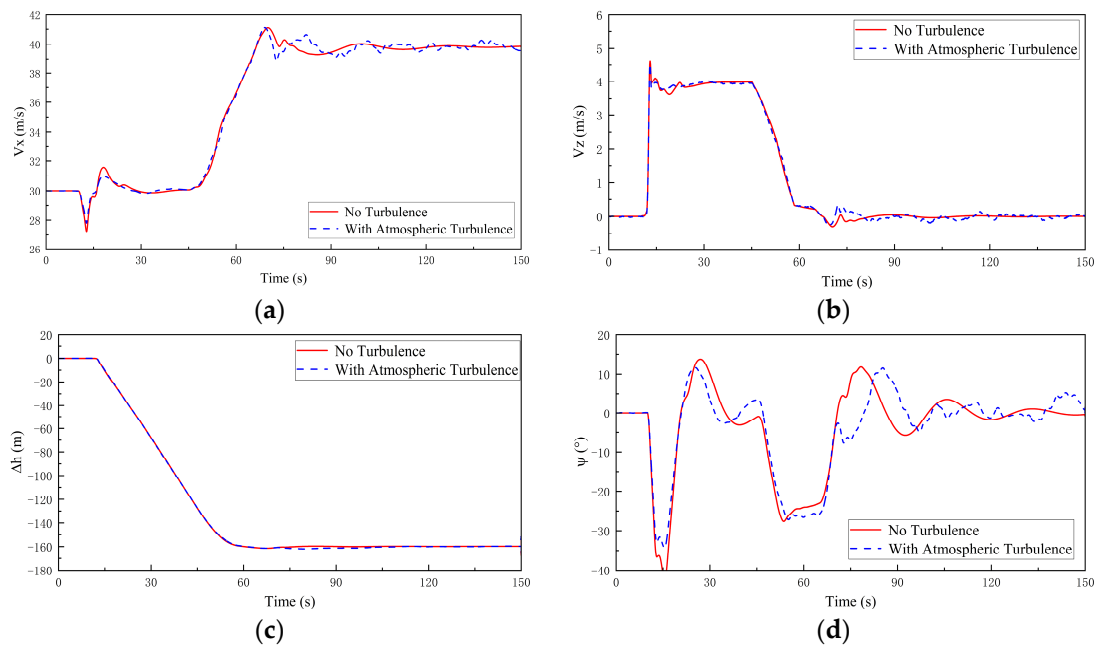


Figure 7. Validation of the emergency response strategy following TRDF: (a) Longitudinal velocity; (b) Vertical velocity; (c) Altitude variation; (d) Yaw angle.

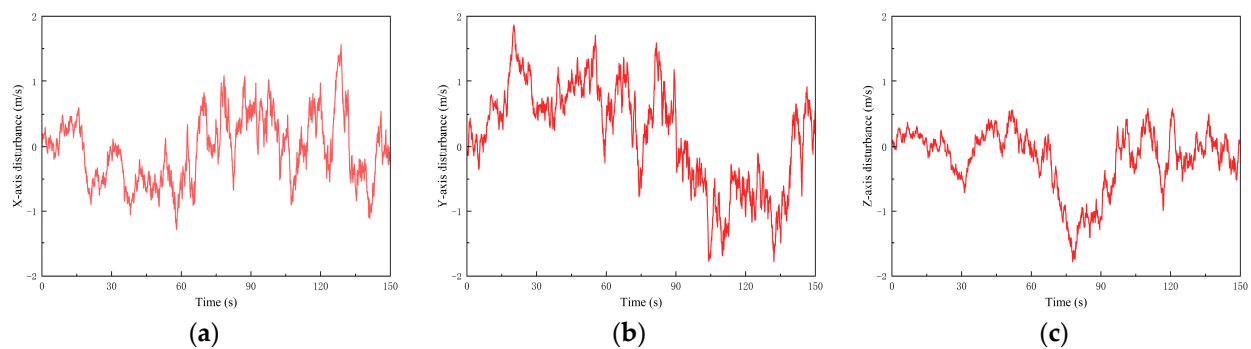


Figure 8. Atmospheric turbulence: (a) X-axis; (b) Y-axis; (c) Z-axis.

5. Conclusions

This paper addresses the loss of directional control following TRDF by proposing a yaw control strategy that leverages the vertical stabilizer sideslip effect in conjunction with regulated descent-rate management. A directional stability control loop is developed based on the post-failure trim characteristics, and the impact of incorporating lateral velocity is subsequently analyzed. Simulations are performed to examine the influence of descent rate on yaw convergence behavior and altitude loss. The following conclusions can be drawn:

- (1) Descent-rate modulation effectively reduces the reliance on sideslip. Following TRDF, a higher descent rate alters the rotor-induced velocity, alleviating adverse torque imbalances and thereby reducing the demand on vertical stabilizer authority. At a constant forward velocity, this lowers the sideslip angle required for trim, mitigating vertical stabilizer stall risk.
- (2) The integration of lateral velocity feedback improves yaw stability at the expense of diminished roll-axis responsiveness. Although the time to the yaw angle's first zero crossing is marginally extended, this modification effectively damps directional oscillations and shortens the overall settling time.
- (3) Yaw stability improvement exhibits diminishing returns with increasing descent rate. While a higher descent rate reduces stabilization time, it incurs greater altitude loss. A

compromise descent rate exists that reconciles rapid yaw stabilization with acceptable altitude expenditure.

Future research should prioritize evaluating the efficacy of the proposed control strategy across varying altitudes. Given the reduced air density at high elevations, which degrades the aerodynamic effectiveness of the vertical tail, it is essential to define the operational altitude envelope to ensure control performance.

Author Contributions: Conceptualization, J.L. and X.F.; methodology, X.F.; software, H.T. and R.Z.; validation, X.F. and H.T.; formal analysis, X.F. and R.Z.; investigation, H.T. and Y.L.; resources, J.L. and H.T.; data curation, X.F. and Y.L.; writing—original draft preparation, X.F.; writing—review and editing, J.L.; visualization, R.Z. and Y.L.; supervision, J.L. and H.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Atmospheric Turbulence Model

Atmospheric turbulence is a ubiquitous stochastic phenomenon characterized by irregular, random airflow motions. During flight, it induces unsteady aerodynamic loads, causing small-amplitude, irregular oscillations in vehicle states. The atmospheric turbulence model is implemented by passing Gaussian white noise through a suitably designed shaping filter. The corresponding transfer functions for the turbulent velocity components along the three body axes are defined as follows:

$$G_x(s) = \frac{\sigma_x \sqrt{\left(L_x / \pi v_a\right)}}{\left(L_x / v_a\right) s + 1} \quad (\text{A1})$$

$$G_y(s) = \frac{\sigma_y \sqrt{\left(L_y / \pi v_a\right)}}{\left(2 L_y / \sqrt{3} v_a\right) s + 1} \quad (\text{A2})$$

$$G_z(s) = \frac{\sigma_z \sqrt{\left(L_z / \pi v_a\right)}}{\left(2 L_z / \sqrt{3} v_a\right) s + 1} \quad (\text{A3})$$

In these equations, $\sigma_x, \sigma_y, \sigma_z$ denote the turbulence intensities along the respective body axes; L_x, L_y, L_z represent the corresponding turbulence scales; and v_a signifies the aircraft airspeed.

For aircraft altitudes h below the gradient height z_G :

$$\left\{ \begin{cases} \sigma_x = 0.76 \left(0.867 + 0.556 \lg(h) - 0.246 \lg^2(h) \right) v_a / \left(\ln \left(\frac{h}{z_0} \right) z_0^{0.07} \right) \\ \sigma_y = \left(0.655 + 0.201 \lg(h) - 0.095 \lg^2(h) \right) v_a / \ln \left(\frac{h}{z_0} \right) \\ \sigma_z = \left(0.381 + 0.172 \lg(h) - 0.062 \lg^2(h) \right) v_a / \ln \left(\frac{h}{z_0} \right) \\ L_x = L_y = 25h^{0.35} / z_0^{0.063} \\ L_z = 0.7h \end{cases} \right. \quad (A4)$$

For aircraft altitudes h above the gradient height z_G :

$$\left\{ \begin{cases} \sigma_x = \sigma_y = \sigma_z = 0.15v_a \\ L_x = L_y = L_z = 280m \end{cases} \right. \quad (A5)$$

In Equation (A5), $z_0 = 0.046$ is an empirical constant.

References

1. Saleh, J.H.; Xu, Z.; Guvir, A.I.; Margousian, A.; Zhang, W.; Ma, M. Data-Driven Analysis and New Findings on the Loss of Tail Rotor Effectiveness in Helicopter Accidents. *Sci. Rep.* **2022**, *12*, 2575. [CrossRef] [PubMed]
2. Yan, X.; Yuan, Y.; Chen, R. Landing Trajectory and Control Optimization for Helicopter Encountering Different Tail Rotor Pitch Lockups. *Aerosp. Sci. Technol.* **2024**, *145*, 108828. [CrossRef]
3. O'Rourke, M.J. Simulation Model for Tail Rotor Failure. *J. Aircr.* **1994**, *31*, 197–205. [CrossRef] [PubMed]
4. Rajendran, S.; Gu, D. Fault Tolerant Control of a Small Helicopter with Tail Rotor Failures in Forward Flight. *IFAC Proc. Vol.* **2014**, *47*, 8843–8848. [CrossRef]
5. Yan, X.; Chen, R.; Zhu, S.; Xie, A.; Gu, J. Study of Helicopter Optimal Autorotation Landing Procedure in Tail Rotor Drive Failure. In *Proceedings of the 2022 IEEE International Conference on Robotics and Biomimetics (ROBIO)*; IEEE: New York, NY, USA, 2022; pp. 668–673.
6. Yu, Q.; Zhang, H. Analysis of the Tail-Rotor Failure from Mechanical Malfunction and Research in Flight-Test. *Flight Dyn.* **2008**, *26*, 74–77.
7. De Martin, A.; Jacazio, G.; Nesci, A.; Sorli, M. In-Depth Feature Selection for PHM System's Feasibility Study for Helicopters' Main and Tail Rotor Actuators. *PHM Soc. Eur. Conf.* **2020**, *5*, 9. [CrossRef]
8. Zanello, P.; Prasad, J.V.R.; Johnson, C.; Mavris, D.N. A Framework to Enhance the Mitigation of Loss of Tail Rotor Effectiveness. In *Proceedings of the AIAA AVIATION 2022 Forum*; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2022.
9. Rajendran, S.; Gu, D. Fault Tolerant Control of a Small Helicopter with Tail Rotor Failures in Hovering Mode. In *Proceedings of the 11th IEEE International Conference on Control & Automation (ICCA)*; IEEE: New York, NY, USA, 2014; pp. 348–353.
10. Garcia, R.D.; Valavanis, K.P.; Kandel, A. Autonomous Helicopter Navigation during a Tail Rotor Failure Utilizing Fuzzy Logic. In *Proceedings of the 2007 Mediterranean Conference on Control & Automation*; IEEE: New York, NY, USA, 2007; pp. 1–6.
11. Ke, C.; Cai, K.-Y.; Quan, Q. Uniform Passive Fault-Tolerant Control of a Quadcopter with One, Two, or Three Rotor Failure. *IEEE Trans. Robot.* **2023**, *39*, 4297–4311. [CrossRef]
12. Johnson, E.N.; Schrage, D.P.; Vachtsevanos, G. Rotary Wing Final Experiments for the Software Enabled Control Program. In *Proceedings of the American Helicopter Society 61st Annual Forum*; Curran Associates: Red Hook, NY, USA, 2005.
13. Yan, X.; Chen, R. Helicopter autorotation landing trajectory optimization after tail-rotor total failure. *J. Beijing Univ. Aeronaut. Astronaut.* **2018**, *44*, 1203–1212.
14. Ragazzi, A.; Mengotti, R.B.; Sabato, P.; Afruni, G.; Hyder, C. AW169 loss of tail rotor effectiveness simulation. In *Proceedings of the 43rd European Rotorcraft Forum*, Milan, Italy, 12–15 September 2017.
15. Yomchinda, T.; Horn, J.; Langelaan, J. Flight Path Planning for Descent-Phase Helicopter Autorotation. In *Proceedings of the AIAA Guidance, Navigation, and Control Conference*; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2011.
16. Jump, M.; Alam, M.; Rogers, J.; Eberle, B. Progress in the Development of a Time-To-Contact Autorotation Cueing System. In *Proceedings of the 44th European Rotorcraft Forum*, Delft, The Netherlands, 18–21 September 2018.
17. Rogers, J.; Eberle, B.; Jump, M.; Cameron, N. Time-to-Contact-Based Control Laws for Flare Trajectory Generation and Landing Point Tracking in Autorotation. In *Proceedings of the AHS International 74th Annual Forum & Technology Display*, Phoenix, AZ, USA, 14–17 May 2018.
18. Saetti, U.; Rogers, J.D.; Alam, M.; Jump, M.; Cameron, N. Dynamic inversion-based flare control law for autonomous helicopter autorotation. In *Proceedings of the AIAA SCITECH 2022 Forum*, San Diego, CA, USA, 3–7 January 2022.

19. Fattizzo, D. Attitude and Trajectory Control System Design for the Emergency Maneuver of an Unmanned Helicopter. Ph.D. Thesis, University of Bologna, Bologna, Italy, 2024.
20. Fattizzo, D.; Giulietti, F.; de Angelis, E.L.; Avanzini, G. Trajectory Design and Control of a Small-Scale Helicopter Automatic Autorotation Maneuver. *J. Aircr.* **2026**. [[CrossRef](#)]
21. Tierney, S.; Langelaan, J.W. Autorotation path planning using backwards reachable set and optimal control. In Proceedings of the 2010 AHS Forum, Phoenix, AZ, USA, 11–13 May 2010.
22. Eberle, B.F.; Rogers, J.D. Real-Time Trajectory Generation and Reachability Determination in Autorotative Flare. *J. Am. Helicopter Soc.* **2020**, *65*, 1–17. [[CrossRef](#)]
23. Gao, Z.; Chen, R. *Helicopter Flight Dynamics*; Progress in Science Press: Beijing, China, 2003; pp. 168–184.
24. Lin, G.; Guo, C. The Estimation Method for Helicopter Group Weight. *J. Nanjing Univ. Aeronaut. Astronaut.* **1985**, *3*, 13–21.
25. Johnson, W. *NASA Design and Analysis of Rotorcraft: Theory*; Technical Publication NASA/TP-20020000355; National Aeronautics and Space Administration: Moffett Field, CA, USA, 2022.
26. Ye, C.; Huang, L.; Lu, C. A New Method to Weight Estimation of Helicopter's Systems and Components. *Helicopter Tech.* **2006**, *2*, 1–4.
27. Wen, J.; Song, Y.; Wang, H.; Han, D.; Yang, C. Hybrid Adaptive Control for Tiltrotor Aircraft Flight Control Law Reconfiguration. *Aerospace* **2023**, *10*, 1001. [[CrossRef](#)]
28. Gaonkar, G.; Peters, D. Review of Dynamic Inflow Modeling for Rotorcraft Flight Dynamics. In *Proceedings of the 27th Structures, Structural Dynamics and Materials Conference*; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 1986.
29. Yu, X.; Chen, R.; Wang, L.; Yan, X.; Yuan, Y. An Optimization for Alleviating Pilot Workload during Tilt Rotor Aircraft Conversion and Reconversion Maneuvers. *Aerosp. Sci. Technol.* **2022**, *129*, 107854. [[CrossRef](#)]
30. Yu, Z.; Yan, X.; Chen, R. Prediction of Pilot Workload in Helicopter Landing after One Engine Failure. *Chin. J. Aeronaut.* **2020**, *33*, 3112–3124. [[CrossRef](#)]
31. Åström, K.J.; Hägglund, T. The Future of PID Control. *Control Eng. Pract.* **2001**, *9*, 1163–1175. [[CrossRef](#)]
32. Franklin, G.; Powell, J.D.; Emami-Naeini, A. Feedback control of dynamic systems, 3e. In *ASME International Mechanical Engineering Congress and Exposition*; American Society of Mechanical Engineers: New York, NY, USA, 1994; Volume 14148, pp. 1053–1054.
33. Cheung, B. Nonvisual Spatial Orientation Mechanisms. In *Spatial Disorientation in Aviation*; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2004; pp. 37–94.
34. Hinckley, J. Enhancing Spatial Disorientation Training in Aviation: Simulator Development and Validation for Future Pilots. Master's Thesis, Oklahoma State University, Stillwater, OK, USA, 2022.
35. Zhao, Z.; Xiao, Y.; Shi, Y. A Digital Simulation Technique for Dryden Atmospheric Turbulence Model. *Acta Aeronaut. Astronaut. Sin.* **1986**, *7*, 433–443.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.