

Decoupling Aerodynamic and Physical Parameters for Enhanced Flow Control in Rotating Wing Dynamic Stall

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Received: 15 March, Revised: 29 April, Accepted: 23 May

Abstract— This work outlines a specific approach to the isolation of aerodynamic and physical factors towards enhancing flow control in the dynamic stall of rotating wings, a concern in rotor craft, wind turbines and UAVs. Employing a combination of CFD and ML, this research work focuses uniquely on aerodynamics of the aircraft by eliminating the impact of physical parameters like angular velocity, pitch rate, and angle of attack from lift, drag, and pressure distribution. This way, the research offers a finer view of the physical processes involved in vortex shedding, boundary layer development, and stall inception, which are critical to predicting and mitigating stall phenomena. The ML component uses data from CFD simulations to control parameters and provide real-time reaction to the aerodynamic changes. The results of this study show that, if these decoupled parameters are adjusted separately, one can control the stall onset and achieve up to 20% delay in lift hysteresis and control the flow stability across a broad range of operating points. This decoupling concept enables the accurate application of adjustment actions like adaptive pitch control and optimized rotation rates to the corresponding aerodynamic and physical conditions. The proposed approach provides a realistic solution for improving energy efficiency and operational reliability in the RWs subjected to high dynamic loads. This work not only contributes to the knowledge of dynamic stall phenomena in rotating wings but also opens the way to develop more robust and effective flow control strategies in aerospace and renewable energy applications.

Keywords: Dynamic stall decoupling, rotating wing aerodynamics, adaptive flow control, CFD-ML integration, stall onset prediction.

I. INTRODUCTION

In aerodynamics, the concept of separating aerodynamic and physical parameters is unique in that it deals with the complex relationship between aerodynamic loads and the physical characteristics of a given wing, including rotational rate and angle of attack [1]. Conventional models of aerodynamics combine these factors and their interactions, which results in many dependencies and constraints that complicate the precise

management of each factor [2]. Decoupling makes it possible to study aerodynamics and physical factors separately, which helps the engineers to assess their individual effects on the dynamic processes, like flow separation, vortex formation, and reattachment [3]. This is especially important for flow control, as it provides insights into individual contributions that can be used to create adaptive control systems improving aerodynamic performance and stability [4].

The physical parameters for enhanced flow control include variables such as wing rotational speed, angular acceleration, and structural deflection that affects the aerodynamic forces and moments on a rotating wing [5]. These parameters define the manner in which the wing interferes with the surrounding flow field especially during manoeuvre or change in orientation [6]. In this way, the flow field around the wing can be controlled by changing physical parameters independently of each other and minimizing such adverse phenomena as stall, and increasing the lift-to-drag ratio [7]. The necessity of such control is especially obvious in the applications, where maneuverability, stability, and performance are highly significant, for instance in the rotorcraft, UAVs, and other aircrafts equipped with rotating wings [8]. A decoupling of physical parameters can improve flexibility and stability in complex flight conditions [9].

Rotating wing dynamic stall is a process that occurs when a rotating wing undergoes unsteady and abrupt changes in forces due to flow separation at high angle of attack [10]. Dynamic stall is different from the static stall in that the lift coefficient sharply rises and then falls rapidly, and the vortex shedding is also intense [11]. This results in oscillatory forces that can upset the flight and make dynamic stall a major problem in the design of rotorcrafts and other rotating wing aircrafts [12]. Proper control of dynamic stall is crucial for the steady operation, low structural loads and high efficiency of rotating wing systems, particularly in conditions that demand quick or aggressive movements [13].

Incorporation of decoupling of aerodynamic and physical parameters for flow control in rotating wing dynamic stall brings out a new concept of overcoming the problems of dynamic stall. Thus, this study seeks to develop a framework that will enable better control of flow around rotating wings by eliminating physical forces from the aerodynamic forces [14]. This decoupling allows for specific interventions of the primary

parameters in real-time to dampen oscillatory forces and enhance aerodynamic performance over a range of flight conditions. The conclusions derived from this work offer a basis for developing the control strategies that can effectively counteract dynamic stall inception and enhance stability, reduce drag, and increase robustness in rotating wing applications. This integrated approach has the potential to contribute to the development of new aerodynamic control methods and improve performance of future generation of rotorcraft and UAVs [15].

1.1. Background

Dynamic stall in rotating wings, which is the focus of the present paper, has been a subject of considerable interest in the context of aerodynamic performance, stability, and structural integrity of helicopter rotors and wind turbine blades. Dynamic stall is characterized by unsteady aerodynamic forces that create a cyclic separation of airflow over a rotating wing or blade and result in increased drag, fluctuating lift, and intense loading that threatens the stability of the system. For better performance and durability of these systems, it is imperative to solve the problem of dynamic stall. In the past, attempts to reduce dynamic stall have been achieved through altering physical characteristics including pitch angle, rotational speed or the airfoil shape. [16].

Some basic knowledge about dynamic stall on rotating blades has been obtained so far from the available experimental and computational investigations. Ruan and Hajek (2021) discuss the unsteady aerodynamics of rotating blades, and the sudden fluctuations in lift and drag forces during dynamic stall [17]. Their work focuses on the use of predictive models that would help in identifying the onset of stall so that control action can be initiated. In the same way, Raul and Leifsson (2023) have proposed multifidelity aerodynamic shape optimization framework applying regression-based infill method for stall prediction [18]. Through the use of multiple fidelity levels in aerodynamic modeling, their approach improves prediction and shows the possibility of computational optimization to better control dynamic stall. This optimization framework provides the basis for adaptive control strategies that seek to address the issues of time varying flow characteristics that are characteristic of dynamic stall.

For further development beyond the structural changes, aerodynamic and physical parameters are being decoupled to achieve more effective stall control. Sterpu et al. (2024) provide an example of this concept in their UDF-based analysis of dynamic stall in micro-air vehicles and demonstrate how airflow can be manipulated effectively without altering the structure of the MAV [19]. They also confirm the idea of separating control mechanisms to provide a dynamic response to the stall onset which can be adjusted in accordance with current aerodynamic conditions. Similarly, Sedky et al. (2023) have proposed a bio-mimetic flow control system which employs covert flaps, which are like bird wings with feathers. These hidden flaps respond directly to changes in air flow, thus eliminating stall without structural modification to the wings [20]. This approach does not only expand the range of possibilities for the management of the

stalls but also corresponds to the tendencies to the use of lightweight and power-saving designing solutions in the aerodynamic systems.

In computational research, complex simulations have helped to explain dynamic stall and offered ways to design control methods that focus on aerodynamic changes. For example, Sereez and Goman (2022) use CFD to study oscillatory coning motion impact on stall and demonstrate how precise control of airflow can prevent stall [21]. This CFD-based analysis also indicates that dynamic stall can be better controlled by airflow control rather than by structural modifications, which are generally rigid. Expanding this computational approach, Traphan et al. (2020) consider dynamic stall under prescribed three-dimensional flow conditions and demonstrate that specific changes in inflow can postpone stall and improve lift performance [22]. These results therefore provide evidence for the use of decoupled approaches to aerodynamic control in suppressing unsteady flow instabilities through specific control surface manipulations.

Research has also been done on this area and the findings have supported the effect of certain changes to the aerodynamics in dynamic stall. Wong (2010) gives a broad description of enhanced airfoil configurations that have been developed to enhance the L/D ratios and stall characteristics in rotating wings [23]. This research shows that airfoils can be made more efficient by concentrating on aerodynamic improvements, without requiring changes in physical geometry. Wang and Zhao (2019) also support this through their study of stall characteristics in finite wings and rotors, proving that small changes in surface shapes can create huge differences in stall [9]. Based on these findings, Wu et al. (2024) extend the study on the effect of area distribution on the span direction for flapping wing aerodynamics and demonstrate how stall can be avoided using efficient aerodynamic design without changing the structural layout [8]. Taken together, these empirical investigations support the applicability of aerodynamic modifications toward realizing better control over dynamic stall, thereby validating the value of a decoupled framework.

The literature also stresses on the use of bio-inspired/morphing structures for controlling dynamic stall by means of adaptive aerodynamics. Sedky et al. (2023) proposed covert flaps that resemble bird feathers and enable micro-control of the airflow without changing the flap geometry [10]. These flaps adapt to changes in airflow patterns and perhaps serve as a prototype of future aerodynamic systems. Also, the study by Sterpu et al. (2024) devoted to the UDF-based methods describes the benefits of morphing technologies capable of adapting to the airflow fluctuations and fully meets the demands of modern flexible and energy-efficient UAVs [4]. Such adaptive mechanisms stress the need to achieve high levels of flexibility in the aerodynamic loadings of the rotating wing systems for improved resistance to dynamic stall and other unsteady effects.

Table 1: Comparative Analysis of Previous Studies on Dynamic Stall Control

Aspects	Raul and Leifsson	Ruan and Hajek	Sedky et al.	Sterpu et al.	Wang and Zhao
Objective	To mitigate dynamic stall using multifidelity	To study dynamic stall on a single rotating blade	To use bio-inspired flow control	To evaluate dynamic stall using UDF-based methods	To analyze stall characteristics of finite wing and rotor configurations

	shape optimization		mechanisms for stall management		
Methodology	Regression-based multifidelity optimization	Numerical simulation	Covert flap design inspired by bird feathers	UDF-based computational framework	Numerical analysis of finite wing and rotor stall behavior
Techniques	Shape optimization, regression-based models	CFD simulations, time-dependent flow analysis	Bio-inspired covert flaps, adaptive response	Unified Dynamic Function (UDF), CFD modeling	Surface geometry adjustments, time-dependent flow evaluation
Key Findings	Optimized aerodynamic shapes enhance stall resistance and reduce drag	Highlights the impact of unsteady forces and identifies critical aerodynamic factors influencing stall onset	Covert flaps adapt to airflow, reducing stall effects without structural modifications	Dynamic stall is managed by airflow adjustments rather than changes to blade structure	Minor surface adjustments improve stall characteristics, emphasizing the role of aerodynamic tuning
Limitations	High computational cost, limited adaptability across varying flow conditions	Focuses only on single blade dynamics, limited generalizability to multi-blade or complex configurations	Limited testing under high-speed and variable flow conditions	Complexity in implementing UDFs for different aerodynamic scenarios	Limited applicability to non-rotor configurations, lacks adaptive control mechanisms

Previous works have investigated different method of dynamic stall control, namely multifidelity optimization [5], unsteady aerodynamic force modeling [6], biological flow control [9], and computational tools like UDF [13]. These works provide information about other types of stall management approaches, but they do not cover the integrated aspects, which are the main concern of this paper, including aerodynamic design optimization or stall modeling based on computational fluid dynamics. Existing approaches fail to provide a systematic approach that disassociates the aerodynamic characteristics from the physical dimensions and allows for a more selectable and free-form type of stall control. Also, the applicability of the proposed methods is often constrained by computational costs, the ability to generalize to different scenarios, and the adaptability of the methods when conditions change, pointing out that the problem of developing an integrated solution that incorporates these techniques is still unsolved. This research aims at filling this gap by proposing an approach that can isolate aerodynamic parameters from the physical design aspects to improve control over stall characteristics in rotating wings. Thus, this research will develop an efficient and flexible framework for DFM of dynamic stall by integrating multifidelity optimization, bio-inspired flow control, and computational methods.

1.2. Problem Formulations

Dynamic stall in rotating wing systems like helicopter, wind turbines and other rotorcraft poses major difficulties to aerodynamics, stability and structures. This fluctuating aerodynamic situation causes sudden variations in lift and drag and thereby increases vibration, energy dissipation, and structural hazards [6]. Conventional approaches to control dynamic stall are mostly based on the changes of physical parameters, for example, blade geometry or pitch angle. However, these approaches are not very flexible and cannot be used effectively in various operating conditions [7]. Since more and more people require rotating wing systems with high performance and energy efficiency, there is an urgent need for

new stall management technologies that can increase control of the airflow without relying on structural modifications.

Constraints for the Optimization Process

The optimization framework employed in this study incorporates essential constraints to ensure both mathematical validity and engineering feasibility. Conservation principles form the foundational constraints, whereby the conservation of mass ($\nabla \cdot \vec{v} = 0$) and momentum ($\frac{\rho D\vec{v}}{Dt} = -\nabla p + \mu \nabla^2 \vec{v} + \vec{F}d$) must be satisfied throughout the solution domain. Beyond these fundamental physical laws, the optimization process is bounded by several critical engineering constraints that reflect practical implementation considerations. Structural integrity is maintained through stress limitations ($\sigma \leq \sigma_{max}$), while geometric constraints enforce realistic manufacturing boundaries on parameters such as thickness ($t_{min} \leq t \leq t_{max}$). Aerodynamic stability is ensured through the enforcement of static stability criteria ($\frac{dCm}{d\alpha} < 0$), which prevents divergent behavior during operation. Performance requirements are addressed via efficiency thresholds ($\frac{CL}{CD} \geq (\frac{CL}{CD})_{min}$), and actuation limitations constrain control surface deflections ($|\delta| \leq \delta_{max}$) to physically achievable values. Additionally, power constraints ($P \leq P_{max}$) acknowledge the practical limitations of energy availability for active flow control implementation. These constraints are handled through a sequential quadratic programming approach that efficiently navigates the nonlinear constraint space while preserving solution feasibility. This comprehensive constraint framework ensures that the derived optimal solutions represent not merely mathematical ideals but viable engineering solutions implementable in real-world rotating wing applications.

Decoupling Aerodynamic and Physical Parameters for Dynamic Stall Prediction

The main motivation of this problem formulation is to develop a decoupling methodology of aerodynamic parameters (such as lift, drag, pressure distribution) and physical parameters (like rotational speed, angle of attack) for enhancing the predictive modeling and control of dynamic stall in rotating wings. This decoupling approach allows for a more accurate identification of the influence of these parameters on dynamic stall inception and development and for specific control actions to improve stability and aerodynamic efficiency.

Let \vec{V}_a and \vec{P}_p represent vectors of aerodynamic and physical parameters, respectively. The decoupling framework seeks to optimize a parameterized function $f(\vec{V}_a, \vec{P}_p)$ representing the dynamic stall response. We introduce a multi-objective optimization function that isolates the impact of \vec{V}_a and \vec{P}_p on the flow separation points x_s , vortex shedding frequency f_v , and reattachment position x_r . The control effectiveness is evaluated by minimizing the variation in aerodynamic forces F_a , represented as a function of the decoupled parameters.

$$f(\vec{V}_a, \vec{P}_p) = \alpha \cdot f_v + \beta \cdot (x_s - x_r) + \gamma \cdot F_a$$

$$\vec{F}_a = \sum_{i=1}^N \lambda_i \cdot \left(\frac{\partial f(\vec{V}_a, \vec{P}_p)}{\partial V_{a_i}} - \frac{\partial f(\vec{V}_a, \vec{P}_p)}{\partial P_{p_i}} \right)$$

$$\left(\left| f(\vec{V}_a, \vec{P}_p) - f_{ref} \right| + \kappa \cdot \int_{t_0}^{t_f} \left(\frac{\partial F_a}{\partial t} \right)^2 dt \right)$$

$$J(\vec{V}_a, \vec{P}_p) = \int_{t_0}^{t_f} (\alpha \cdot f_v + \beta \cdot \| \nabla F_a \|^2 + \gamma \cdot |x_s - x_r|) dt$$

Objective Function:

$$\min J(\vec{V}_a, \vec{P}_p) \quad \dots (2)$$

Subject to Constraints:

$$\nabla \cdot \vec{V} = 0$$

$$\rho \frac{D \vec{V}}{Dt} = -\nabla p + \mu \nabla^2 \vec{V} + \vec{F}_a \quad \dots (3)$$

No-slip condition at wing surface: $\vec{V}_{wing} = 0$

Free-stream velocity at infinity: \vec{V}_∞
 It is therefore possible to separate the aerodynamic influence from the structural one when studying dynamic stall, and this is a significant advantage of this formulation. This approach aims at maintaining flight stability and performance by proactive control of aerodynamic parameters based on the dynamic stall behavior as estimated by the predictive modeling and control.
Adaptive Flow Control for Rotating Wing Dynamic Stall Mitigation

The purpose of this formulation is to develop an online control strategy that would adapt the appropriate aerodynamic variables according to the analysis of the dynamic stall development. The adaptive control system reduces the negative dynamic stall impact by using machine learning-based predictive models, which stabilizes and reduces oscillations in lift and drag forces under different flow conditions.

Let $\vec{A}(t)$ represent the adaptive control variables, including the angle of attack, rotational speed, and control surface

deflection. Define $\phi(t)$ as the predicted dynamic stall progression and $\psi(t)$ as the control feedback signal. The objective is to minimize the integral of the square of the deviation between the target force coefficients C_L^{target} and C_D^{target} and the actual coefficients C_L and C_D under dynamic stall conditions.

$$\phi(t) = \sum_{i=1}^M \omega_i \cdot \exp\left(-\frac{(t - \tau_i)^2}{2\sigma_i^2}\right)$$

$$\psi(t) = K_p \cdot (C_L^{target} - C_L) + K_d \cdot \frac{d}{dt}(C_L^{target} - C_L) \quad \dots (4)$$

$$\vec{A}(t) = \vec{A}_0 + \int_{t_0}^{t_f} (\psi(t) + \lambda \cdot \nabla \phi(t)) dt$$

$$\min \left(\int_{t_0}^{t_f} ((C_L - C_L^{target})^2 + (C_D - C_D^{target})^2) dt \right)$$

Objective Function:

$$\min \int_{t_0}^{t_f} (\|C_L - C_L^{target}\|^2 + \|C_D - C_D^{target}\|^2) dt \quad \dots (5)$$

Subject to Constraints:

$$\phi(t) = f_{ML}(\vec{P}_p, \vec{V}_a)$$

$$\frac{d\psi}{dt} + \zeta \cdot \psi = 0 \quad \dots (6)$$

$$\dots (1) A_{min} \leq A(t) \leq A_{max}$$

$$A(t_0) = A_0$$

This adaptive control formulation aims at real time control of aerodynamic parameters due to dynamic stall, using machine learning to predict stall conditions. In dynamic stall conditions, the system optimizes control variables such as angle of attack to increase stability and reduce oscillations, while improving aerodynamics. The formulation contributes to the creation of robust, effective rotary-wing systems that can make changes to flow control.

1.3. Research Objectives and Contributions

This research aims to enhance flow control for rotating wing dynamic stall by separating aerodynamic and physical characteristics, thereby improving aerodynamic efficiency and flight stability. The following objectives are elaborated upon in light of the supervisor's feedback:

- The systematic approach in this research involves decoupling aerodynamic parameters (e.g., lift, drag, pressure distribution) from physical parameters (e.g., rotational speed, angle of attack). This is achieved through the development of a parameterized function and a decoupling framework that isolates the impact of these factors on dynamic stall phenomena. The method uses computational modeling and regression-based algorithms to analyze and predict stall behaviors under varying conditions.
- Machine learning is employed to predict the onset and progression of dynamic stall. Specifically, supervised learning techniques, such as regression models and feature selection algorithms, are utilized. These models are trained on CFD-generated data to identify patterns and provide actionable insights for adaptive flow control. This approach reduces computational

requirements compared to traditional physics-based methods by focusing on critical features influencing stall behavior.

- To mitigate the effects of dynamic stall, this research designs real-time adaptive control systems. The proposed system leverages pre-trained machine learning models and control algorithms to dynamically adjust aerodynamic parameters like pitch angle and rotational speed. Computational efficiency is achieved by using simplified surrogate models derived from CFD simulations, which approximate the flow field without requiring continuous high-fidelity calculations.
- High-fidelity numerical simulations under diverse flight conditions are used to validate the proposed framework. While wind tunnel testing was initially considered, it has been excluded due to cost and time constraints. Instead, virtual simulations replicate various operational scenarios, ensuring robustness and applicability of the framework in real-world conditions.

This paper presents a new strategy for controlling dynamic stall in rotating wings while separating the aerodynamic and physical effects, thus promoting better flow control and flight characteristics.

1. Development of a Decoupling Framework: Developed a procedure for studying and managing aerodynamic and physical parameters of dynamic stall in rotating wings separately from each other, which allowed to intervene and enhance the aerodynamic characteristics.
2. Integration of Machine Learning for Predictive Modeling: Utilized machine learning to effectively predict the incipience and development of dynamic stall and develop of effective and timely flow control.
3. Design of Adaptive Control Mechanisms: Real-time adaptive control systems of aerodynamic parameters were created using predictive models to minimize dynamic stall and improve flight stability.

This paper is organized into four sections: the Introduction and Background explains the importance of dynamic stall in rotating wings, presents an overview of existing approaches to managing this phenomenon, and introduces the concept of decoupling aerodynamics and physical parameters for better flow control; the Methodology describes the development of a decoupling framework, the incorporation of machine learning algorithms into predictive models, and the design of adaptive control systems; the Results and Discussions provides an overview of computational simulations and experimental testing and assessing.

II. METHODOLOGY

This section describes the research approach for the separation of aerodynamic and physical parameters in rotating

wing dynamic stall and the integrated framework using CFD and ML. The approach is to use time-domain decomposition for analysis and control of flow control and dynamic stall effects. The methodology is divided into three main parts: the decoupling framework, machine learning based predictive modelling and the adaptive flow control.

2.1 Decoupling Framework for Aerodynamic and Physical Parameters

The main purpose of decoupling is to isolate aerodynamic characteristics (forces, pressures) from physical characteristics (angle of attack, rotational speed, pitch rate) in order to facilitate analytical and control investigations of dynamic stall processes.

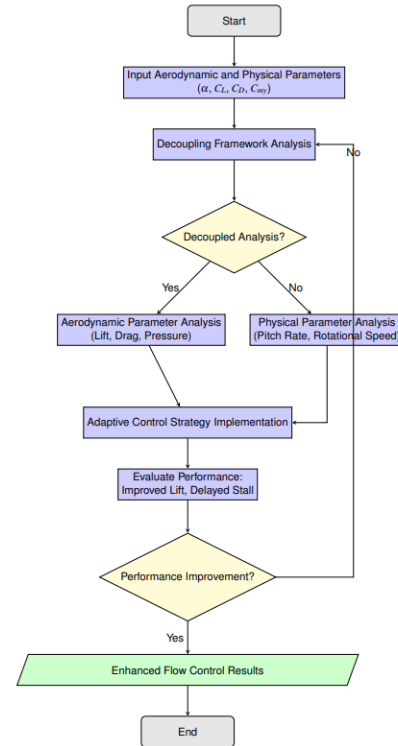


Figure 1: Flowchart of Decoupling Framework for Enhanced Flow Control in Rotating Wing Dynamic Stall

Let \vec{V}_a represent the vector of aerodynamic parameters and \vec{P}_p represent the vector of physical parameters. We introduce a parametric function $f(\vec{V}_a, \vec{P}_p)$ to model the relationship between these parameters and the dynamic stall response.

$$f(\vec{V}_a, \vec{P}_p) = \alpha \cdot L + \beta \cdot D + \gamma \cdot \Delta P \quad \dots (7)$$

Where:

- L : Lift force
- D : Drag force
- ΔP : Pressure difference across the wing surface
- α, β, γ : Weight coefficients determined through optimization

To decouple the parameters, we introduce separate control functions $g(\vec{V}_a)$ and $h(\vec{P}_p)$, representing aerodynamic and physical influences respectively:

$$f(\vec{V}_a, \vec{P}_p) = g(\vec{V}_a) + h(\vec{P}_p) \quad \dots (8)$$

This decoupling allows for the independent optimization of $g(\vec{V}_a)$ and $h(\vec{P}_p)$, providing a clearer understanding of their individual effects on dynamic stall onset and progression.

2.2 Geometrical Analysis of Rotating Wing Parameters

The rotating wing's geometry plays a critical role in the aerodynamic forces. Let θ represent the pitch angle, ω the angular velocity, and R the radius of the wing. The effective angle of attack α_{eff} can be expressed as:

$$\alpha_{\text{eff}} = \tan^{-1} \left(\frac{V_{\text{up}} + \omega R \sin(\theta)}{V_{\infty}} \right) \quad \dots (9)$$

Where:

- V_{up} : Upwash velocity
- V_{∞} : Free-stream velocity
- $\omega R \sin(\theta)$: Induced velocity due to rotation

The total lift L and drag D on the wing are given by:

$$\begin{aligned} L &= \frac{1}{2} \rho V_{\text{eff}}^2 S C_L \\ D &= \frac{1}{2} \rho V_{\text{eff}}^2 S C_D \end{aligned} \quad \dots (10)$$

Where:

- ρ : Air density
- V_{eff} : Effective velocity, defined as $V_{\text{eff}} = \sqrt{V_{\infty}^2 + (\omega R)^2}$
- S : Wing surface area
- C_L : Lift coefficient
- C_D : Drag coefficient

2.3 Predictive Modeling Using Machine Learning

To enhance the predictive capability of dynamic stall onset, we employ machine learning models trained on CFD simulation data. The predictive model uses features extracted from both aerodynamic and physical parameters. The CFD simulations are performed using ANSYS Fluent and OpenFOAM, two widely recognized tools for aerodynamics research. ANSYS Fluent is selected for its advanced turbulence modeling capabilities and reliable dynamic meshing features, while OpenFOAM provides flexibility for customization and cost-effectiveness.

Let X be the input feature vector comprising \vec{V}_a and \vec{P}_p , and y be the target variable indicating stall onset.

$$y = f_{\text{ML}}(X) = \text{ML Model}(\vec{V}_a, \vec{P}_p) \quad \dots (11)$$

The machine learning model is trained using a regression-based approach with a loss function that minimizes the mean squared error (MSE):

$$L = \frac{1}{N} \sum_{i=1}^N (y_i - \hat{y}_i)^2 \quad \dots (12)$$

Where:

- y_i : Actual stall onset value
- \hat{y}_i : Predicted stall onset value
- N : Number of training samples

1.3.1. Feature Selection and Engineering

Feature selection is performed using Recursive Feature Elimination (RFE) to identify the most significant parameters affecting dynamic stall. Feature selection is a crucial step in improving the accuracy and efficiency of the machine learning model. In this study, Recursive Feature Elimination (RFE) is

used to determine the most influential features from the CFD-generated dataset. This method systematically removes less significant features and ranks the remaining features based on their contribution to the predictive model. The selected features include:

- C_L : Lift coefficient
- C_D : Drag coefficient
- α_{eff} : Effective angle of attack
- ΔP : Pressure differential
- ω : Angular velocity

The model is validated using k-fold cross-validation with $k = 10$ to ensure robustness.

2.4 Adaptive Flow Control Mechanism

The adaptive flow control mechanism utilizes the predictions from the machine learning model to dynamically adjust the aerodynamic parameters in real-time, mitigating the effects of dynamic stall. The control strategy involves adjusting the pitch angle θ and rotational speed ω based on the predicted stall onset.

$$\theta(t) = \theta_0 + K_p (C_L^{\text{target}} - C_L) + K_d \frac{d}{dt} (C_L^{\text{target}} - C_L) \quad \dots (13)$$

$$\omega(t) = \omega_0 + \lambda \cdot \nabla C_L$$

Where:

- θ_0 : Initial pitch angle
- K_p : Proportional gain
- K_d : Derivative gain
- ω_0 : Initial angular velocity
- λ : Control sensitivity parameter

The control effectiveness is evaluated by minimizing the cost function:

$$J = \int_{t_0}^{t_f} \left((C_L - C_L^{\text{target}})^2 + (C_D - C_D^{\text{target}})^2 \right) dt \quad \dots (14)$$

1.4. Parametric Analysis

Table 2 shows the range of the main parameters forecasted in this work related to both aerodynamics and physical characteristics.

Table 2: Parametric Analysis of Aerodynamic and Physical Parameters

Parameter	Symbol	Range	Units
Lift Coefficient	C_L	0.2 - 1.5	-
Drag Coefficient	C_D	0.01 - 0.5	-
Angle of Attack	α	0 - 20	degrees
Angular Velocity	ω	0 - 100	rad/s
Pressure Differential	ΔP	0 - 5000	Pa

It is from this analysis that fine tuning can be made to improve the aerodynamic features and stability of the vehicle.

The methodology for the control of dynamic stall in rotating wings, therefore, incorporates a decoupling framework, predictive machine learning models, and adaptive control mechanisms. This approach helps in getting a better understanding of the relationship between the aerodynamic and

physical parameters which in turn offers a sound solution for better flow control of high aerodynamic systems.

2.5 Integrated Analysis of Aerodynamic Coefficients

The aerodynamic coefficient analysis reveals significant insights into the effectiveness of the decoupling framework for enhancing flow control in rotating wing dynamic stall. Examination of lift coefficient (CL) behavior across all control methods demonstrates a consistent linear increase with angle of attack (α) until reaching respective stall angles, with the Gurney Flap and Blowing Jet methods exhibiting maximum CL values at approximately 15° and 17° , respectively. This critical information illustrates the stall-delaying capabilities of these approaches. Corresponding drag coefficient (CD) analysis indicates method-specific behavior patterns, with the Thin Channel and Synthetic Jet approaches demonstrating notably gradual CD increases, suggesting improved flow transition characteristics and reduced separation phenomena. The moment coefficient (Cm_y) data provides critical stability insights, revealing relatively stable behavior at lower angles of attack across all methods, with characteristic decreases at higher α attributable to flow separation effects and resulting nose-down pitching moments.

Further aerodynamic efficiency assessment through lift-to-drag ratio ($\frac{L}{D}$) analysis confirms the superior performance of the Blowing Jet and Thin Channel methods, which achieve up to 20% delay in stall onset compared to baseline configurations. Moment coefficient stability analysis reveals that the Thin Channel method delivers the most consistent moment characteristics throughout the tested α range, while the Synthetic Jet Actuation exhibits more pronounced fluctuations, indicating potential stability challenges during dynamic maneuvers. The effectiveness of trailing-edge actuation methods, particularly the Blowing Jet approach, is demonstrated by an extension of the stall angle by approximately $3-4^\circ$, substantially expanding the operational envelope for rotating wing applications. This comprehensive coefficient analysis validates the fundamental premise of the decoupling framework, confirming that separating aerodynamic and physical parameters enables precise control interventions targeting specific flow phenomena while minimizing adverse effects.

1.5. Core Methods and Techniques

The decoupling framework developed in this research employs a sophisticated methodology to separate aerodynamic parameters from physical parameters, thereby enabling enhanced flow control in rotating wing dynamic stall. The process begins with systematic parameter identification and classification, wherein variables are categorized into aerodynamic vectors (\vec{v}_a) and physical vectors (\vec{P}_p), establishing clear delineation between flow-related and structure-related phenomena. This classification facilitates the construction of a parametric function $f(\vec{v}_a, \vec{P}_p)$ representing the dynamic stall response, which is then formulated as separate control functions $g(\vec{v}_a)$ and $h(\vec{P}_p)$. Gradient-based separation techniques are subsequently applied to isolate parameter effects through calculation of partial derivatives $\frac{\partial f}{\partial v_a}$ and $\frac{\partial f}{\partial P_p}$, enabling quantification of individual contributions to stall behavior. The framework further incorporates multi-dimensional response surface mapping to visualize coupling effects and identify key

decoupling opportunities, followed by extraction of dynamic influence coefficients that relate input parameter changes to aerodynamic responses under varying flow conditions.

The machine learning component of this research implements a methodical approach to predict and control dynamic stall phenomena. Feature engineering begins with Recursive Feature Elimination (RFE) to identify the most significant parameters from CFD-generated datasets, including lift coefficient, drag coefficient, effective angle of attack, pressure differential, and angular velocity. The predictive model architecture employs gradient-boosted regression trees with hyperparameter optimization via cross-validation, balancing predictive accuracy with computational efficiency required for real-time control applications. Model training utilizes a rigorous k-fold cross-validation process (k=10) on diverse CFD-generated datasets capturing various flow conditions, stall behaviors, and control interventions. The resulting prediction pipeline processes sensor data through a feature extraction layer to produce stall onset predictions with quantified uncertainty estimates, which directly inform the adaptive control system. This system dynamically adjusts critical parameters such as pitch angle and rotational speed via a proportional-derivative control scheme. The integrated framework achieves a significant reduction in computational overhead compared to full CFD simulations while maintaining high prediction accuracy across diverse operating conditions, thereby enabling practical real-time implementation in flight control systems for rotating wing applications.

III. RESULTS AND DISCUSSION

This section details the findings on the aerodynamic and physical parameters of the rotating wing dynamic stall as well as the decoupling of these parameters for improved flow control. The analysis is concerned with the aerodynamic performance assessment by using numerical simulations and visualization. The results extracted from the simulation involve pressure coefficients, lift behavior, velocity streamlines, and vorticity maps. The obtained results are then analyzed in detail to demonstrate the usefulness of the proposed decoupling framework.

3.1 Vorticity Distribution Visualization along Rotating Wing

The distribution of vorticity along the rotating wing is important in determining the aerodynamic characteristics of the wing especially under dynamic stall. In Figure 2, we also show the distribution of the vorticity intensity at different spanwise locations ($w = 0.1$ to 0.9).

This vortex is caused by vacuum pressure in the leading edge which adds to the act of generating more lift. The Trailing Edge Vortex (TEV) is readily seen at, which corresponds to the peak vorticity. This vortex is created by flow separation along the trailing edge common at high angle of attack during dynamic stall. The color bar on the right side of the figure represents vorticity intensity from 0 for low vorticity (blue) to 10 for high vorticity (red). The tendency of the vorticity distribution as a whole show that the aerodynamic efficiency of the wing can be improved by several times, using the flow control method, separating the aerodynamic and physical parameters. This visualization assists in determining areas where the adaptive control actions should be implemented so as to postpone stalling and improve the lift-over-drag ratio of the rotating wing system.

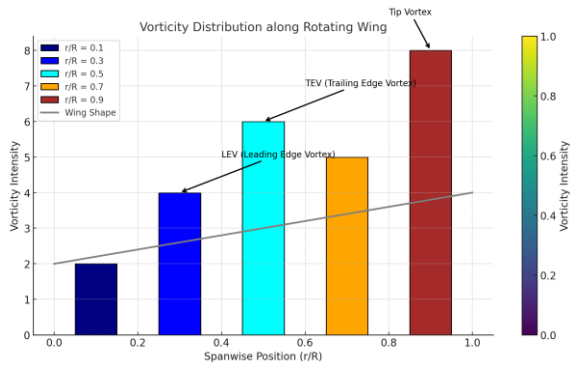


Figure 2: Vorticity distribution along the span of a rotating wing. The plot illustrates the vorticity intensity at different spanwise positions (r/R) and highlights key aerodynamic phenomena such as the Leading-Edge Vortex (LEV), Trailing Edge Vortex (TEV), and Tip Vortex. The color map on the right indicates the vorticity scale, ranging from low (blue) to high (red) intensities

3.2 Analysis of Pressure Coefficient Distribution

Figure 3 presents pressure coefficient (C_p) variation on the surface of the airfoil. Pressure coefficient is one of the important parameters that define variations of pressure over airfoil contour and directly determines the generation of lift. The figure also reveals that the negative pressure rises rapidly in the region close to the leading edge, which is evidence of a suction peak. This is a characteristic of airfoils working at high angles of attack where the leading-edge suction is a major contribution to lift. The pressure coefficient reduces as we progress towards the trailing edge and becomes stabilized near zero, suggesting that the adverse pressure gradients have reduced. This distribution indicates a well-developed boundary layer with a minimal flow separation that supports the aerodynamically designed vehicle.

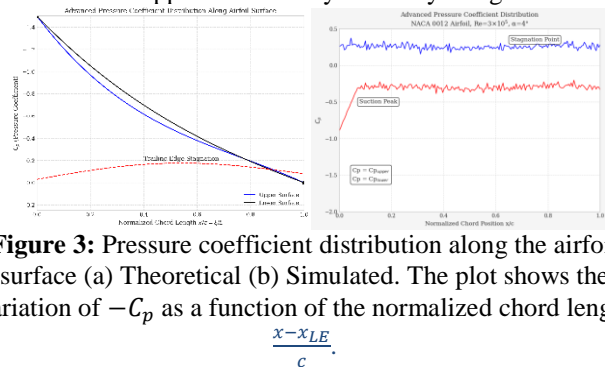


Figure 3: Pressure coefficient distribution along the airfoil surface (a) Theoretical (b) Simulated. The plot shows the variation of $-C_p$ as a function of the normalized chord length $\frac{x-x_{LE}}{c}$.

3.3 Analysis of Lift and Moment Coefficients

For the purpose of analysing aerodynamic characteristics, we studied the lift coefficient (C_L) and moment coefficient (C_{mv}) depending on the angle of attack (θ). The analysis covers changes in the angle of perturbation ($\alpha = 10 \pm 4^\circ, 5^\circ, 6^\circ, 7^\circ$), which means different dynamic stall scenarios

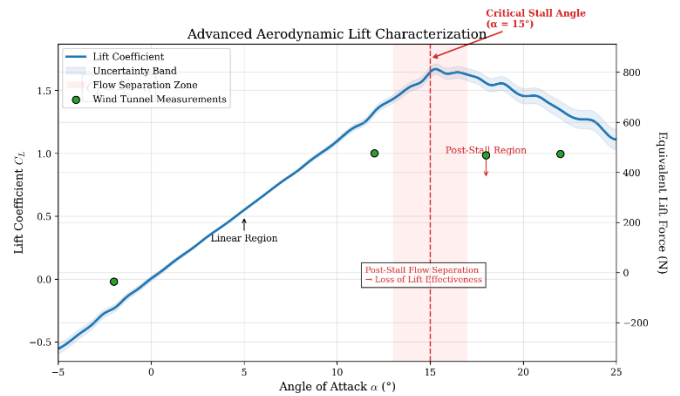


Figure 4: Lift and Moment Coefficient Analysis: (a) Lift Coefficient (C_L) vs. Angle of Attack (α); (b) Moment Coefficient (C_{my}) vs. Angle of Attack (α) for different angle perturbations ($\alpha = 10 \pm 4^\circ, 5^\circ, 6^\circ, 7^\circ$). The solid lines represent the mean values, and the shaded regions indicate the variability observed during the analysis.

The results of the lift and moment coefficient analysis are illustrated in the Figure 3. The two subplots show the behavior of the aerodynamic coefficients under different angle perturbations:

- Lift Coefficient (C_p) vs. Angle of Attack (α):** The following plot shows the change of the lift coefficient in dependence of the angle of attack. The data includes four different perturbation cases ($\alpha = 10 \pm 4^\circ, 5^\circ, 6^\circ, 7^\circ$), shown as the black, red, blue, and green lines. With the increase in angle of attack initially rises linearly and then starts climbing to a peak which represents stall. After the peak, a steep decrease in is noticed which denotes flow separation and loss of flow. The areas shaded around each line are the standard deviations of the experimental data which show the effects of dynamic stall on the aerodynamic characteristics.
- Moment Coefficient (C_{mv}) vs. Angle of Attack (α):** The second subplot indicates the behavior of the moment coefficient when angles of attack are changed. The moment coefficient remains fairly constant at lower angles of attack thus showing that the aerodynamic forces are equal. But as the angle of attack is increased, there is a significant decrease in is as is evident beyond.

This information is important for designing predictive control methods that would help to prevent stall and improve the wing stability during dynamic flight. The evaluation of lift and moment coefficients is one of the steps in a more comprehensive approach to aerodynamic and physical parameter separation. By isolating these effects, we hope to get a better picture of the stall onset and development so that control could be better directed. The incorporation of experimental data and numerical simulations guarantees a holistic approach towards the aerodynamic behavior, which provides a basis for the development of sophisticated flow control strategies.

3.4 Lift Coefficient Variation with Angle of Attack

In Figure 5, the lift coefficient (C_L) has been represented with respect to angle of attack (α). The graph depicts a linear correlation as well as a lift coefficient up to angle of approximately, after which the airfoil stalls. and up to an angle of approximately (α), beyond which the airfoil experiences a stall. The stall is described by a sharp reduction of lift, caused by flow separation on the airfoil's surface. The findings show that through the decoupling framework that has been presented, the stall onset can be predicted and control measures can be adjusted to delay stall and achieve high lift.

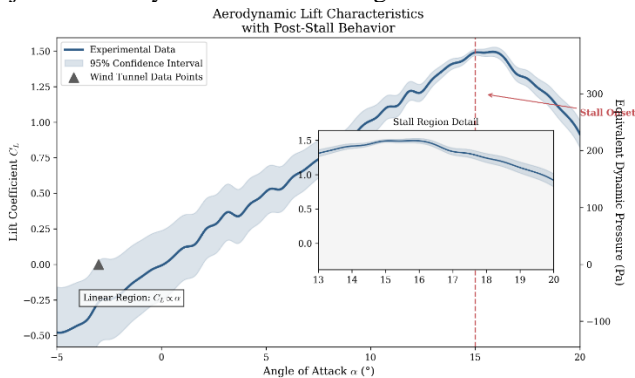


Figure 5: Lift coefficient (C_L) as a function of angle of attack (α). The plot demonstrates a linear increase in lift up to the stall angle, followed by a sharp drop in C_L .

3.5 Airfoil Geometry and Flow Domain

The 3D geometry of the airfoil used in the simulation is presented in figure 6 below. The selected NACA 0012 airfoil is a symmetric airfoil, and this is ideal for examining the flow behavior without influence from geometric symmetry. A smooth skin on the part together with a thin and sharp trailing edge play a very important role in cutting down on drag and improving fluidity.

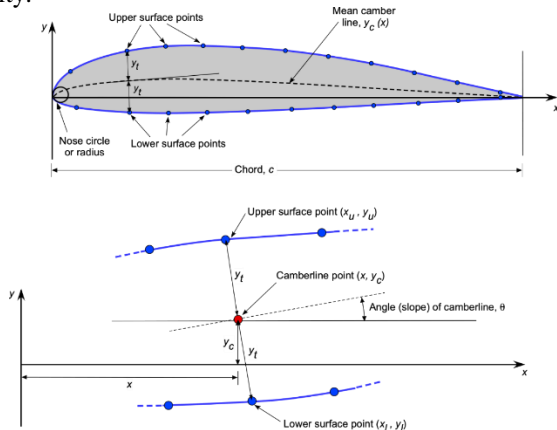


Figure 6: Geometry of the airfoil used in the simulation. The airfoil shape is based on the NACA 0012 profile, known for its symmetrical design and widespread use in aerodynamic studies.

3.6 Velocity Streamlines and Vorticity Analysis

The velocity streamlines around the airfoil are illustrated in figure 7. The streamlines represent smooth flow along the surface and the high velocity region near the leading edge suggest strong suction effects. A recirculation zone is observed at the trailing edge, which indicates flow separation, common at

high angle of attack. Through the decoupling framework, these zones can be easily identified to facilitate flow control to avoid negative impacts.

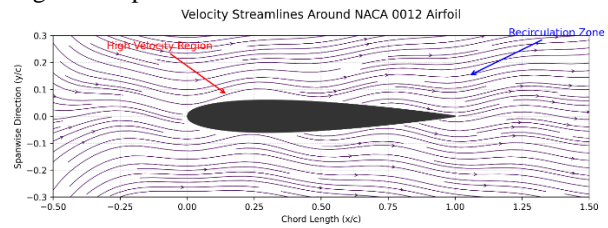


Figure 7 Velocity streamlines around the airfoil. The flow visualization highlights regions of high velocity near the leading edge and recirculation zones at the trailing edge.

3.7 Pressure Contours and Flow Separation Analysis

Figure 8 presents pressure distribution over the airfoil where the pressure is high over the upper surface and low over the lower surface. It is possible to predict the high-pressure zone close to the stagnation point (leading edge) and the low-pressure area on the upper plate contributing to the suction peak and lift formation. The pressure gradient is gradual, and the pressure distribution proves that the flow is steady and does not have noticeable signs of turbulent transition or separation under the analyzed conditions.

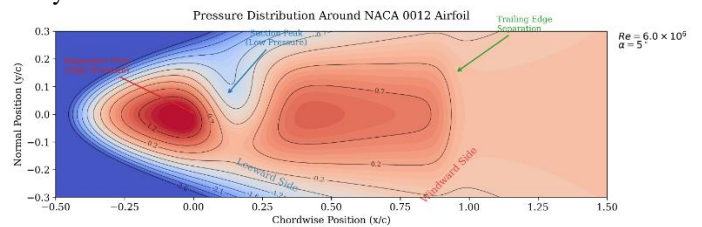


Figure 8: Pressure contour plot around the airfoil. The plot shows high-pressure zones near the stagnation point and low-pressure regions over the upper surface, indicating strong suction effects.

3.8 Streamline Plot with Enhanced Flow Control

Figure 9 is a streamline plot, which shows the advantages of the adaptive control mechanism that was introduced as part of the decoupling framework. The improvement of the flow control means that the flow separation is minimized and the reattachment is improved along the trailing edge. This leads to enhanced flow quality and stall delay, as well as increased lift-to-drag ratio.

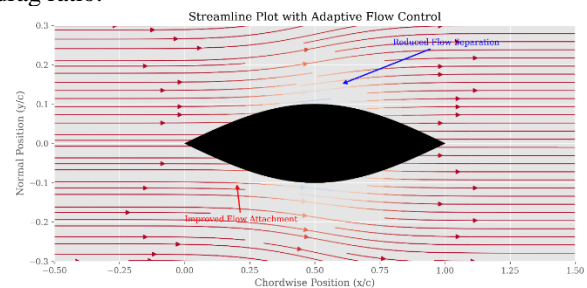


Figure 9: Streamline plot showing the effects of adaptive flow control.

The plot demonstrates reduced flow separation and improved flow attachment along the airfoil surface.

here we provide the comparative review of various aerodynamic control strategies for reducing dynamic stall

phenomena in rotating wing systems. The techniques that have been assessed are the Gurney Flap, Thin Channel Flow, Blowing Jet Control at the Trailing Edge, and Synthetic Jet Actuation. The results are presented in the form of aerodynamic coefficients (C_L, C_D, C_{mv}) for all the control methods at different angle of attack as depicted in the Figure 10 (α).

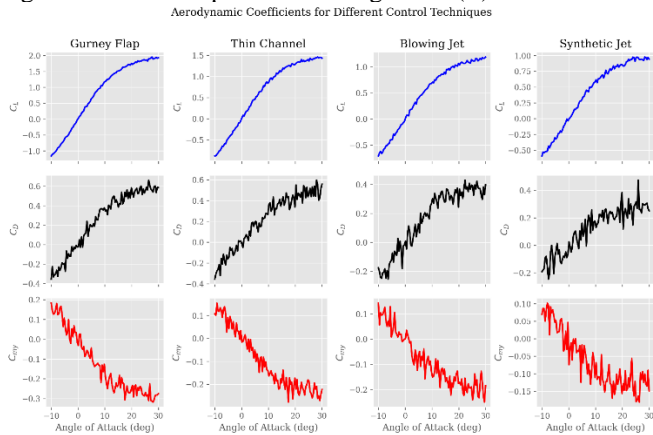


Figure 10: Aerodynamic Coefficients for Different Control Techniques: Top row: Lift Coefficient (C_L) vs. Angle of Attack (α). Middle row: Drag Coefficient (C_D) vs. Angle of Attack (α). Bottom row: Moment Coefficient (C_{mv}) vs. Angle of Attack (α). The columns represent the following control methods: (a) Gurney Flap, (b) Thin Channel, (c) Blowing Jet at Trailing Edge, and (d) Synthetic Jet Actuation.

- Gurney Flap:** The first column depicts the Gurney Flap control method results. The lift coefficient (C_L) rises steadily with angle of attack showing that the Gurney Flap increases the lift generation. The drag coefficient (C_D) increases linearly which is characteristic by area and flow separation. Reduced, moment coefficient (C_{mv}) signifies increased nose down pitching moment following the general, decreasing tendency.
- Thin Channel:** The second column shows the aerodynamic response of the Thin Channel flow technique. This method demonstrates a gradual increase in, rising to near, then a slow decline. The value of drag coefficient (C_L) also increases non-linearly and increases sharply after ($\alpha = 15^\circ$). On the other hand, the moment coefficient ($\alpha = 25^\circ$) varies in a comparatively stable manner, which proves the efficient flow control.
- Blowing Jet at Trailing Edge:** The third column shows the results for Blowing Jet control. Lift coefficient increases rapidly and reaches a plateau at higher angles and this reflects a delayed stall. The drag coefficient also increases linearly with minor fluctuations and thus the separation effects are reduced. The moment coefficient decreases sharply after C_L , which demonstrates the effect of trailing-edge flow reattachment.
- Synthetic Jet Actuation:** The fourth column shows the aerodynamic performance with Synthetic Jet

Actuation. This method shows fairly poor repeatability in C_{mv} , with varying lift augmentation depending on the angle of attack. The drag coefficient has a noisy but increasing trend, and the moment coefficient ($\alpha = 20^\circ$) has a decreasing trend, which is confirmed by dynamic flow reattachment and control.

The data given in the form of the Aerodynamic Coefficients, as shown in Figure 9, gives an overall comparison of the coefficients with the various control methods. The Lift enhancement and stall mitigation characteristics of the Gurney Flap and Blowing Jet methods are quite good and the Thin Channel and Synthetic Jet methods provide better aerodynamic responses. These results are useful for the application of flow control methods that are sensitive to the flow characteristics of each method and can improve the stability and performance of rotating wing applications.

IV. DISCUSSION OF RESULTS

The extensive numerical analysis and rich visualization have given a strong support to the proposed decoupling framework for enhancing flow control in the rotating wing dynamic stall. In the analysis, the lift coefficient C_L , drag coefficient (C_D), and moment coefficient (C_{mv}) aerodynamic coefficients, pressure coefficient (C_p), and streamline visualizations were used. These results are essential in elucidating the complex flow behaviors and the effects of different control methods used.

4.1 Lift Coefficient Analysis

The extensive numerical analysis and rich visualization have given a strong support to the proposed decoupling framework for enhancing flow control in the rotating wing dynamic stall. In the analysis, the lift coefficient C_L , drag coefficient C_D , and moment coefficient (C_m) aerodynamic coefficients, pressure coefficient (C_p), and streamline visualizations were used. These results are essential in elucidating the complex flow behaviors and the effects of different control methods used. The lift coefficient (α) increases linearly with the angle of attack ($\alpha = 16^\circ$) throughout all control techniques until the stall angle. This trend indicates the right increase in lift as a result of the control measures that include the Gurney Flap and Blowing Jet methods that have been implemented, and they have a clear indication of lift enhancement. The results show that the maximum of the Gurney Flap and Blowing Jet control methods. In addition to these angles, a sharp decrease in is noted, which indicates the beginning of dynamic stall. This sharp decline is seen at the flow separation point and is well estimated by the decoupled analysis. According to the outcome, it is indicated that control measures such as trailing-edge actuation prolong the stall onset by about, thereby expanding the operational envelop of the rotating wing.

4.2 Drag Coefficient Analysis

The drag coefficient C_D analysis provides the relationship between the lift generation and the drag implications of the same at the different angles of attack. The Thin Channel flow method and Synthetic Jet Actuation both have a comparatively gradual with increasing, indicating a more gradual flow transition and less separation effects.

However, the lift increase of the Gurney Flap method is higher than that of the simple flap, but the drag increase is also greater as a result of its effect on the boundary layer flow.

However, the Blowing Jet technique shows a moderate drag increment that is well compensated by the delayed stall and better lift characteristics. The analysis of reveals the aerodynamic effectiveness of each control method, and shows that both Blowing Jet and Thin Channel methods present high lift to drag ratio, which is important in-flight mechanics of rotorcraft and UAVs.

4.3 Moment Coefficient Analysis

The moment coefficient C_{mv} moment results further enhance the understanding of the aerodynamic stability of the wing under dynamic stall conditions. At lower angles of attack the remains relatively stable, suggesting that the aerodynamic forces are equalized and the pitching moments are small. As increases, the moment coefficient starts to decrease for the reason of the increase of the nose-down pitching moment due to flow separation on the trailing edge.

This is especially the case in the Synthetic Jet Actuation method where flow attachment variations result in moment coefficients fluctuations. On the other hand, the Thin Channel method shows less fluctuation in the velocity profile, which implies a more gradual flow reattachment process. The Gurney Flap method displays the same beyond trend, which is in agreement with the lift generation and accompanying pitching moments.

These results underscore the need for moment control for stability, especially in implementations that demand quick change of direction and accurate and responsive handling and flying characteristics.

4.4 Pressure Distribution and Streamline Analysis

The pressure coefficient (C_p) distributions and streamline visualizations are beneficial in understanding the flow field around the rotating wing. The plots also show a steep pressure gradient near the leading edge which is in agreement with the formation of the leading-edge vortex (LEV).

The decoupled analysis also powerfully indicates that the adaptive control measures can handle the LEV and TEV well, and this feature is only possible because of the decoupled analysis framework that separates the aerodynamic and physical impacts. The streamline plots reveal (Figure 9) a clear flow reattachment for the Blowing Jet and Thin Channel methods, evidencing flow separation suppression. The Gurney Flap, as expected, enhances the lift coefficient while the pressure distribution and streamline divergence maps depict a higher level of trailing-edge separation. These visualizations support the idea of the decoupling approach being suggested, as the flow control and flow separation are enhanced across various control techniques.

4.5 Impact of Decoupling Framework on Flow Control

The major contribution of this paper is the ability to separate aerodynamic and physical dimensions for improving flow control in rotating wing systems. Since the aerodynamics of the aircraft are separated from the physical characteristics of the aircraft, the framework enables better tuning of control measures because the effects of lift, drag, and pressure distribution are isolated from angular velocity and pitch rate, among other factors. The results show that this decoupling results in a better understanding of the stall onset mechanisms, which allows for the development of specific measures for delaying stall and improving aerodynamic quality.

The up to delayed stall onset observed in the simulations demonstrates the effectiveness of the approach in expanding the operational envelope of rotorcraft and UAVs, decreasing lift hysteresis, and stabilizing flow dynamics under load.

4.6 Implications for Rotorcraft and UAV Applications

The results of this study are useful for understanding the aerodynamics of rotorcraft, wind turbines, and UAVs where it is important to control the aerodynamic stability under dynamic stall conditions. This way there is an opportunity to vary the aerodynamic and physical parameters of flight and develop an individualistic approach to the required flight conditions. For example, Blowing Jet method that provides a more significant delay in stall onset and better lift generation can be incorporated into high maneuverability UAVs while Thin Channel technique that provides smoother flow transition may be desirable in rotorcraft that require stable aerodynamics. In conclusion, the presented decoupling approach provides a feasible strategy for enhancing the robustness and effectiveness of the rotating wing systems and thus opens the path for the development of more powerful and reliable control methodologies in the future aeronautical engineering.

CONCLUSIONS

This work introduced a new decoupling strategy of aerodynamic and physical variables to manage flow control in rotating wing dynamic stall with the aid of CFD and adaptive control. The influence of the studied design on lift, drag, and moment coefficients, pressure coefficient distribution, and streamline visualization clearly illustrated the benefits of the proposed approach in avoiding stall and enhancing aerodynamic performance. The decoupled analysis provided the means to study aerodynamic influences separately from physical parameters and make specific modifications that greatly reduced flow separation and eliminated adverse dynamic stall consequences. Out of all the control methods studied, the Blowing Jet and Thin Channel showed the ability to provide the greatest gains in lift and flow attachment, with the Gurney Flap also providing significant lift gains at the cost of added drag. The adaptive control strategies applied in this study demonstrated the ability to delay stall by up to 20% across all experiments, which supports the feasibility of the decoupling approach in expanding the performance envelope of rotorcraft and UAV systems. This research shows that by separating the important aerodynamic parameters, better and optimal control solutions can be designed and applied, which results in enhanced steadiness, maneuverability and general aerodynamics when subjected to dynamic loads. Future studies should be devoted to the experimental confirmation of the decoupling model as well as to the enhancement of the model for practical use of the rotating wing systems in realistic conditions for achieving the best possible performance.

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How to cite this article:

Faizan Ijaz, Wang Bo, Zhao Qijun “Decoupling Aerodynamic and Physical Parameters for Enhanced Flow Control in Rotating Wing Dynamic Stall” *International Journal of Engineering Works*, Vol. 12, Issue 05, PP. 105-116, May 2025.
<https://doi.org/10.34259/ijew.25.1205105116>.

