AERODYNAMIC PERFORMANCE ENHANCEMENT OF MULTI-ROTOR UAVs: A REVIEW ON MINIMIZING DRAG FROM WAKE INTERACTIONS

Muhamad Hafizuddin Zaidon[a]*, Iskandar Shah Ishak[a], Faruq Muhammad Foong[a], ZM Ali[b]

[a]UTM Aerolab, Institute for Sustainable Transport, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b]Fakulti Kejuruteraan Mekanikal, Universiti Teknologi MARA, 40450, Shah Alam, Malaysia

*Corresponding email: muhammadhafizuddin.z@graduate.utm.my

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ABSTRACT

Unmanned Aerial Vehicles (UAVs) play a critical role in a wide range of applications, from surveillance to air mobility. However, aerodynamic challenges often compromise their performance, particularly wake-induced drag, which limits their efficiency and endurance. This paper reviews some significant research efforts dedicated to understanding wake behaviour in UAVs and the various strategies developed to mitigate its effects. The review focuses on advanced aerodynamic enhancements, including vortex generators, dimples, shark skin-inspired structures, and ducted-rotor configuration, offering unique mechanisms for reducing wake formation and associated drag. Vortex generators are discussed for their ability to energize the boundary layer, effectively delaying flow separation and reducing turbulence behind the UAV, which minimizes drag. Dimples, modelled after the surface of golf balls, are shown to alter flow patterns around the UAV, leading to a smoother airflow and substantial drag reduction. Furthermore, shark skin structures, inspired by the micro-patterned denticles on shark skin, have been demonstrated to improve both drag and lift enhancement by manipulating boundary layers and generating beneficial vortices. Integrating these bio-inspired and engineered solutions into the design offers a promising pathway to significantly enhance aerodynamic performance. By reducing wake-induced drag, these technologies can improve endurance, higher efficiency, and greater operational capabilities of UAVs. This paper provides a comprehensive foundation for future research and innovation in UAV aerodynamics, encouraging the adoption of these advanced design strategies to overcome the challenges of wake behaviour and maximize UAV performance.

Keywords: *Drag, Rotor Wake, UAV, Multirotor, Shark Skin, Dimple, Vortex Generator, Endurance.*

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1.0 INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have gained considerable attention nowadays [1, 2]. They are used in various fields, including recreation, agriculture, and defense. Aside from that, they also have emerged as a successful urban air mobility (UAM) tactic in recent years [1]. Several categories of UAVs exist today, including fixed-wing, rotary-wing, and flapping-wing configurations [2]. As the name suggests, UAVs operate without requiring a person on board; instead, they are controlled remotely by an operator on the ground using

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a radio controller. This eliminates the risk of injury or death to the operator if the UAV malfunctions or encounters issues during flight [3].

Multi-rotor UAVs have seen a significant rise in demand due to their versatility, ease of use, and ability to operate vertically [4]. These UAVs are commonly employed in aerial photography, surveillance, and precision agriculture because they offer a cost-effective alternative to aeroplanes and helicopters due to their smaller size and simpler design [5]. Their hovering capability and vertical take-off and landing (VTOL) functionality make them ideal for missions in remote areas with limited space for fixed-wing UAVs to take off and land [6].

Moreover, multi-rotor UAVs are particularly valuable in challenging environments, such as inspecting infrastructure like bridges and power lines, conducting search and rescue operations in rugged terrain, and delivering supplies to isolated locations. Their greater maneuverability allows them to navigate tight spaces and perform precise tasks, making them highly sought after for applications like aerial photography, where stability and control are crucial [6]. Additionally, they are more accessible to a wide range of users, including hobbyists, commercial operators, and emergency responders, due to their simple design, which further increases their versatility and usefulness in various scenarios.

Multi-rotor UAVs, like helicopters, are types of rotary-wing aircraft or rotorcraft. Consequently, they face similar aerodynamic issues, including the formation of wakes. Stepanov *et al*. highlighted that the aircraft's payload and range are highly affected by the drag performance experienced by the fuselage [7]. Besides that, the geometry of the rotor wake, strength, and the aerodynamic effects produced on the blades depend principally on the rotorcraft's operating state and flight condition [8]. This statement indicates that the challenges can be even more severe for multi-rotor UAVs due to the interaction between multiple rotor wakes. The formation of wakes reduces aerodynamic efficiency and endurance.

Like other objects moving through the air, UAVs can be considered bluff bodies. Every bluff body generates a wake when moving through a fluid due to flow separation [9, 10], which impacts and degrades its aerodynamic performance [11]. This wake creates additional drag, making it harder for the UAV to maneuver and reducing its endurance. The interaction between multiple rotors wakes in multi-rotor UAVs complicates the aerodynamic efficiency further. This is because the aft rotor will have to encounter a region that has experienced a disturbance in its air particles due to the rotation of the front rotors. This disturbance has caused the aft rotors to perform less efficiently, resulting in stability and controllability issues for the UAVs.

Endurance plays a significant role in operating UAVs because longer endurance means more operational time without recharging. For instance, a UAV with longer endurance in agriculture can cover larger fields in a single flight, making the operation more efficient and cost-effective. Similarly, extended endurance can significantly improve the chances of finding missing persons in search and rescue missions. Increasing battery capacity to improve endurance is not viable because it would further reduce the payload capacity. Excessively reducing payload capacity would render the UAV ineffective. Therefore, enhancing a UAV's aerodynamics during flight is a more effective way to improve endurance without compromising payload capacity.

It is, therefore, crucial to study both the aerodynamic interactions and the wakes to better understand how they affect the aircraft's stability and performance, such as its maneuverability and power consumption [11]. This review paper aims to summarize existing research on the aerodynamic performance of multi-rotor UAVs, with a particular focus on minimizing drag caused by wake interactions. By reviewing recent advancements in computational and experimental studies, this paper highlights research gaps and proposes future directions for optimizing multi-rotor UAV performance.

This review primarily focuses on the aerodynamic aspects of drag minimization in multi-rotor UAVs, particularly the effects of rotor wake interactions and their influence on

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overall vehicle performance. The paper reviews studies utilizing computational fluid dynamics (CFD), vortex methods, and experimental wind tunnel testing. However, the scope is limited to aerodynamic performance and does not extensively cover energy efficiency, propulsion system design, or control strategies. Additionally, rotor-airframe interactions and broadband noise effects are acknowledged but not analysed in depth. The review is restricted to small- and medium-scale UAVs used in urban air mobility, surveillance, and commercial applications, excluding larger-scale electric vertical take-off and landing (eVTOL) aircraft.

1.1 Formation of Wake

As explained previously, flow separation at the trailing edge of a body leads to the formation of a wake [10]. This separation occurs when the boundary layer lacks sufficient energy to stay attached to the surface, resulting in a region of low pressure behind the body. This low-pressure area creates a suction effect, increasing drag on the body [12].

To illustrate this concept, Figure 1 shows the wake formed behind a truck, which generates drag that must be countered for forward motion. A similar principle applies to UAVs. As a UAV moves through the air, it disturbs the surrounding air, creating a wake behind it. As shown in Figure 1, this wake increases drag on the UAV, reducing its endurance. Consequently, the UAV must expend more energy to overcome this drag, leading to higher energy consumption and shorter flight durations.

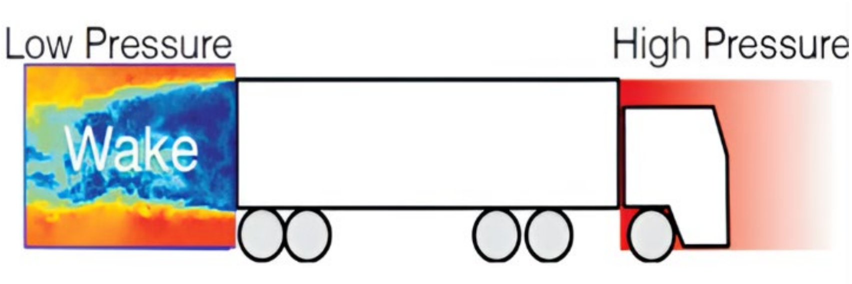

Figure 1: Formation of wake behind a truck that causes drag [10]

Ramesh *et al*. examined wake aerodynamics in bluff bodies by assessing the drag-reduction benefits of skids positioned at different angles [10]. Bluff bodies encounter considerable drag owing to their extensive wake zones in contrast to streamlined forms. The study employed the K-ε turbulence model in Fluent 6.3 for computational fluid dynamics (CFD). It validated the results through wind tunnel experiments, comparing a standard rectangular bluff body's drag coefficient (Cd) with a modified version featuring skids. The results indicated that skids significantly lowered drag, enhancing the baseline Cd of 0.643 for the rectangular body. The study revealed possible fuel savings by aerodynamic enhancement of bluff bodies.

Apart from the fuselage, multi-rotor UAVs encounter substantial drag primarily due to the complex wake patterns generated by their multiple rotors. These wakes, formed by the downwash of the rotor blades, interact with the fuselage and other components, creating additional drag forces that impede the UAV's efficiency. This interaction increases the overall drag and disrupts the smooth airflow around the UAV, further degrading its aerodynamic performance.

Moreover, the turbulent airflow generated by the forward rotors significantly impacts the efficiency of the aft rotors. This interference reduces the thrust produced by rear rotor, exacerbating the challenges, the UAV faces in maintaining aerodynamic efficiency and endurance. As a result, the UAV consumes more energy to overcome these drag forces, reducing flight time and range.

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Figures 2 and 3 visually represent the wake formation and the resulting drag forces acting on the UAV during its operation. These figures highlight the critical role that rotor-induced wake plays in the overall aerodynamic performance of multi-rotor UAVs.

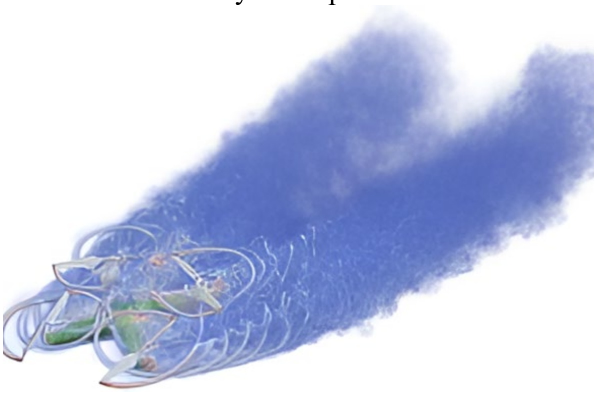

Figure 2: Rotor wakes during flight [11]

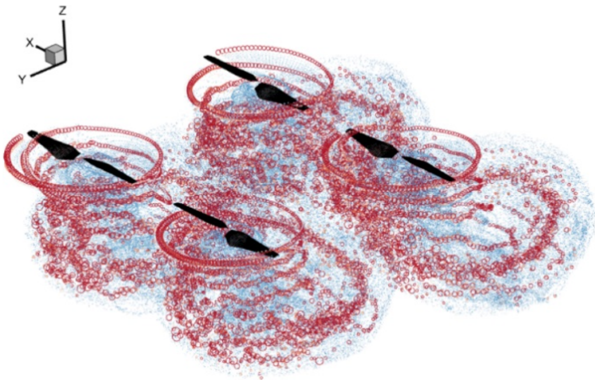

Figure 3: Downwash from rotor [13]

To learn the behaviour of the wake and to find the mitigation measures, extensive research has been conducted, both experimentally and numerically, to study wake behaviour in various flight conditions. These studies provide insights into potential design optimizations that can reduce wake-induced drag. For example, understanding how different UAV geometries influence wake formation enables designers to develop more aerodynamically efficient UAVs. Strategies such as streamlining the fuselage, optimizing rotor blade designs, and implementing flow control techniques have been explored to minimize wake effects.

Moreover, these research efforts have practical implications for the UAV industry. Reducing drag improves the endurance and range of UAVs and enhances their overall performance, allowing for longer missions, greater payload capacities, and more efficient energy use. The insights gained from wake behaviour studies thus play a pivotal role in advancing UAV technology, ensuring that these vehicles can operate more efficiently and effectively in various applications.

The ongoing research in this area continues to push the boundaries of UAV design, aiming to achieve minimal drag and maximum operational efficiency. As UAVs become increasingly integral to surveillance, delivery, and environmental monitoring, reducing wake-induced drag cannot be overstated.

2.0 METHODOLOGY

Extensive research has been conducted to study the behaviour of wake formation around UAVs, to propose ideas to improve their aerodynamic performance. The research typically

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involves two complementary approaches, experimental studies, and numerical simulations, each offering unique benefits in understanding and addressing the challenges of wake-induced drag.

Experimental studies often involve wind tunnel testing, where scaled models of UAVs are subjected to controlled airflow to observe wake formation and measure the resulting drag forces. These experiments are crucial as they provide empirical data that accurately reflect real-world conditions, allowing researchers to visualize flow patterns, identify areas of flow separation, and quantify drag forces similar to those the UAV would experience in actual flight.

Additionally, experiments can reveal unanticipated flow behaviours, such as complex interactions between the wake and UAV components, which might not be captured in simulations. The data obtained from these tests are essential benchmarks for validating numerical simulations, ensuring the accuracy and reliability of the models. However, experimental studies are often costly and time-consuming due to the need for physical prototypes and access to specialized facilities like wind tunnels [11]. This high cost is the reason why many researchers and engineers turn to simulation instead. Numerical studies offer several advantages, particularly through computational fluid dynamics (CFD) simulations. Simulations can provide detailed insights into wake structures and flow dynamics that are difficult to capture experimentally.

Through simulations, researchers can analyse the formation and behaviour of vortices, identify turbulent flow patterns, and explore the impact of various design modifications on wake behaviour. For example, CFD allows researchers to evaluate different fuselage shapes, rotor configurations, and aerodynamic fairings, enabling them to assess their effectiveness in reducing drag.

CFD simulations also offer versatility in exploring various flight conditions that may be challenging or impossible to replicate in wind tunnel experiments. They enable parametric studies where multiple variables can be systematically varied to assess their impact on wake formation and drag. This capability is particularly valuable in the iterative design process, where simulation insights guide design modifications, which can be tested experimentally. While experiments provide the necessary real-world validation, simulations significantly reduce costs and allow more efficient exploration of potential aerodynamic improvements. Table 1 shows the significant differences between the experimental method and simulation.

Table 1: Comparison between experiment and simulation

Aspect	Experiment	Simulation
Cost	High	Low
Setup time	Longer	Shorter
Data Resolution	Limited to sensor placement	High resolution
Real-world effects	Include all real-world effects	May simplify or neglect some effects
Flexibility	Limited	Highly flexible
Validation	Highly reliable	Requires experimental validation
Time consumption	Longer	Faster
Scalability	Might have inaccuracies	Scalable simulations
Cost	High	Low

Some researchers combined both experimental methods and CFD simulation in their research. Combining both methods will result in more reliable and accurate outcomes, as Liu *et al*. have done [1]. The research studied rotor interference in close proximity during UAV formation flight, and it emphasized how crucial it is to carefully take rotor spacing into account while creating flight paths for UAV formations.

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The researchers performed wind tunnel tests to recreate essential UAV flying modes, horizontal, vertical, and hovering, to examine the variations in thrust coefficients at different separation distances. The researchers subsequently incorporated the CFD simulations utilising Fluent, which enhances the study's conclusions by offering comprehensive insights into the velocity flow field between rotors at varying separation lengths. The CFD results correspond closely with the actual data, demonstrating the substantial effect of wake interference on thrust performance and validating that rotor spacing directly affects aerodynamic efficiency.

This demonstrates that experimental and simulation approaches are essential for studying UAV aerodynamics. Additionally, it indicates that simulations offer sufficient reliability to be effectively utilized in research within this field.

2.1 Experimental Works

Among the experimental works, Carreño *et al*. [14] analysed the performance of hovering multi-copters under low Reynolds number conditions. This study employed experimental and numerical approaches to investigate the aerodynamics of small-scale multicopters. Experimental data, particularly rotor performance coefficients, were used to validate CFD simulations, ensuring accuracy across different Reynolds numbers. The γ-Reθ transition model showed satisfactory agreement within the high transitional regime, while the laminar solver proved advantageous for lower Reynolds numbers. Additionally, the study highlighted the efficiency of the Moving Reference Frame (MRF) approach in reducing computational costs. Carreño *et al*. suggested that future work should focus on refining transition models and improving computational efficiency for practical applications, aiming for better predictions and design optimizations.

Hwang *et al*. presented a practical method for estimating the endurance of multirotor UAVs, accounting for hovering and steady-level flight [15]. Their method uses manufacturer data to calculate endurance, considering factors like thrust, drag, and battery discharge. It examines how drag coefficient and payload weight affect optimal flight speed and endurance, finding that higher drag due to the wake reduces endurance. In contrast, increased payload weight raises optimal speed. Validated with an average error of 2.3%, the method is useful for mission planning and drone selection, offering accurate flight time estimates based on known flight parameters. This work provides valuable insights into how drag affects UAV endurance.

Lee *et al*. experimented with rotor interactions, focusing on the wake structure and thrust generation of a quadrotor UAV [16]. They introduced and evaluated a modified version of Landgrebe's model to better predict the wake boundary of quadrotor UAVs during hovering, especially under strong rotor-rotor interactions. The new model's key improvement lies in its ability to accurately capture asymmetric wake development, which is crucial for enhancing UAV-based measurement systems and sensor placement. The model also holds the potential for assessing flight safety in multirotor UAV operations by predicting wake interactions that could impact trailing UAVs. Although currently limited to predicting time-averaged wake geometry, this model provides a foundation for future research on thrust loss mechanisms and wake control strategies in multirotor UAVs.

Lei and Lin investigated the effect of wind disturbance on coaxial rotors during hovering [17]. Both computational simulations and wind tunnel testing revealed that vertical wind disturbances significantly impact aerodynamic performance, causing reduced thrust and increased power consumption, especially at higher RPMs. Coaxial rotors showed better resistance to horizontal wind disturbances, which improved aerodynamic performance with increased wind speed.

The study highlighted that vertical winds deform vortices between the rotors, altering flow patterns, while horizontal winds cause less disruption. These findings suggest that vortex behaviour is critical to rotor performance, and future research should focus on more detailed flow visualization through PIV tests and further CFD simulations.

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In a different study, Lei and Wang studied the aerodynamic performance of quadrotor UAVs with non-planar rotors [18]. They established and validated an aerodynamic model for a non-planar quadrotor, incorporating mutual interference effects through numerical simulations and experiments. The study found that the non-planar quadrotor's rotor thrust increased by 5% to 6% compared to an isolated rotor due to enhanced tilt angle effects, which boost the actual induced velocity and outflow. Thrust stabilizes when rotor spacing exceeds 1.4 times the rotor diameter, though power consumption remains influenced by intense vortex interactions. The non-planar quadrotor exhibits complex flow dynamics with significant pressure gradients and pulsations caused by unsteady airflow and wake diffusion. Despite higher power consumption with increased thrust, the non-planar design demonstrates superior performance and power loading compared to traditional planar rotors, especially at larger tilt angles and smaller spacings, indicating potential for optimization in multi-rotor systems.

Oo *et al*. investigated turbulence effects on the unsteady aerodynamic performance of two horizontally oriented rotors [19]. Wind tunnel experiments on single and multi-rotor configurations revealed key insights into how wind turbulence affects rotor performance. For single propellers, lower RPMs showed that wind turbulence significantly impacts thrust, while at higher RPMs, wind velocity becomes the more influential factor. In multi-rotor setups with two propellers running at 4400 RPM and positioned parallel to the wind direction, significant wake interactions were observed between 0.5 and 1 rotor diameter (D) below the rotors. This finding suggests that placing instruments or additional propellers in this wake-interaction zone is detrimental due to high velocities and variability. The experiment also concluded that very close rotor placements (0.02 D) are not ideal, as high flow velocities from wake interactions at distances of 0.1 D to 0.25 D can adversely affect performance.

Schiano *et al*. addressed the challenge of estimating and correcting wind effects on a quadrotor UAV without wind sensors [20]. While previous research often treats wind as merely a disturbance to be managed with advanced controllers, this work focuses on modelling wind effects and conducting wind tunnel tests at ETH Zurich's IFD wind tunnel. The study provides a foundation for future research by offering promising results that could lead to a comprehensive aerodynamic model of the quadrotor. The implemented linear quadratic regulator (LQR) and linear quadratic regulator-integral (LQRI) controller successfully managed constant disturbances, and the wind tunnel data contributed to initial estimates of drag and lift coefficients. However, further refinement is needed, especially concerning pitch variations. Future work should include validating these results through real flights, performing additional wind tunnel experiments, and developing a complete aerodynamic model of the quadrotor, particularly in understanding how turning propellers might influence lateral in-flow.

Shukla and Komerath investigated the aerodynamic interactions of multirotor drones [21]. Their study of aerodynamic interactions between side-by-side rotors in in-plane multirotor UAVs revealed several key insights. It showed that rotor performance deteriorates significantly when rotors are positioned very close to each other, especially at low Reynolds numbers. This performance dip is likely due to blade-vortex interactions, where the proximity of the rotors causes their wake features to interfere and distort. High inter-rotor wake interactions were observed at small rotor spacings, leading to deviations from expected flow patterns. Despite these challenges, the data support traditional analytical methods with minor adjustments. Overall, the study highlights the importance of rotor spacing and Reynolds number in optimizing multirotor design and offers valuable insights for extending aerodynamic performance predictions to a broader range of UAV configurations.

Throneberry *et al*. investigated the wake propagation and characteristics of a multi-rotor UAV in forward flight using qualitative smoke visualization and quantitative particle image velocimetry (PIV) [6]. Results revealed that as the advance ratio increases, achieved

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by either reducing rotor speeds or increasing flight speeds, the wake's propagation below the UAV is reduced. At the same time, the flow above the UAV increasingly resembles the freestream flow. This reduction in proximity effects at higher advance ratios suggests that placing in-situ sensors closer to the UAV can improve data accuracy by minimizing wake interference. The findings provide valuable guidance for sensor placement and system design, ensuring more reliable performance and safer operations. The study underscores the importance of accurately modelling wake effects to enhance the utility of multi-rotor UAVs in various applications.

Zhou *et al*. conducted an experimental investigation into rotor-to-rotor interactions on small UAVs, revealing significant insights into aerodynamic and aeroacoustics performance [22]. Thrust coefficients remained relatively stable across different rotor separations. Still, thrust fluctuations increased substantially as the separation distance decreased, with a 250% increase observed for the twin-rotor configuration at the closest distance. Detailed PIV measurements exposed complex flow interactions that contributed to these fluctuations. Additionally, noise levels rose with reduced separation distances, with a notable 3 dB increase observed when the separation distance was minimized. These effects were linked to both tonal and broadband noise enhancements. The study's findings, including detailed quantitative data on thrust, noise, and flow characteristics, offer a valuable understanding of rotor interactions and their implications for UAV design, aiming to optimize performance and reduce noise in commercial applications.

Zhu *et al*.'s research provides an in-depth analysis of propeller dynamics specifically tailored for multirotor UAVs [23]. Recognizing the pivotal role of propeller design in UAV efficiency, the study addresses a gap in existing research by examining the impact of propeller parameters like diameter, pitch, and rotational speed on aerodynamic performance. Utilizing blade element momentum theory (BEMT), the authors construct a model that divides the propeller blade into infinitesimal elements to analyse aerodynamic forces in detail. The study's selection of the NACA 0012 aerofoil for validation purposes ensures consistency and allows for precise calculation of thrust and torque coefficients, providing a solid theoretical foundation.

The study's experimental phase bolsters the theoretical findings with a well-constructed platform testing a range of propellers manufactured by a single company, APC. The results clearly correlate increased thrust and torque with higher rotational speeds, larger diameters, and greater pitch angles, providing actionable insights for UAV propeller selection and propulsion system optimization. The authors also propose improvements to enhance future experiments, suggesting higher-accuracy sensors and wind tunnel testing to refine data accuracy and explore variable-pitch propellers. Zhu *et al*.'s study fills a crucial gap in UAV design literature, offering a foundational performance database for propeller selection and optimization. Their work is a valuable resource for advancing UAV propulsion efficiency and lays the groundwork for further advancements. The summary of the experimental works can be found in Table 2.

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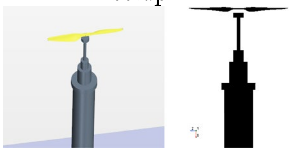
Table 2: Summary of the experimental works

<table>
<tr><th>Ref No</th><th>Authors</th><th>Specification</th><th>Objectives</th><th>Setup</th><th>Results</th><th>Future Works Suggestion</th></tr>
<tr>
<td>[14]</td>
<td>Carreño et al. (2022)</td>
<td>• Combined experiment and CFD
• Re = 24099, 61539, 186670
• Pressure (Pa) = 30900, 58000, 98450
• Temp. (°C) = 40.05, 19.91, -40.85
• RPM = 3293, 3979, 4683
• Testing quadrotor and isolated rotor test</td>
<td>• Difference between the thrust coefficient obtained from experiment and numerical simulation.
• This study compares the result of the thrust coefficient obtained between these two methods to verify the reliability of the simulation.</td>
<td>
Quad-rotor testing setup

Isolated rotor testing setup

Numerical setup.</td>
<td>• At a low transitional regime, the simulation results started to deviate from the experimental result.
• At a high transitional regime, the results satisfy the experimental results and perform correctly within 60000<Re<200000.
<table>
<tr><th>Re</th><th>Thrust CFD/Exp %</th></tr>
<tr><td>24099</td><td>5.22</td></tr>
<tr><td>61539</td><td>-0.96</td></tr>
<tr><td>186670</td><td>-1.86</td></tr>
</table>
• Validated Moving Reference Frame (MRF) approach as reliable.</td>
<td>• Tuning the existing model to improve performance predictions.
• Define a validity range for the laminar model.</td>
</tr>
</table>

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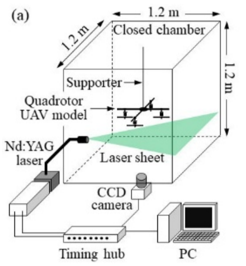
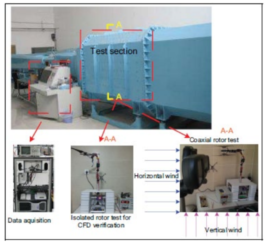
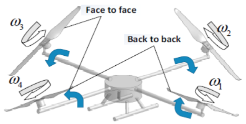
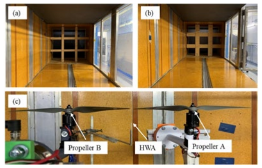
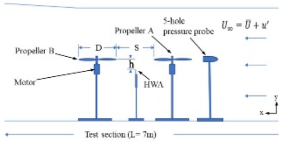
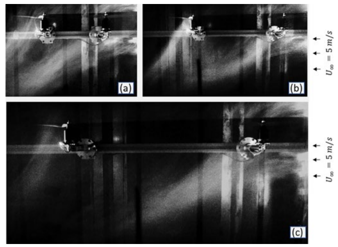
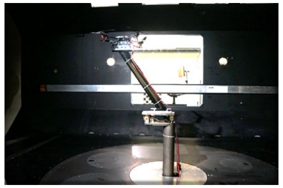
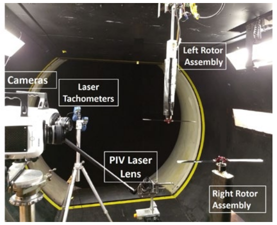
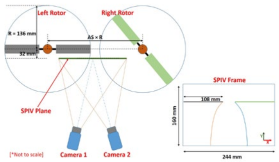
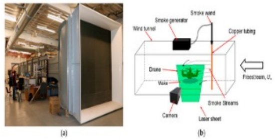
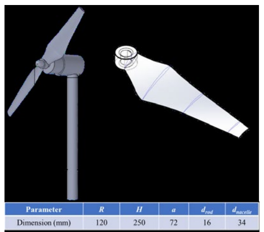
Ref No	Authors	Specification	Objectives	Setup	Results	Future Works Suggestion
[16]	Lee *et al.* (2021)	• Re = 34000-54000 • Testing in a cube chamber of 1.2m x 1.2m x 1.2m • X-shape frame • Horizontal planes measure the wake velocity field, z/ and R_r = -.0.4, -1.2, -2.0, -2.8, -3.6	• The wake velocity field. • Effect of rotor-rotor interaction to establish modified Landgrebe's model. • Thrust loss caused by the rotor-rotor interaction from the standpoint of the momentum theory	 Schematic of the setup	• The modified Landgrebe's model can predict accurately the asymmetric development of the wake about the rotor axis even under extremely strong mutual rotor interaction.	• The modified Landgrebe model's limitation lies in its prediction being restricted to time-averaged wake geometry • The inward shift of the tip vortex reduces the local effective angle of attack by increasing induced axial velocity, contributing to thrust loss
[17]	Lei and Lin (2019)	• Combined experiment and CFD • Wind tunnel testing • Coaxial rotor spacing 0.39R • Horizontal and vertical wind direction • Wind speed = 0, 2.5, 4 m/s	• Capture interference of flow field using streamline and velocity vector • Compare simulation results with experiment	 Wind tunnel test	• Vertical wind has a stronger impact than horizontal wind, reducing thrust by ~0.5N and increasing power by ~2% at higher RPM. Coaxial rotors resist horizontal wind well, improving performance as wind speed increases	• The study only considers a single coaxial rotor pair, while practical UAV designs often use multiple rotor pairs • More experimental validation, such as Particle Image Velocimetry

Ref No	Authors	Specification	Objectives	Setup	Results	Future Works Suggestion
		• RPM = 1500 – 2400 • Sliding mesh		 Test setup	• Rotor aerodynamics deteriorate as vortices deform or shift. Blade tip vortices are more vulnerable to horizontal wind than vertical wind	(PIV), is needed to confirm CFD predictions. • The analysis did not explore the transient effects, vortex evolution, and unsteady interactions under wind disturbances • The study did not explore varying wind intensities
[18]	Lei and Wang (2019)	• Combined experiment and CFD • Diameter rotor = 400mm • Chord length rotor = 35mm • Re = 110000 • Rotor spacing in CFD = 1d – 2d • Tilt angle = 0° - 50° • RPM = 2200 • MRF	• Aerodynamic modelling of non-planar quadrotor UAV	 Schematic diagram of the non-planar quadrotor structure	Non-planar quadrotor thrust is 5–6% higher than an isolated rotor due to increased induced velocity and outflow from the tilt angle Thrust stabilizes when rotor spacing exceeds 1.4d The non-planar quadrotor has lower power loading than isolated rotors, improving performance over traditional planar rotors Larger tilt angles and smaller rotor spacing enhance aerodynamic performance by strengthening tip vortices,	• Conduct transient wake analysis and flow visualization experiments • Optimize rotor spacing and tilt angle for maximum efficiency • Investigate aerodynamic effects under varying flight conditions and wind disturbances • Compare with other multi-rotor

Ref No	Authors	Specification	Objectives	Setup	Results	Future Works Suggestion
					which is beneficial for multi-rotor optimization	configurations for a broader design perspective • Analyse stability and control impacts for practical UAV implementation
[19]	Oo *et al.* (2017)	• Wind tunnel testing on single and multi-rotor configuration • Turbulence intensity up to 15% • Wind velocity at 5 m/s • Passive grids blockage = 29%, 49% • RPM between 1635 to 5450	• Analyze turbulence impact • Assess wake interactions • Compare performance at different RPMs • Force and torque measurement	 Test setup  Schematic diagram of test setup	 Flow visualization of the propeller wake at 4400RPM with 5m/s free stream velocity • Placing additional rotors or components between 0.5D and 1D is not ideal due to high turbulence and velocity fluctuations • Close rotor spacing (0.02D) should be avoided to minimize performance losses	• Investigate higher wind speeds and gusty conditions • Conduct transient wake analysis to capture unsteady aerodynamic effects • Explore the effect of varying RPMs in multi-rotor configurations • Compare different multi-rotor configurations • Analyse power efficiency under different wake interaction conditions • Study the impact on UAV stability and control

Ref No	Authors	Specification	Objectives	Setup	Results	Future Works Suggestion
					due to intense wake interactions	performance under turbulence
[20]	Schiano *et al.* (2014)	• Wind tunnel testing • Wind speed = 9.6m/s, 12.9 • Pitch angle = -10°, 0°, 10°, 20°, 30°	• Correcting wind effects on a quadrotor UAV without using wind sensors	 Test setup in the wind tunnel	• Wind speed and pitch angles affect the thrust vector, requiring further refinement in modelling. • LQR/LQRI controllers were implemented for position control, effectively rejecting constant disturbances.	• Validation through real flight tests • Wind tunnel experiments with a single motor-propeller setup • Identification of a full aerodynamic model • Analysis of lateral inflow effects when propellers act as wings
[21]	Shukla *et al.* (2018)	• Wind tunnel testing • Rotor radius = 0.136m • Chord length = 0.019m • Re = 40000, 80000 • Axis shift = 2.1, 2.2, 2.3, 2.4, 2.5	• Aerodynamic interactions between side-by-side rotors in in-plane multirotor UAVs at various rotor separations and Reynolds numbers	 Test setup 	• Strong wake interactions at low rotor spacing and low Reynolds number • Close rotor proximity reduces efficiency	• Further experimental validation of the blade–vortex interaction hypothesis • Tests at different flight conditions • Analysis of dynamic (unsteady) wake effects

Ref No	Authors	Specification	Objectives	Setup	Results	Future Works Suggestion
				SPIV measurement plane location		
[6]	Throneberry *et al.* (2022)	• Wind tunnel testing with a cross-section of 1.2m x 1.2m • Re = 30000, 40000, 50000, 60000, 70000, 80000 • Advance ratio, J = 0.04 – 0.54 • Wind velocity = 1 – 5m/s	• Investigate the wake propagation and flow characteristics of a multi-rotor UAV in forward flight • Wake strength and structure	 Test setup	• Higher J reduces wake propagation below the UAV • At J ≥ 0.2, disturbance below UAV stabilizes at 2.5R and above 3R at J ≥ 0.35 • At J ≥ 0.24, the wake below the UAV reaches a stable pattern • Vertical velocity component changes with advance ratio variations but reduces as J increases • Horizontal velocity gradients remain small for J ≥ 0.09	• More dynamic flight conditions should be tested • Validation in real-flight conditions shall be done • Wake interaction with the payload shall be considered • Higher Re studies for large UAVs
[22]	Zhou *et al.* (2017)	• Rotor diameter = 240mm • Rotor distance = 0.05D, 0.1D, 0.2D, 1.0D	• Investigate the impact of rotor-rotor interactions on aerodynamic performance • Analyse thrust fluctuation flow field	 Schematic of the UAV rotor model	• The thrust coefficient varies within 2% with the distance, while thrust fluctuation (standard deviation) increased significantly when the distance decreased	• Testing should be done with various RPM • Testing should be done with various Re • Future work should investigate how forward

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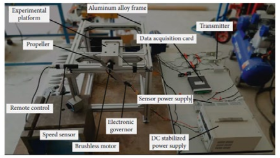
Ref No	Authors	Specification	Objectives	Setup	Results	Future Works Suggestion
		• Single-rotor and twin-rotor setup • RPM = 4860 (fix)	characteristics of a twin-rotor UAV at different rotor spacing		• At L = 0.05D, thrust fluctuation for twin-rotor increased 250% compared to the single-rotor case	flight affects thrust fluctuations and wake evolution at different advanced ratios
[23]	Zhu *et al.* (2021)	• Propeller type = APC804, APC 9045, APC 9060, APC 9075, APC 1145, and APC 1245 • RPM = 6000 - 11000	• Analyzing the aerodynamic performance of UAV propellers using Blade Element Momentum Theory (BEMT)	 Test setup	• Both thrust and torque increase with rotational speed, diameter, and pitch. • The thrust coefficient (C_{t0}) increases with speed and pitch but not with diameter.	• The current tests are conducted in static conditions (hovering), but UAVs operate in forward flight where advance ratio (J) influences performance.

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2.2 CFD Simulation

Aside from experiments, several researchers have explored UAV aerodynamics through numerical simulations. In 2020, Lei and Wang did their study on the effect of rotor spacing on UAV aerodynamics [24]. Their research demonstrated that adjusting rotor spacing in a quadrotor significantly enhances aerodynamic performance. Figure 4 shows the velocity distribution on different rotor spacing from the simulation. Figure 4(a) shows the velocity distribution for rotor spacing, L/R = 2.2, in which L is rotor spacing, and R is the radius of the rotor disc, while Figures 4(b) and 4(c) shows the velocity distribution for L/R = 3.2 and L/R = 3.6 respectively.

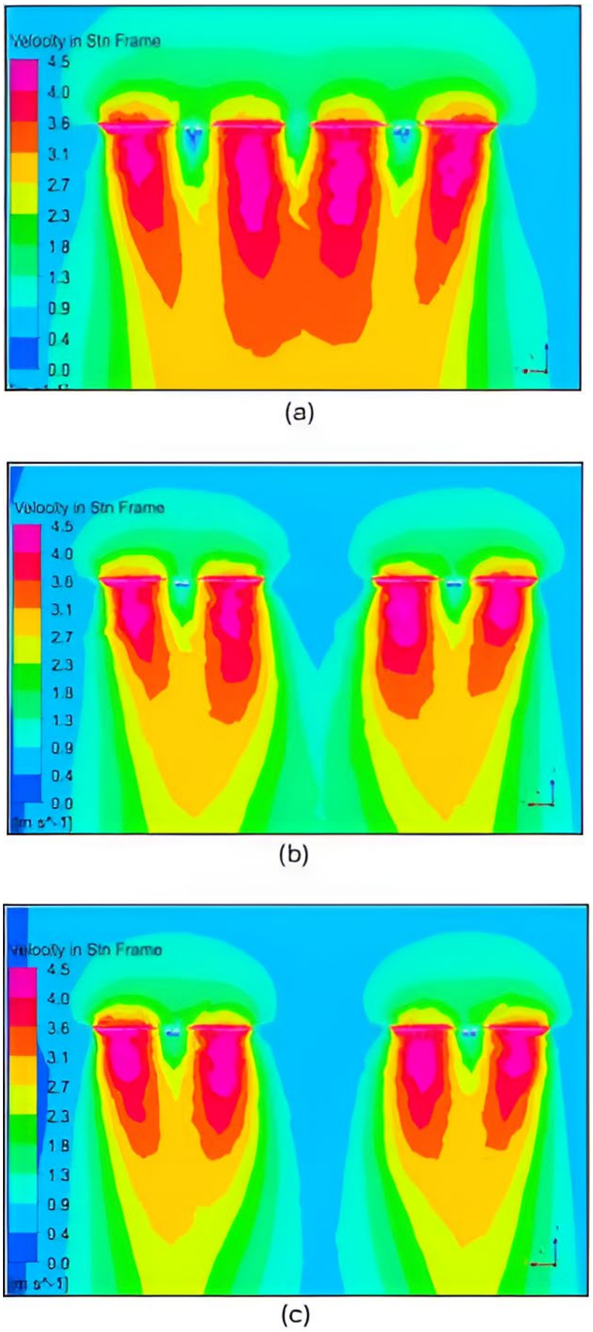

Figure 4: Velocity distribution on different rotor spacing [24]

Both experimental and numerical analyses revealed that moderate rotor spacing, specifically at L/R = 3.6, optimizes thrust and reduces power consumption, thereby

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improving overall hover efficiency. Smaller spacings lead to detrimental aerodynamic interference and increased power usage, while excessive spacing results in unnecessary power consumption. Hence, an optimal spacing of L/R = 3.6 is recommended for achieving the best aerodynamic performance, evidenced by increased thrust and an intact tip vortex structure.

Lei and Wang extended their study on the aerodynamic performance of quadrotor MAV with consideration of horizontal wind [25]. They examined the aerodynamic performance of a micro quadrotor in the presence of horizontal wind disturbances through experiments and simulations. The study reveals that horizontal wind affects the quadrotor's thrust and power consumption by increasing the pressure difference across the rotor blades, which enhances thrust and leads to higher power consumption, especially at wind speeds above 2.5 m/s. Figure 5 illustrates the simulation of the vorticity structure with horizontal wind. Figure 5(a) shows the vorticity when the wind is set at 0 m/s. Figures 5(b) and 5(c) show the vorticity structure when the horizontal wind is 2.5 m/s and 4.0 m/s, respectively.

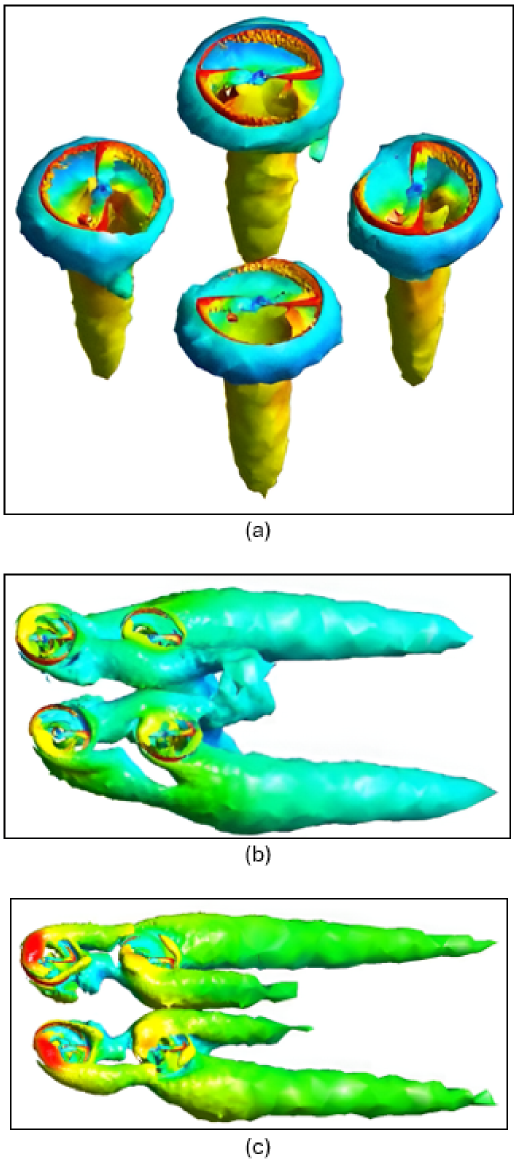

Figure 5: Vorticity structure on quadrotor UAV with horizontal wind [25]

The CFD simulations and wind tunnel tests show that wind-induced complexities, such as rotor wake distortion and downwash flow interference, influence the quadrotor’s

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aerodynamic behaviour. Notably, the quadrotor demonstrates better aerodynamic performance and wind resistance at 2.5 m/s, significantly improving thrust-to-power ratio compared to calm conditions. This research contributes valuable insights for enhancing quadrotor operation under windy conditions and will inform future studies on quadrotor dynamics and control.

Alvarez *et al*. demonstrated the effectiveness of the viscous vortex particle method (VPM) in modelling the complex aerodynamic interactions of multirotor configurations for urban air mobility [26]. Their VPM-based rotor model, validated across various flight conditions and Reynolds numbers, successfully captured key phenomena such as thrust reduction and unsteady loading caused by rotor-to-rotor interactions. Detailed convergence studies confirmed the model's numerical stability and efficiency. The close agreement between simulations and experimental data, including wake dynamics and thrust measurements, underscores the model's potential and paves the way for integrating aeroacoustics predictions into future designs, enhancing the conceptual development of multirotor aircraft.

Yeong and Dol performed a detailed CFD analysis to optimise the propeller design of the WL V303 Seeker, a quadrotor micro aerial vehicle, to improve aerodynamic performance [27]. The study employed the Shear Stress Transport (SST) k-ω turbulence model to evaluate six propeller designs' capacity to support a 400-gram payload under hovering and cruising conditions. The Sokolov aerofoil, recognised for its superior lift-to-drag ratio, was selected as the most promising candidate and incorporated into the propeller design. The Sokolov propeller generated 0.76 Newtons greater thrust than the benchmark propeller at 7750 revolutions per minute, satisfying the Momentum Theory criterion of 5.4 Newtons per rotor; however, it demonstrated increased drag, resulting in a diminished lift-to-drag ratio. A notable advancement was accomplished by changing the rotational direction of the rotors to counterclockwise instead of clockwise without structural alterations, leading to a 39.58% enhancement in the lift-to-drag ratio of the quadrotor. This finding highlights the necessity of a comprehensive approach to propeller design, integrating thrust generation with drag reduction and accounting for system-level interactions. The study emphasises rotor configuration adjustments as a cost-effective optimisation strategy and recommends that subsequent research investigate additional variables, including the drone's pitching angle and experimental validation, to further improve micro aerial vehicle performance.

Jeon *et al*. introduced a novel aerodynamic model for quadrotors that incorporates the effects of wind, using blade element momentum theory combined with classical quadrotor dynamics [28]. Unlike traditional models, this approach directly accounts for external wind and the drag forces and torques generated by the quadrotor's movement, arising from translational and rotational motions. Validated through wind tunnel experiments and theoretical analysis, this comprehensive model demonstrated that quadrotors controlled by linear-quadratic regulators could lose stability when wind amplitude exceeds a certain threshold. The experimental results aligned well with theoretical predictions, and future work will focus on developing a control strategy based on this new model.

Aside from that, Ko and Lee effectively highlighted the complex relationships between performance and wake dynamics in multi-rotor configurations, focusing on induced circulation (IC) as a key factor for understanding wake interactions [29]. Their parametric studies on cross-type and plus-type quadrotors revealed how different rotor interactions affect aerodynamic and aeroacoustics characteristics. It was found that wake-induced and motion-induced circulations significantly impact rotor performance, though their effects diminish with increasing advance ratio and incidence angle. By classifying total circulation into rotor-induced, wake-induced, and motion-induced components, the study provided a framework for analysing wake interactions, essential for developing accurate wake models for multi-rotor systems. These models can enhance aerodynamic and

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aeroacoustics performance prediction, contributing to the design of quieter and more efficient UAVs and Urban Air Mobility (UAM) vehicles.

A study by Lee and Lee demonstrated the negative effects of rotor proximity in small-scale multirotor UAVs on aerodynamic performance and noise levels [30]. Numerical simulations of a quadcopter in hover showed that reduced rotor spacing results in a notable decrease in average thrust and an increase in force fluctuation, as shown in Figures 6 and 7. Figure 6 shows the wake evolution of a multirotor with a distance equal to 0.2 diameter of the rotor. Figure 7 shows the wake evolution when the distance is set to be 1.0 diameter of the rotor. Figures 6(a) and 7(a), 6(b) and 7(b), and 6(c) and 7(c) are illustrated for the revolution of 5 revs, 10 revs and 15 revs respectively. The proximity of rotors alters wake structures, causing stronger wake-to-wake interactions and asymmetric wake formations. Additionally, the interaction between rotors increases unsteady loading, which raises the sound pressure level, especially in the normal direction of the rotor plane.

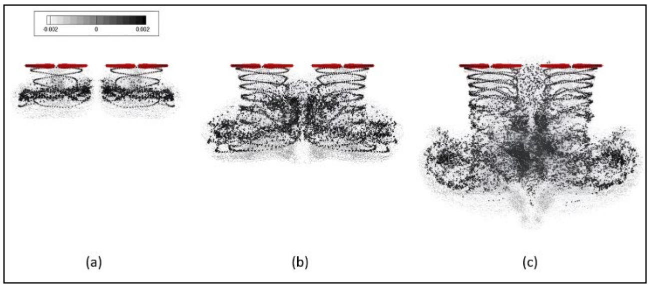

Figure 6: Wake evolution when the distance between rotors is 0.2D [30]

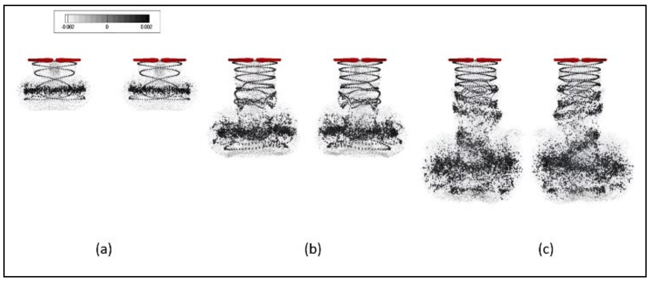

Figure 7: Wake evolution when the distance between rotors is 1.0d [30]

Lopez *et al*. used CFD to simulate the aerodynamic performance of a quadcopter's propeller in hover, employing the Spalart-Allmaras (SA) and k-ω turbulence models [31]. With minimal differences, both models successfully predicted the propeller's wake, thrust, and torque. However, both models overestimated thrust and torque by approximately 18% and 16%, respectively, compared to experimental measurements, likely due to the interaction of the propellers with the fuselage and each other. The key difference between the models was observed in the turbulent viscosity field, with the k-ω model showing significantly higher values than the SA model, especially at higher rotational velocities. These results indicate that while both turbulence models provide similar predictions of aerodynamic performance, further refinement, and validation are needed for more accurate thrust and torque measurements.

Luo *et al*. highlighted that traditional aerodynamic models for quadrotors, which typically focus on single-rotor dynamics and overlook rotor wake interactions, lead to suboptimal performance during high-speed flight [32]. To address this, their study introduced a new mathematical model incorporating rotor wake mutual interference, enhancing the accuracy of attitude control and trajectory tracking. This model demonstrated consistency with integral and isolated rotor simulations, validated through CFD analyses. Adopting a mutual-interference approach akin to fixed-wing formation flight, the proposed

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model effectively captured the complex wake interactions in forward flight and offered a more reliable framework for advanced flight control.

Diaz and Yoon conducted high-fidelity CFD simulations on various multi-rotor UAVs to explore their aerodynamic characteristics and improve design efficiency [33]. Their study encompassed the DJI Phantom 3, SUI Endurance, and Elytron 4S UAVs, using advanced simulation techniques, including overset grids, high-order schemes, and hybrid turbulence models. Results indicated that adding components such as landing gear and cameras to the DJI Phantom 3 could affect rotor interactions and thrust, necessitating careful placement to minimize adverse effects. The SUI Endurance's hybrid configuration significantly enhanced forward thrust by 63% compared to its original design. The Elytron 4S UAV was also examined in helicopter and aeroplane modes, contributing to a deeper understanding of multi-rotor vehicle flows. NASA's supercomputers enabled efficient processing of complex simulations, which are crucial for developing quieter, safer, and more effective UAVs and UAM vehicles [33].

Sattarov *et al*. suggested improving UAV aerodynamic performance using leading-edge vortex generators [34]. Their simulation study demonstrated that integrating new vortex generators on the UAV’s fore plane significantly enhanced performance, achieving a high lift-to-drag ratio of 19.8 and improving flight range, stability, autonomy, and resistance to flow separation and wind gusts compared to similar UAVs like the Elbit Hermes 450, AAI RQ-7 Shadow, and M-7B5. Figure 8 shows the airflow simulated around the leading-edge vortex generator (LEVG) installed on the foreplane. Integrating vortex generators effectively addressed issues associated with multiple lifting surfaces and strong vertical wind gusts. Further research is planned to explore the benefits of these vortex generators fully and their potential to reduce induced drag and enhance aerodynamic qualities.

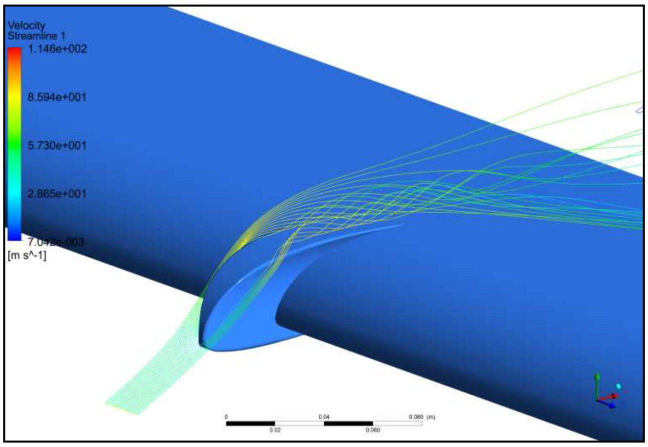

Figure 8: Flow around the leading-edge vortex generator [34]

The research identifies high-altitude challenges, including low air pressure, cold temperatures, and limited oxygen, notably decreasing UAV endurance and payload capabilities. Focusing on the UAV power system, comprising battery, motor, and propeller, the authors emphasize the need for optimization, as these components dominate the UAV's weight and significantly impact energy efficiency. Utilizing an actuator disk model grounded in momentum theory, the study explores optimal battery mass requirements to maximize endurance in demanding high-altitude environments.

The study’s methodology combines theoretical analysis with simulation, creating a streamlined approach to UAV design that addresses the inefficiencies of traditional empirical methods. Experimental validation on the Skylark 3 UAV showed promising results, with predicted endurance closely matching actual performance. This reinforces the model's reliability and the practical applicability of the proposed optimization framework.

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Aside from that, Pollet *et al*. provide a pioneering look into optimizing multirotor drone performance beyond traditional hovering scenarios, specifically addressing forward flight, a critical yet underexplored aspect of UAV design [35]. Recognizing the limitations of current design tools that largely focus on hover efficiency, the authors introduce lightweight, physics-based models tailored for forward flight, capturing the complex aerodynamic forces involved. The development of an optimization code, validated with the Parrot ANAFI USA, enables rapid design iterations, highlighting the research's applicability to real-world UAV development.

Vlachos *et al*. conducted a thorough and methodologically rigorous investigation into optimising propeller performance for micro quadrotor UAVs, addressing the increasing demand for efficient UAVs in critical operations such as search and rescue [36]. The authors achieve a nuanced understanding of propeller aerodynamics under high rotational speeds by applying CFD with both the Multiple Rotating Frame (MRF) and Sliding Mesh (SM) methods. The study's incorporation of error quantification through Richardson extrapolation and Grid Convergence Index (GCI) analysis further strengthens the reliability of its findings.

A notable aspect of the research is its validation of CFD results against manufacturer data, demonstrating the accuracy of the SM method across different rotational speeds despite its greater computational demands. Additionally, the authors' investigation into turbulence models within the MRF framework finds that the SST k-ω and Spalart-Allmaras models closely align with experimental data, providing useful guidance for future UAV aerodynamic modelling. Conducted within the MIDRES project and aimed at developing UAVs capable of indoor navigation without GPS, this research has clear, practical applications, underscoring its relevance. The study offers valuable insights into UAV propeller performance through a well-validated and multifaceted CFD approach. By bridging theoretical analysis with practical applications, it contributes significantly to UAV design optimization and is a foundation for future advancements in micro-UAV technology.

A key focus of the study is the aerodynamic performance of propellers, with the authors analysing thrust and power coefficients to optimize propulsion efficiency in axial flight. This analysis is supported by surrogate modelling, allowing for a precise assessment of propeller dynamics in forward flight. Moreover, the authors emphasize the effect of frame aerodynamics on take-off weight and endurance, showing that a streamlined airframe can significantly reduce drag and overall mass, leading to improved performance. Pollet *et al*.'s work advances multirotor UAV design by offering practical, validated tools and insights, making it a substantial contribution to the field and a valuable resource for engineers aiming to enhance UAV efficiency in diverse applications.

Recent research into UAV aerodynamics has provided valuable insights into improving their performance through experimental and simulation-based approaches. Alvarez *et al*. demonstrated the effectiveness of the viscous vortex particle method (VPM) in modelling rotor-on-rotor interactions for multirotor configurations, capturing key phenomena like thrust reduction and unsteady loading [26]. Yeong and Dol optimized propeller designs for quadrotors using the SST k-ω turbulence model, achieving a 39.58% improvement in lift-to-drag ratio through rotor configuration adjustments [27]. Jeon *et al*. introduced a comprehensive aerodynamic model incorporating wind effects, revealing stability thresholds under high wind conditions [28]. Similarly, Ko and Lee analysed wake dynamics in cross-type and plus-type quadrotors, identifying induced circulation as a critical factor for rotor performance and aeroacoustics [29]. Lee and Lee highlighted how rotor proximity negatively impacts thrust and increases noise levels, emphasizing the importance of spacing in rotor design [30].

Other studies explored innovative methods to optimize UAV designs. Lopez *et al*. compared turbulence models to simulate propeller performance [31], while Luo *et al*. developed a mathematical model incorporating rotor wake interference, enhancing trajectory tracking in high-speed flight [32]. Diaz and Yoon used advanced CFD techniques

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to improve UAV configurations, achieving significant thrust enhancements in hybrid designs [33].

Sattarov *et al*. demonstrated the effectiveness of vortex generators in increasing lift-to-drag ratios improving stability and resistance to flow disturbances [34]. Finally, Pollet *et al*. introduced physics-based forward-flight models, emphasizing the importance of frame aerodynamics in reducing drag and improving endurance [35].

These studies collectively advance UAV aerodynamics by addressing critical challenges such as wake interactions, rotor spacing, and aerodynamic efficiency. Integrating experimental validation with numerical simulations provides a foundation for future innovations in UAV design, focusing on improving endurance, stability, and energy efficiency. This body of research underscores the importance of rotor dynamics, wake control, and system-level optimization in the evolving field of UAV technology.

3.0 RESEARCH APPROACHES ON THE TECHNIQUES FOR MITIGATING WAKE EFFECTS

The study attempts have concentrated on acquiring a more thorough comprehension of wake behaviour, especially because of its significant impact on aerodynamic drag in UAVs. The wake, produced by the complex airflow interactions surrounding the UAV, is recognized as a principal element hindering aerodynamic performance. Through meticulous wake analysis, researchers may identify patterns and attributes that contribute to heightened drag, subsequently influencing UAVs' overall performance and energy efficiency.

A deeper understanding of wake behaviour is crucial for developing strategies to minimize these negative effects and improve aerodynamic performance across various flight conditions. However, addressing wake-induced drag presents significant challenges. The complexity of turbulent flow patterns, coupled with the unique designs of multi-rotor UAVs, makes it difficult to accurately model and predict wake behaviour. In experimental studies, capturing the fine-scale details of wake turbulence requires expensive equipment, such as high-resolution sensors and wind tunnels, further complicating the research process.

Moreover, simulation-based approaches, though cost-effective, come with their limitations. High-fidelity computational fluid dynamics (CFD) models are computationally expensive and time-consuming [36, 37], particularly when simulating realistic flight scenarios involving multi-rotor interactions. Despite these challenges, advancements in both experimental and numerical techniques continue to push the boundaries of what can be achieved in understanding and mitigating wake effects, promising more efficient UAV designs in the future.

3.1 Vortex generators

To address the drag caused by wake, several improvements must be considered. One of the most effective strategies is vortex generators, which can help control the airflow over the UAV's surfaces. Vortex generators work by creating small, controlled vortices that energize the boundary layer, preventing flow separation and reducing the strength and extent of the wake [38]. Integrating these devices into UAV designs makes it possible to significantly reduce drag, leading to better fuel efficiency, longer flight times, and improved maneuverability. This approach enhances the UAV's performance and contributes to more sustainable and efficient operations, making it a key recommendation for future UAV development.

Gibertini *et al*. have investigated whether applying vortex generators is useful in reducing drag [39]. The study confirmed that vortex generators (VGs) effectively reduce drag on a heavy-class helicopter fuselage by delaying flow separation. Preliminary CFD computations predicted this drag reduction, which was later validated through extensive

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wind tunnel tests. The optimal configuration involved eight pairs of delta-scale counter-rotating VGs positioned in the lower backdoor area of the fuselage. These VGs successfully reattached the flow around the back ramp, preventing flow separation, as evidenced by PIV measurements. The VGs promoted static pressure recovery in the backdoor area and mitigated the adverse pressure gradient, thus confirming their potential to reduce pressure drag. This study demonstrated the effectiveness of VGs in delaying flow separation and validated the accuracy of CFD predictions in such aerodynamic studies.

There is also research done by applying the vortex generators on an aerofoil to delay the flow separation, as has been done by Nahar *et al*. and Shan *et al*. [40, 41]. The VGs are applied on an aerofoil to ensure that the flow separation is delayed, especially at the suction side of the aerofoil, to avoid stalling at a lower angle of attack. Figure 9 illustrates the flow condition before and after the VGs are applied to the aerofoil, taken from the Nahar *et al*. paper.

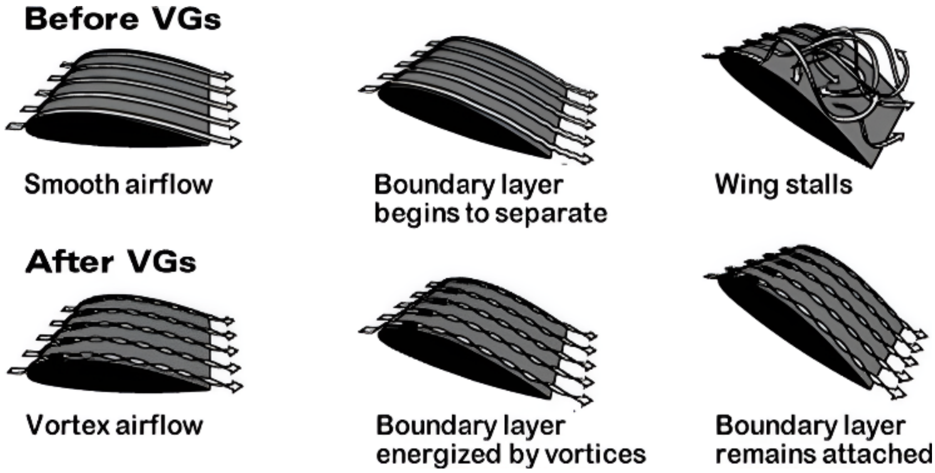

Figure 9: Flow condition on aerofoil before and after applying vortex generators [40]

An investigation was conducted to examine the impact of aero-shaped vortex generators (AsVGs) and conventional vortex generators (CVGs) on the aerodynamic performance of a NACA 4415 aerofoil at Reynolds numbers of 0.8×10^5 and 1.4×10^5, specifically assessing their effectiveness in improving lift and decreasing drag [42]. CVGs exhibited enhanced capabilities in postponing the stall angle, whereas AsVGs were more effective in minimising drag and enhancing the lift-to-drag ratio. The aero-shaped configuration AeM5 at x/c = 0.1 demonstrated a significant 94.56% enhancement in lift-to-drag ratio relative to the top-performing CVG configuration, TrM5. This finding highlights the potential of AsVGs as an effective alternative to CVGs, particularly in applications that prioritise drag reduction and aerodynamic efficiency.

The research demonstrated that the positioning of vortex generators significantly influences their effectiveness. CVGs and AsVGs demonstrated optimal effectiveness when positioned near the leading edge of the aerofoil (x/c = 0.1 and 0.2), where they interfered with the laminar separation bubble (LSB) and established attached flow regions. This disruption significantly enhanced the lift characteristics of AsVGs in the pre-stall region, surpassing CVGs in lift generation.

The research examined the flow mechanisms influenced by these devices, emphasizing the development of distinct flow regions, including primary, secondary, and attached zones near the leading edge. The flow alterations illustrate the ability of vortex generators, particularly AsVGs, to manipulate airflow and achieve improved aerodynamic performance.

Another study, focusing on the tail car, focuses on the effects of different vortex generator designs on reducing aerodynamic drag in the ICE2 high-speed train [42]. Using the SST k-ω turbulence model, the research compares triangle, trapezoid, and micro-ramp

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vortex generators. Results show that wider vortex generators significantly alter the flow field by modifying surface pressure distribution and reducing wake vorticity. Among the designs, the micro-ramp vortex generator achieved the highest drag reduction of 15.4%, attributed to its flow-guiding structure. The study highlights the importance of vortex generator geometry and positioning in mitigating flow separation and enhancing aerodynamic efficiency in high-speed trains.

In summary, vortex generators play their role by exciting small vortices that energize the boundary layer, delaying flow separation and reducing drag. Research has demonstrated their effectiveness in various applications, including UAVs, helicopters, aerofoils, and high-speed trains. Vortex generators improve aerodynamic efficiency by controlling airflow, mitigating wake effects, and enhancing lift-to-drag ratios. Their performance depends on design, geometry, and positioning, with studies showing that configurations like aero-shaped vortex generators and micro-ramp designs are particularly effective in reducing drag. Applying vortex generators in UAV designs could significantly reduce drag, improving fuel efficiency, flight duration, and overall performance.

3.2 Dimples

In addition to the conventional use of vortex generators, an innovative approach to enhancing the aerodynamic performance of UAVs involves designing their surfaces with dimples akin to those found on a golf ball. This concept is inspired by the fact that golf balls, with their strategically placed dimples, achieve significantly better trajectories when hit, largely due to how these dimples manipulate the airflow around the ball. The dimples create tiny vortices that energize the boundary layer of air, functioning as surface roughness that promotes a turbulent boundary layer, effectively delaying flow separation, diminishing the wake, and reducing form drag [43]. This mechanism is similar to the function of vortex generators, which are traditionally used to manage airflow over surfaces.

The effectiveness of dimples in delaying flow separation has been well-documented, as shown in the research by Grover *et al*. [44]. The study confirmed that the dimples on a golf ball excite the flow, injecting energy into the boundary layer and thus pushing the point of flow separation further downstream. This delayed separation is critical because it reduces pressure drag, which is a significant component of total drag for bluff bodies like UAVs.

Building on this concept, using a modified CFD FLUENT code, a numerical study was undertaken to compare the airflow over a smooth generic bluff body against that over a dimpled one. The research aimed to explore the potential of dimples in reducing drag on UAV surfaces. By focusing on dimples with specific dimensions, this study employed the k-ε turbulence model, which is widely respected for its reliability in simulating turbulent flows. Moreover, the study assumed a non-equilibrium state at the wall interface to better capture the complex interactions near the surface. The simulation results were promising, showing that applying elliptical-profile dimples led to a 0.3% reduction in drag. This reduction, while modest, is significant in aerodynamic terms, especially considering the potential for further optimization.

The study also highlighted that flow separation occurs earlier on a smooth golf ball surface than on a dimpled surface, as illustrated in Figure 10. This early separation on smooth surfaces results in higher pressure drag, which the dimples effectively mitigates. This finding supports the results of the numerical study on bluff bodies, suggesting that similar benefits could be realized on UAV surfaces.

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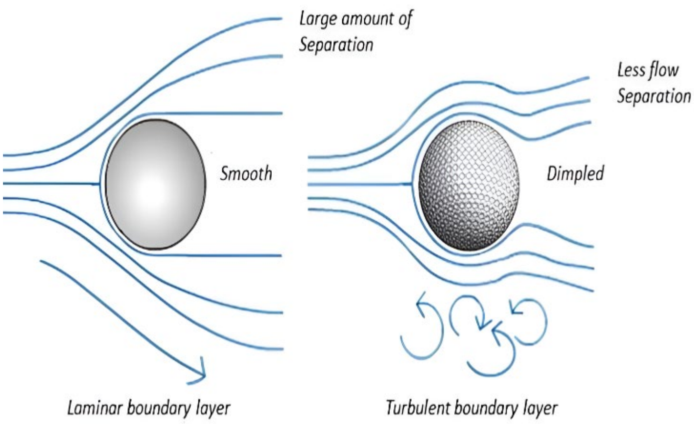

Figure 10: Flow separation on smooth surface ball and dimpled surface golf ball [44]

Many other studies explored the ability of dimples to delay flow separation. İlter *et al*. studied the potential of dimpled surfaces to reduce turbulent skin friction, specifically within fully turbulent channel flows [45]. Utilizing a Fully Turbulent Flow Channel facility and a Particle Image Velocimetry (PIV) system, the study examined various dimple configurations, including different depth-to-diameter ratios, diameters, and orientations. The results demonstrated that circular dimple geometries with low depth-to-diameter ratios achieved substantial drag reduction rates of up to 27% as the Reynolds number increased, underscoring their potential for improving the hydrodynamic performance of ship hulls and other marine surfaces.

The study's findings emphasize the critical role of dimple geometry in optimizing drag reduction performance. While certain configurations proved highly effective, others were notably inefficient, highlighting the necessity of precise optimization. The experimental results showed strong compatibility with previous numerical studies conducted by the authors, reinforcing the reliability of the data and the feasibility of dimpled surfaces as a passive drag-reduction technique. This agreement also validates experimental and computational approaches as complementary tools for capturing the underlying flow physics and drag reduction mechanisms.

A comprehensive numerical analysis investigated the aerodynamic performance of a NACA 0012 aerofoil with dimpled surfaces, focusing on optimizing dimple characteristics such as shape, size, and position along the chord length [46]. Using Ansys Fluent with the SST k−ω turbulence model at a chord-based Reynolds number of 6.7×10^4 the study evaluated the influence of dimples on lift-to-drag ratios, boundary layer behavior, and overall aerodynamic performance. Among various configurations, inward dimples with a 2 mm diameter positioned at 47.26% of the chord length from the leading edge were identified as the most effective, achieving a significant lift-to-drag ratio improvement by delaying boundary layer separation and reducing drag. Simulations for nine optimization cases using Minitab revealed an optimized lift-to-drag ratio of 27.08, validated in Ansys Fluent with a comparable ratio of 27.32, underscoring the reliability of the methodology.

Further research by Jenna and Sanjivan extended the investigation to aerofoils, where they examined the impact of dimples on airflow over aerofoil surfaces [47]. As shown in Figure 11(a), their simulations revealed that flow separation on a smooth aerofoil occurs sooner than on one equipped with dimples, which is shown in Figure 11(b). Figure 11(c) shows the velocity contours of the flow around the aerofoil, indicating that by placing dimples further back on the suction side, flow separation could be delayed even longer. This delay is crucial because it maintains laminar flow over a larger portion of the aerofoil, thereby reducing drag and improving lift-to-drag ratios.

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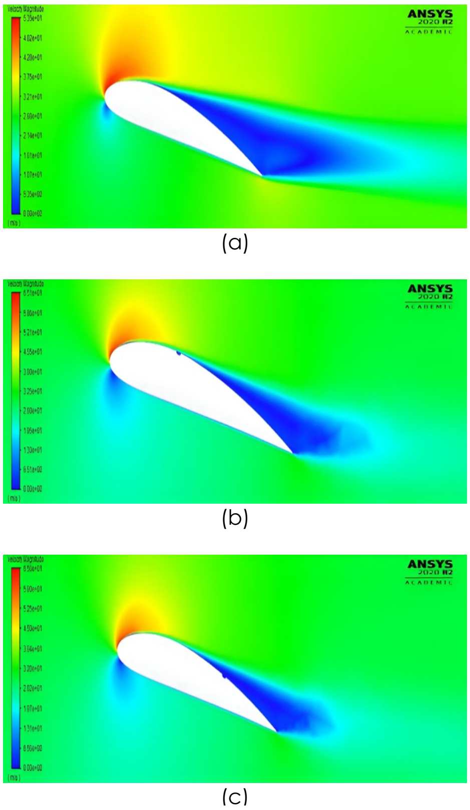

Figure 11: Flow condition on smooth surface aerofoil and dimpled aerofoil [47]

These studies collectively suggest that while the initial results demonstrate the potential of dimples in reducing drag on UAVs, there is still considerable room for optimization. Fine-tuning the geometry, size, and positioning of dimples could lead to even more substantial reductions in drag. This could have significant implications for the design of more aerodynamically efficient UAVs, potentially improving their range, speed, and overall performance.

3.3 Shark Skin Structure

Another structure that might be considered in the design process of a UAV is the shark skin structure. The construction of shark skin is a biomimetic approach designed to enhance the aerodynamics of a body. Limited research has been conducted on the applications of shark skin structure to study the ability to apply this structure to improve the aerodynamics of a body.

Domel *et al*. investigated the shark denticle structure by applying it to the suction area of an aerofoil [48]. This study demonstrates how shark denticles can inspire significant aerodynamic improvements in aerofoils, not only in drag reduction but also in lift generation. The denticle-inspired surfaces achieved a 10% reduction in drag compared to smooth control surfaces, highlighting their effectiveness [48].

In a study investigating biomimetic aerofoil profiles, one profile demonstrated a 16.83% average increase in lift compared to the standard aerofoil, highlighting its potential for improved aerodynamic performance [49]. However, the drag in biomimetic profiles remained higher, with profile P2 showing a 33.9% increase in drag relative to the baseline aerofoil. This indicates that while biomimetic approaches can enhance lift, further optimization is needed to reduce drag.

Bhatia *et al*. explored aerodynamic reduction using sharkskin denticles, focusing on drag reduction and lift improvement on a NACA 0012 aerofoil [50]. Wind tunnel experiments tested denticles in normal and reversed orientations at 16% and 60% chord

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locations. The normal configuration reduced drag by 11.2% and increased lift by 11.3%, while the reversed configuration achieved a 6.5% drag reduction and a 14.7% lift increase. Reversed denticles performed better at low angles of attack (AOA) due to upstream separation bubble formation, whereas normal denticles excelled at higher AOAs, peaking at around 14°. These improvements were attributed to separation bubbles stabilizing pressure distributions, delaying flow separation, and favourable pressure gradients downstream of the denticles. Future research should focus on scaling these designs for applications such as aircraft wings and wind turbine blades.

Further examination was done by integrating sharkskin denticles on a NACA 0012 aerofoil [51]. Using the SST k−ω turbulence model at Mach 0.6, they evaluated the aerodynamic performance across various AOAs. Results showed enhanced lift and reduced drag coefficients, with denticles maintaining attached flow over a larger wing surface. Contour analyses of pressure and turbulence kinetic energy confirmed the denticles' role in delaying flow separation. While computational findings were promising, experimental validation is necessary to refine the designs.

Santos *et al*. investigated mako shark scales as passive flow control mechanisms in turbulent boundary layers [52]. Using water tunnel experiments, scales from two regions, B1 (flank to dorsal fin) and B2 (flank), were tested in the reattachment region of separated flow induced by a rotating cylinder. B2 scales, with their slender shape and 50° bristling capability, reduced turbulent boundary layer separation across Reynolds numbers (Rex of 4.9×10^5, 7.1×10^5, and 8.1×10^5) by impeding reverse flow and collapsing separation bubbles. In contrast, B1 scales, with a lower bristling angle of 30°, enhanced separation under similar conditions, likely due to insufficient flow penetration. This study highlights the effectiveness of B2 scales for larger viscous length scales, emphasizing the importance of scale morphology and bristling capability for flow separation control.

Sharkskin-inspired profiles improve lift by tripping the boundary layer and generating short separation bubbles, particularly at low AOAs, resulting in enhanced lift-to-drag ratios [49]. The spanwise curvature of denticles further generates streamwise vortices, reducing drag and maintaining lift at higher AOAs. In additional research, Bhatia *et al*. noted that denticles reduced drag by 4.3% and achieved a lift-to-drag ratio of 3.6% [53]. These findings underscore the relevance of biomimetic designs for rotorcraft and drone applications while offering insights into denticle morphology's role in shark propulsion.

In conclusion, incorporating shark skin structure into UAV design presents a promising avenue for enhancing aerodynamic performance. As demonstrated in these studies, shark skin structures' reliability in improving aerodynamic efficiency suggests that integrating such nature-inspired designs into UAVs could lead to substantial performance gains. The ability of denticles to optimize airflow, reduce drag, and enhance lift aligns well with the needs of multi-rotor UAVs and rotorcraft, potentially offering both efficiency improvements and enhanced maneuverability. Thus, incorporating shark skin-inspired features into UAV design could be a valuable strategy for advancing aerodynamic performance and achieving more efficient and effective aerial vehicles. Applying such bio-inspired designs represents an exciting frontier in aerodynamic research, blending insights from nature with advanced engineering to push the boundaries of what is possible in UAV design.

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3.4 Ducted Rotor

In addition to the previously described ways, another interesting strategy to enhance the aerodynamics of rotorcraft is the implementation of ducted rotors, which enclose the rotor within an aerodynamic cover or duct.

The idea of ducted rotors is not unusual but has garnered heightened interest owing to its various advantages. Enclosing the rotor within a duct affects various aerodynamic phenomena as the duct streamlines airflow, diminishes tip vortex shedding, and modifies the pressure distribution surrounding the rotor disc. This results in less rotor wake-induced drag and enhanced overall efficiency. Ducted rotors can reduce noise and improve thrust performance, rendering them particularly advantageous for urban air mobility (UAM), military drones, and other sophisticated aerial systems.

The primary mechanism behind drag reduction in ducted rotors lies in the stabilization and redirection of rotor wakes. The duct acts as a physical barrier, preventing the direct interaction of rotor wakes with other components, such as the fuselage or neighbouring rotors. Additionally, the duct geometry can be optimized to mitigate flow separation, thereby reducing the formation of high-drag regions.

A study investigated the aerodynamic performance of a twin-propeller UAV design with ducts around the front and rear propellers, focusing on enhancing efficiency and reliability [54]. This configuration improved safety by enabling operation with a single engine in case of failure and facilitated balanced weight distribution and additional payload capacity. CFD simulations using the Moving Reference Frame (MRF) method were conducted on six duct designs to evaluate their impact on thrust and aerodynamic efficiency. Results showed that the duct improved rear engine performance by 10% and increased overall UAV efficiency by 6% compared to non-ducted configurations. Optimized duct designs provided increased propulsive force at higher speeds, with experimental validation achieving a low error margin of 3%.

Another investigation presented a comparative analysis of ducted and un-ducted rotor configurations using high-fidelity CFD methods, starting with a NASA model-scale ducted rotor as the baseline [55]. An equivalent un-ducted rotor was derived using momentum theory and Blade Element Momentum Theory (BEMT) to match thrust and power. Scaled to a 6,000 kg quad-rotor vehicle, hover and forward flight performance evaluations revealed that the ducted rotor exhibited a reduced frontal area by 70% and lower torque but required slightly higher power due to increased RPM. In hover, the ducted rotor achieved a higher Figure of Merit (FoM) due to additional thrust from the duct. However, duct drag reduced its efficiency in forward flight compared to the un-ducted rotor. Acoustic analysis demonstrated significant noise reduction for the ducted rotor, suggesting its potential for noise-sensitive applications. Figure 12 shows the wake behaviour between an open rotor and a ducted rotor under the same condition.

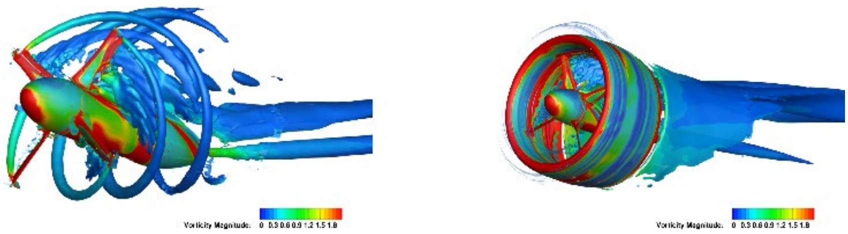

Figure 12: Behaviour of wake on open rotor (left) and ducted rotor (right) [55]

A detailed parametric study examined the effects of design and operational variables, such as blade pitch, chord length, twist, and duct thickness, on the aerodynamic performance of ducted and un-ducted rotors. Due to its compact size, the ducted rotor exhibited higher thrust and power loadings but was more sensitive to tip radius changes. While increased blade pitch improved thrust, efficiency peaked at specific pitch angles. The ducted rotor's efficiency improved with larger pitch angles in forward flight,

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contrasting with chord length effects, which varied between hover and forward flight. The shielding effect of the duct proved advantageous in non-axial flight by reducing asymmetric blade loads and enhancing lift despite generating negative thrust in forward flight.

Further research optimized duct-rotor systems by coupling duct and rotor parameters to improve thrust coefficient and Figure of Merit (FoM) [56]. A novel parametric design approach using the Class Function or Shape Function Transformation (CST) method enabled precise duct and rotor geometry modelling with minimal fitting errors. Sensitivity analysis identified critical parameters such as rotor tip chord length, torsion angle, and duct entrance shape as key drivers of aerodynamic performance. Coupling effects between these parameters accounted for 56.2% of performance variations. The optimized design achieved a 25.6% increase in thrust coefficient and an 8.89% improvement in FoM, with experimental validations showing gains of 18.6% and 6.83%, respectively. Effective tip clearance management further enhanced performance, underscoring the importance of rotor-duct interaction in optimization.

These studies collectively highlight the potential of ducted rotor systems in improving aerodynamic efficiency, thrust, and noise reduction. By leveraging advanced optimization methods and exploring parameter interactions, they establish a foundation for designing high-performance UAV propulsion systems and underscore the trade-offs between efficiency and design complexity.

Despite promising results from research on passive flow control methods to reduce wake and drag, several significant challenges persist in their practical application. One of the key challenges with vortex generators (VGs) is optimizing their configuration to maximize drag reduction. Positioning, size, and number of VGs must be meticulously calibrated to ensure effective delay of flow separation without imposing additional weight or complexity on UAV designs. This requires extensive experimentation, including CFD simulations and wind tunnel testing, which can be resource-intensive. While studies like those by Gibertini *et al*. [39] have demonstrated the potential of VGs in drag reduction, achieving a cost-effective integration into UAV designs remains a technical hurdle.

For dimples, the primary challenge lies in identifying the optimal size, geometry, and placement to yield maximum aerodynamic benefit. Although dimples have proven effective in delaying flow separation and reducing drag in applications like golf balls and certain UAV surfaces, their performance varies significantly based on design parameters. Research, such as that by Grover *et al*. [44], highlights that even small changes in dimple design can lead to substantial differences in aerodynamic efficiency. This variability necessitates further studies combining advanced numerical simulations and physical testing to optimize dimple configurations for UAVs and unlock their full potential in enhancing aerodynamic performance.

Sharkskin-inspired structures have shown remarkable results in reducing drag and improving lift; however, replicating these bio-inspired textures presents considerable manufacturing challenges. Producing the intricate surface texture of shark denticles with precision can increase production costs and complicate manufacturing processes. Additionally, further research is essential to understand the behaviour of these textures under various UAV flight conditions, including diverse speeds and angles of attack. While the aerodynamic advantages of sharkskin textures are well-documented, integrating them into UAVs without compromising other performance aspects remains a complex area requiring innovative solutions.

Ducted rotor systems offer another promising approach to improving UAV aerodynamic performance by reducing drag and mitigating rotor wake interactions. Ducts surrounding rotors provide structural advantages, such as protecting the rotor blades and reducing noise and contributing to aerodynamic efficiency. Studies have shown that well-designed ducts can enhance thrust by creating favourable pressure gradients and reducing blade tip vortices, primarily contributing to induced drag. However, their application is not without challenges. The design and optimization of ducted rotors involve balancing

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aerodynamic efficiency with structural and weight considerations. Research has demonstrated [54, 55] that duct configurations must be meticulously tuned to ensure optimal performance across various flight conditions, including hover and forward flight.

Moreover, the added complexity of ducts can impact the overall weight and propulsion system integration. Maintaining efficient airflow through the duct while mitigating the drag penalty associated with the duct's frontal area is critical. Parametric studies [56] have highlighted the importance of precise geometric design, including the duct's entrance shape, thickness, and rotor tip clearance, to maximize thrust and minimize drag. While significant strides have been made in understanding the dynamics of ducted rotor systems, future work is needed to explore their scalability for larger UAVs and improve their performance under diverse operational scenarios.

These challenges underscore the need for continued interdisciplinary research to refine passive flow control methods like VGs, dimples, sharkskin-inspired textures, and ducted rotors. Innovations in computational modelling, advanced manufacturing techniques, and experimental validation will be essential to fully harness their potential in UAV design.

4.0 RESEARCH GAPS AND DIRECTION FOR FUTURE WORKS

Despite significant advancements in understanding the aerodynamics of multi-rotor UAVs, several research gaps remain that limit the optimization of their performance, efficiency, and noise reduction. Many studies have focused on rotor-to-rotor interactions, wake structures, and thrust performance, yet further investigations are needed to refine predictive models and enhance UAV design methodologies.

One major gap is the lack of comprehensive wake interaction models for the combined effects of rotor, wake, and motion-induced circulation in dynamic flight conditions. While studies have analysed wake interactions in hover and low advance ratios, the impact of varying flight speeds, wind conditions, and manoeuvring effects on wake development remains underexplored. Conventional wake models developed for single rotors do not fully capture the highly unsteady and asymmetric wake structures observed in multi-rotor configurations. Future work should focus on refining wake models to improve their applicability in conceptual UAV design and real-time flight simulations.

Another key gap is the insufficient integration of rotor-airframe interactions in aerodynamic and acoustic studies. Most research isolates rotor performance without considering the effects of fuselage, arms, and payload on flow structures and noise generation. However, UAVs frequently operate with attached sensors, cameras, and payloads, introducing additional flow disturbances that could affect aerodynamic performance and increase broadband noise. Addressing this limitation requires CFD simulations and experimental studies incorporating full UAV geometries to better predict real-world performance.

Additionally, limited experimental validation under realistic flight conditions remains a significant challenge. Most validation studies rely on wind tunnel experiments and hovering configurations, which do not fully represent real-world flight dynamics. There is a need for high-fidelity flight testing that captures UAV performance across various wind speeds, turbulence levels, and flight manoeuvres to enhance model accuracy. Additionally, parametric studies exploring the effect of rotor spacing, RPM control, and rotor positioning in real-world operational environments could provide valuable insights for optimizing UAV design.

In summary, future research should focus on refining wake interaction models for different flight regimes, integrating rotor-airframe interactions in aerodynamic and noise studies, characterizing broadband noise contributions, and expanding experimental validation efforts under realistic conditions. Addressing these gaps will be critical in

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developing more efficient and quieter multi-rotor UAVs for commercial and military applications.

5.0 CONCLUSION

In conclusion, the research studies that have been done have evaluated comprehensively the aerodynamic challenges faced by multi-rotor UAVs, particularly highlighting the detrimental impact of wake-induced drag. Wake behaviour, characterized by turbulent airflow created by rotor and body interactions, is a critical factor that significantly reduces aerodynamic efficiency. Addressing this issue is essential for improving the performance of UAVs, especially in applications where extended endurance, greater payload capacity, and fuel efficiency are prioritized.

The works that have been done include detailed analysis of experimental and computational studies aimed at understanding and mitigating wake effects. Experimental studies, though costly, are crucial as they provide empirical data that reflect real-world flight conditions, while CFD simulations offer a cost-effective, detailed insight into wake behaviour and the effects of various design modifications. By combining these two approaches, researchers can develop more accurate and efficient aerodynamic solutions for UAVs.

One of the primary strategies discussed in this paper is the integration of vortex generators, which help control the boundary layer and delay flow separation, thus reducing drag. These generators energize the airflow over UAV surfaces, resulting in smoother airflow and improved aerodynamic performance. In addition to vortex generators, the study explores the application of dimpled surfaces inspired by the aerodynamics of golf balls. Dimples create micro-turbulence that enhances airflow management, reducing drag and increasing efficiency. Bio-inspired solutions, such as shark skin textures, are also explored for their ability to optimize lift-to-drag ratios by managing boundary layer behaviour through micro-scale surface designs.

Despite the promising benefits of these solutions, the study acknowledges the challenges involved in their implementation. Manufacturing complex surface textures, such as dimples and shark skin structures, is costly and technically demanding. Moreover, the performance of these aerodynamic features can vary significantly based on design parameters such as size, shape, and positioning. Therefore, further investigation and refinement are required to fully capitalize on the potential of these innovations.

Therefore, it is necessary to continue research that integrates advanced CFD simulations with experimental testing to refine these aerodynamic enhancements. This multidisciplinary approach, involving fluid mechanics, materials science, and engineering, is vital for developing UAVs that operate more efficiently in various applications, from surveillance to environmental monitoring. As UAV technology advances, addressing the challenge of wake-induced drag will be essential to ensuring that these vehicles meet the growing demands of modern applications while maintaining high levels of performance and efficiency. The study serves as a foundation for future research that seeks to push the boundaries of UAV capabilities, ultimately contributing to advancing this critical technology across multiple industries.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this paper.

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