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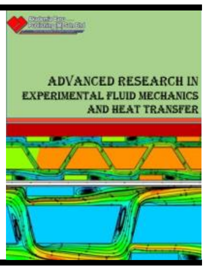

A Review of Experimental Approaches for Investigating the Aerodynamic Performance of Drones and Multicopters

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ABSTRACT

The growing popularity of multicopters has heightened interest in improving and optimizing UAVs. This has become a major source of inspiration for scholars. Extensive aerodynamics research would result in improved multicopters and boost their appeal to major sectors. Various aspects of the performance of various propeller designs and configurations have been studied by researchers. Various performance metrics have also been investigated and discussed in this paper. Aerodynamic testing of propellers and multicopter designs are discussed in this paper. Numerical simulations are also used widely in the study of drone and multicopter aerodynamics. This method enables high resolution observation on wake propagation and flow visualizations. Nonetheless, as new multicopter concepts are introduced, new aerodynamic challenges emerge in this field. Therefore, more studies need to be done on uncommon but rather important configurations so that these can have a beneficiary effect on the multicopter industry.

Keywords:
Multicopters; wind tunnel; CFD; aerodynamic performance

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1. Introduction

The convenience of use and versatility that multirotor drones, such as quadcopters offer, allows them to start dominating consumer VTOL (vertical take-off and landing) and UAV (unmanned aerial vehicles) sectors. Aerodynamic behaviors are vital to consider while developing multirotor drones. The ease of fabricating the frame for the multicopter using 3D composite also plays a role in its dominance [2]. The size, shape, and weight of the drone, as well as the numerous features of the drone's propellers, all influence the flying characteristics of the drone.

A rotor or propeller is a rotating wing that is a crucial aerodynamic component. Figure 1 shows the 13-inch propeller used for aerodynamic study.

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Fig.1. A close up of a propeller [5]

The propeller generates thrust when the blades of the propeller rotate. The airfoil shape of the propeller blades enables it to take advantage of Bernoulli’s principle where the rotational movement of the propeller produces thrust due to a pressure difference between the upper surface and lower surface of the airfoil shaped propeller occur causing upward force on the airfoil shape of the propeller blades. The aerodynamics of multirotor drones differ from those of fixed-wing drones. While fixed-wing drones exhibit interactions like those seen in airplanes, multirotor drones are more akin to helicopter aerodynamics. Because of the fluid movement over the aircraft and how thrust is created, the forces differ.

A multirotor drone's motor is the main source of thrust. To accomplish flight, the motors should generate about 50% greater thrust than the UAV's weight. This will assist the drone in flying in windy circumstances and making sharp maneuvers [31]. Brushed and brushless motors are the two types of motors available. Brushless motors provide more power and are better suited for heavier and bigger drones. Figure 2 shows the internals of a brushless DC motor.

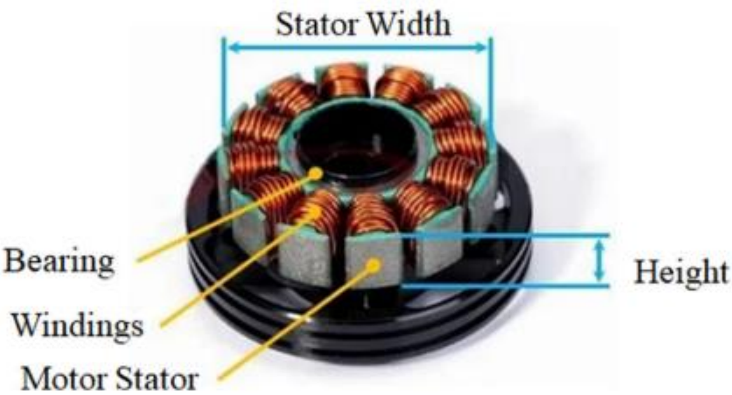

Fig.2. Internal components of brushless DC motor [1]

The efficiency of a propeller is determined by the angle of attack. Efficiency is evaluated as a ratio of output to input power, and well-designed propellers have an efficiency of 80% [31]. Propellers may be made to spin either clockwise or counterclockwise. Two propellers on a quadcopter rotate counterclockwise, while the other two spin clockwise. Otherwise, the quadcopter will yaw and become unstable.

Structural factors such as shape and size of the drone also play a role in the performance of the multicopter. The large range of structural configurations and mission profiles caused by inadequate data resulted in the challenges of Unmanned Aerial Vehicle design being less clearly defined. Weak or incorrect structural design has resulted in a variety of operational issues, ranging from mission failure to payload malfunction to poor flight performance. Materials used has an impact as the total weight of the airframe can be reduced without compromising structural strength [17].

Drone aerodynamics have attracted a lot of attention in estimating and increasing their performance to extend their flight periods. Due to their poor efficiency relative to fixed-wing systems, which results in short flight periods, the research of aerodynamics for multi-rotors has generally focused on improving vehicle characteristics and propulsion to increase endurance. Current field of research that is being done on aerodynamics performance involves the use of computational fluid dynamics (CFD) method to predict the performance of small to medium sized rotors. Although CFD has become an integral part of the performance studies [10], experimental data is still being used as primary data to verify the results and for conditions that require less cost and time compared to CFD.

Wind tunnel testing and flight testing are two experimental methodologies for researching the aerodynamic performance of multicopters. Wind tunnel testing is a significant method in multicopter aerodynamics research because it allows researchers to analyze multicopter aerodynamic performance in a controlled setting. It can assist researchers in understanding how different parameters such as the drone's size, shape, and weight, as well as the properties of the drone's propellers, impact its flying characteristics [47]. Another experimental strategy used to examine the aerodynamic performance of multicopters is flight testing. Flight testing includes flying the drone and assessing its performance in real-world settings. Flight test can also be done by designing a testbed that can simulate the dynamic behavior of the multicopter [22]. Flight testing can offer useful information about how the drone performs in real-world settings, but it is more expensive and time-consuming than wind tunnel testing [26]. Wind tunnel testing and flight testing are two experimental methodologies for examining the aerodynamic performance of multicopters. This review of previous studies is done to get an understanding of the overall benefits and weaknesses of the experimental approach in multicopter aerodynamics performance.

Aerodynamic interactions between rotors have a significant impact on the performance of in-plane multirotor Unmanned Air Vehicles (UAVs) or drones, which account for most small size UAVs (or mini-drones). Knowledge of the flow aspects is required for optimal design. The low Reynolds number of many UAV rotors begs the issue of how these characteristics differ from those predicted by classic rotorcraft analytical methods. The aerodynamics of a pair of side-by-side rotors in hover are investigated utilizing high-speed Stereo Particle Image Velocimetry (SPIV) and performance measurements throughout a range of rotor spacing and Reynolds number [35]. The importance and relevance of multicopter aerodynamics research is derived from its capacity to improve the design and performance of multirotor drones. Researchers can increase the efficiency, stability, and maneuverability of multirotor drones by studying how aerodynamic interactions impact their performance. This research can also aid in identifying areas for more research and development in this discipline [35].

The structure of this review is as follows: the multicopter aerodynamics basics and fundamentals theories and concepts are explained in Section 1. Section 2 will discuss experimental and simulation studies on aerodynamics performance of drones and multicopter. Lastly, the conclusion comprised of comparison between the previous studies are looked at closely.

2. Multicopter Aerodynamics

The fundamental aerodynamic principles of drones are like those of conventional aircraft. Lift, weight, propulsion, and drag are the four factors that impact a drone's flight. Lift is the force that overcomes gravity and keeps the drone aloft and is produced by the drone's wings or rotors besides being proportional to the speed and angle of attack of the wings or rotors. The force that pushes the drone down towards the surface is known as weight. It is governed by the drone's mass and is proportional to gravity's acceleration. The force that drives the drone forward is known as thrust. It is produced by the drone's motors and propellers and is proportionate to its speed and power. Drag is the force that opposes propulsion and causes the drone to slow down. It is caused by the air's resistance to the motion of the drone and is proportionate to its speed and geometry. To summarise, knowing these fundamental aerodynamic principles can help researchers optimise their designs to maximise efficiency, stability, and manoeuvrability [30]. Table 1 shows the components of the multicopter and its use.

Table 1
Components of multicopter and its use [1]

S.No:	Components	Purpose
1.	Frame	The main platform holds all the electronic components intact
2.	BLDC Motors	Motors that can produce huge thrust with the least weight.
3.	Propellers	Helps in producing the Lift when rotated with motors.
4.	ESC	Controls the speed of the motors.
5.	LiPO Battery	Has high discharge rate that would help in speed.
6.	Transmitter & Receiver	Sends and Receives commands from pilot to the drone.
7.	Flight Controller	Takes the input commands from Transmitter and controls the various sensors and actuators of drones.

The resultant aerodynamic force is determined by the magnitudes of four forces: weight, lift, thrust, and drag. Figure 3 shows the aerodynamic forces acting on a multicopter.

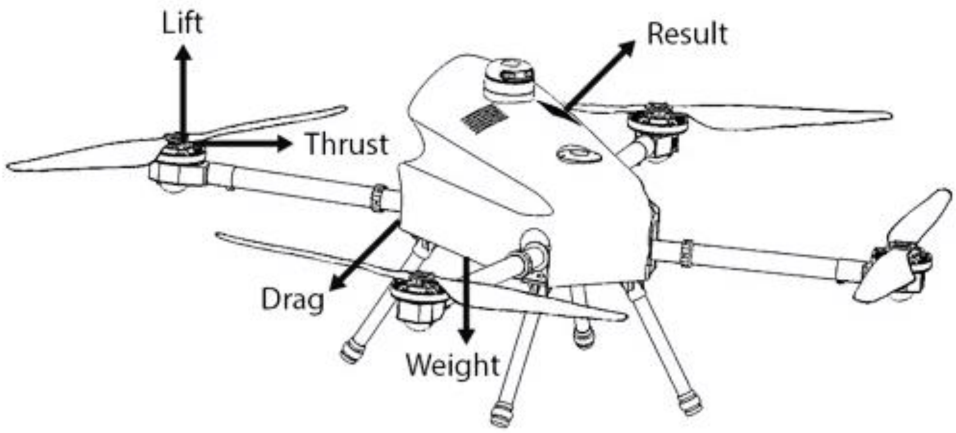

Fig.3. Aerodynamic forces on a multicopter [11]

The drone will either ascend, dive, or bank according on the relative magnitude and direction of these four vectors [31]. A multirotor drone's motor is in charge of providing thrust. To attain flight, the motors should create about 50% greater thrust than the UAV's weight. This will assist the drone in flying in windy circumstances and making sharp manoeuvres [31]. Figure 4 demonstrates the angle of attack and pitch of a propeller.

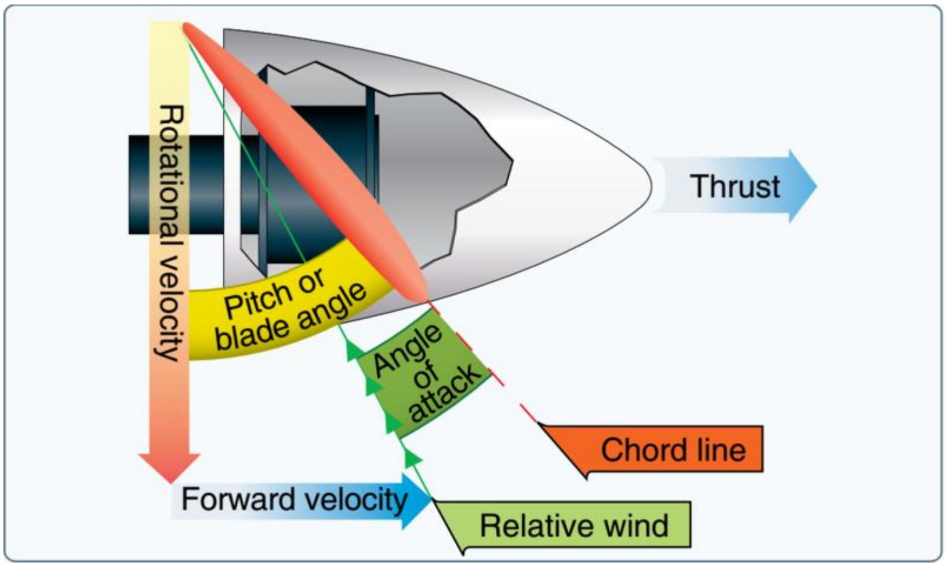

Fig.4. Angle of attack and pitch of propeller [11]

The efficiency of a propeller is determined by the angle of attack. Efficiency is evaluated as a ratio of output to input power, and well-designed propellers have an efficiency of 80%. Propellers may be made to spin either clockwise or counterclockwise. Two propellers on a quadcopter rotate counterclockwise, while the other two spin clockwise. Otherwise, the quadcopter will yaw and become unstable [31].

Researchers have just begun to explore the wake effects and proximity impacts of multi-rotors. The interaction of the vehicle wake with a physical barrier causes proximity effects such as ground, ceiling, and wall effects, which provide some insight into wake propagation [37]. Figure 5 shows the wake propagation observed using CFD model of a DJI Phantom 3 multicopter.

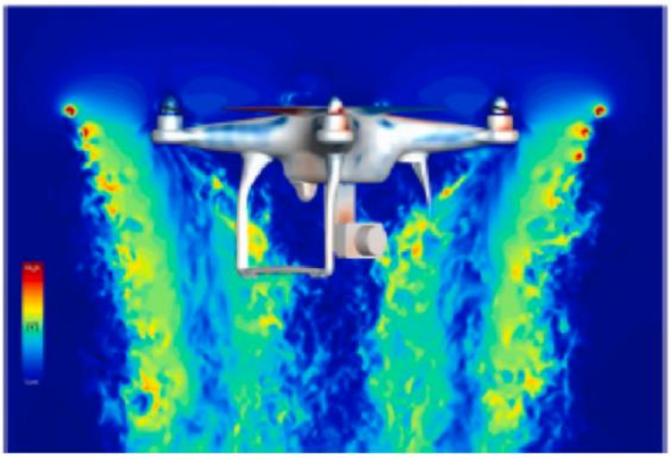

Fig.5. Wake propagation of DJI Phantom 3 [37]

The ground effect becomes negligible as the distance between the vehicle and the ground increases; hence these phenomena can indicate the strength of the wake and the distance the wake propagates from the vehicle. A similar phenomenon may be noticed when a multi-rotor works near a ceiling, although it is referred to as ceiling effect in this situation. Finally, wall effects relate to the interaction of the wake with vertical impediments such as walls [37].

Multicopter aerodynamic performance is a complicated subject of research that necessitates a full grasp of the different factors and coefficients that influence the flight characteristics of these drones. Figure 6 shows the aerodynamic forces and moment produced on an aircraft and airfoil.

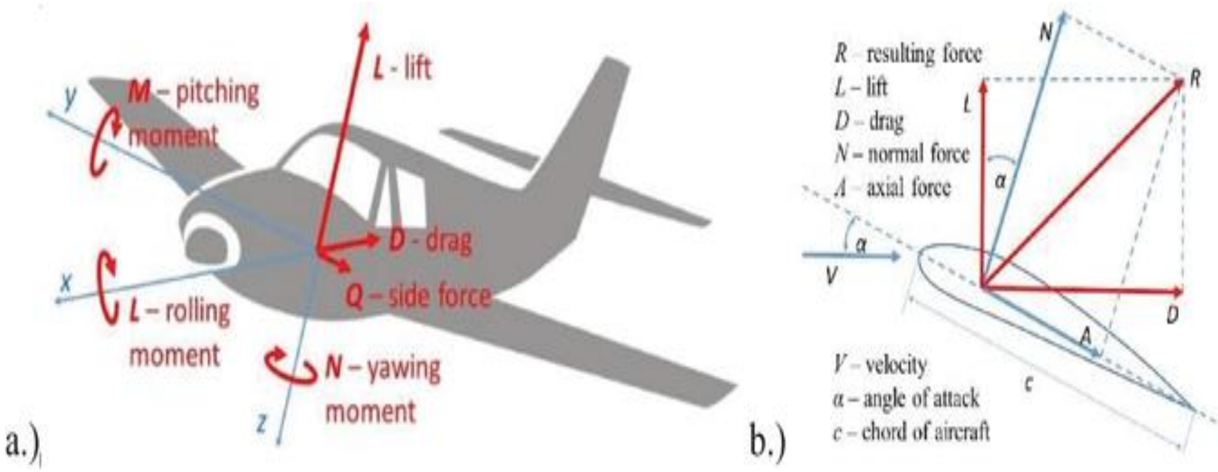

Fig.6. Aerodynamic forces and moment produced on (a) aircraft and (b) airfoil [28]

Here are some critical factors and coefficients often used to analyse multicopter aerodynamic performance

i. Lift coefficient (C_l): It is the proportion of lift force to dynamic pressure and wing area. It is a crucial parameter that influences how much lift the drone's wings create try to design illustrations that make good use of the available space—avoid unnecessarily large amounts of white space within the graphic;
ii. Drag coefficient (C_d): It is the proportion of drag force to dynamic pressure and wing area. It is a critical parameter that influences the drag produced by the drone's wings.
iii. Momentum coefficient ($_{Cm}$): It is the relationship between the moment created by the drone's wings and the dynamic pressure and wing area. It is a crucial parameter that influences the drone's steadiness. The momentum coefficient is initially used to calculate the intensity of the aerofoil [45]. It is defined as follows:
    a. Angle of attack ($_{AoA}$): It is the angle formed by a wing's chord line and the relative wind. It is a crucial metric that con trols how much lift and drag a wing generates.
    b. Thrust coefficient ($_{Ct}$): It is the ratio of a propeller's thrust to its dynamic pressure and area. It is a critical metric that controls how much thrust a propeller produces [15].

These characteristics and coefficients are used to study different aspects of multicopter aerodynamics, including lift, drag, stability, and thrust production. Researchers can increase the efficiency, stability, and manoeuvrability of multicopter designs by studying how these aspects impact their aerodynamics [30].

3. Experimental Methods

Wind tunnel testing is a technique for testing an object's aerodynamic qualities by placing it in a wind tunnel and measuring the forces acting on it. Wind tunnel testing is a significant method in multicopter aerodynamics research because it allows researchers to analyse multicopter aerodynamic performance in a controlled setting. Wind tunnel testing can assist researchers in understanding how different parameters such as the drone's size, shape, and weight, as well as the characteristics of the drone's propellers, impact its flying characteristics [7].

It can also assist scholars enhance the design of multicopter drones by detecting flaws. Researchers may find locations where drag can be decreased, lift can be raised, and stability can be enhanced by analysing the aerodynamic performance of multicopters in a wind tunnel. This data may then be utilised to increase the efficiency, stability, and manoeuvrability of multicopter drones by optimising their design[7].

Wind tunnel testing is a significant technique in multicopter aerodynamics research because it allows researchers to analyse multicopter aerodynamic performance in a controlled environment. Researchers can increase the efficiency, stability, and manoeuvrability of multicopter drones by studying how numerous elements impact their flying characteristics[7].

It is also an excellent resource for researching the aerodynamic aspects of multicopters. Wind tunnels of various varieties are often used for this purpose. Subsonic wind tunnels are used to research the aerodynamics of multicopters at low speeds, generally less than 0.8 Mach. Transonic are used to research the aerodynamics of multicopters at close to the speed of sound, often between 0.8 and 1.2 Mach number. Supersonic wind tunnels enable the investigation of the aerodynamics of multicopters at high speeds, generally 1.2 to 5 Mach while hypersonic wind tunnels are used to investigate the aerodynamics of multicopters at extremely high speeds, often more than 5 Mach number [21].

Wind tunnels are also classed according to their setup, style, and output. The most frequent types of return wind tunnels are open and closed, with differences in form and air circulation [14]. In short, Wind tunnels of various varieties can be used to examine the aerodynamic aspects of multicopters. The type of wind tunnel chosen is determined by the speed range of interest and the individual research objectives.

A wind tunnel is a very useful instrument for researching the aerodynamic aspects of multicopters. Table 2 shows some of the benefits and drawbacks of wind tunnel testing.

Table 2
Advantages and drawbacks of wind tunnel testing

Advantages	Drawbacks
Controlled environment - enables researchers to examine the aerodynamic performance of multicopters in a controlled setting, which can aid in the identification of areas for improvement	Scale issues - have inherent limits when it comes to correctly recreating turbulence and dealing with scale difficulties.
Accurate results - may yield precise data that can be utilised to improve the design of multicopter drones	Costs - might be costly to develop and run, making them less accessible to smaller research organisations
Cost-effective - as compared to other approaches like as flight testing, can be a cost-effective way to evaluate the aerodynamic performance of multicopters	Limited scope - restricted in breadth and incapable of simulating all real-world circumstances [20]
Safety - a risk-free method of studying multicopter aerodynamic performance since it avoids the dangers involved with flight testing	Interference effects - The addition of walls and other objects in the wind tunnel might generate interference effects, which can impair the accuracy of the results [20].

3.1 Rotor Optimization

Hu *et al.,* [8] investigated the use of leading edge (LE) serrations to reduce noise of isolated multicopter rotors. Aerodynamic loads and noise emissions of these multi-copter rotors are monitored and investigated during forward flight conditions using a force balance and microphones in an anechoic wind tunnel by selecting different serration parameters of height and wavelength. The thrust and torque produced by the serrated rotor and motor respectively were measured using thing the force balances to determine the effect on the aerodynamics performance. It was found that the thrust produced by the rotors decreases while the torque and power consumption of the moto increases which therefore shows the decrease in aerodynamics performance in this investigation, all serrated rotors exhibit lower tonal, broadband, and total noise levels than the baseline rotor. All serrated rotor noise reductions are reported to follow a scaling law with the Strouhal number in the mid-to-high frequency region [8]. The leading-edge serrations are a way to optimize the rotor so that the aeroacoustics of the rotor can be improved and thus gain an advantage in terms of aerodynamics performance at post-stall conditions.

Rotor optimization is also needed to improve flight time and usability. Dantsker *et al.*, [5]did a performance test of 17 APC Thin Electric 2-bladed, fixed propeller with diameters 12 to 21 inches with various pitch values. An optimum permutation of propulsion unit was needed for a mission specific multicopter. This raised the importance of rotor optimization. Depending on the propeller and testing equipment restrictions, the propellers were tested at rotation rates ranging from 1,000 to 7,000 RPM with advance flows ranging from 8 to 80 ft/s. Figure 7 shows the test rig setup.

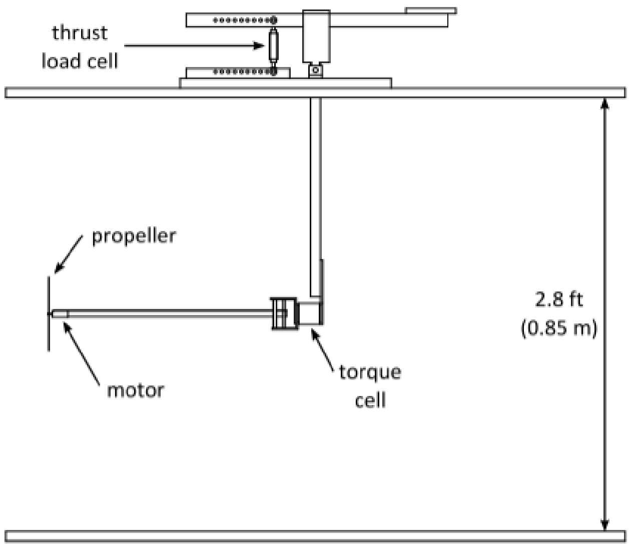

Fig.7. Test rig setup [5]

The rotor speeds, thrust, torque, dynamic pressure, atmospheric pressure and temperature was measured to assist in the determination of the aerodynamic performance of the propulsion system. The geometries of APC-E propellers were found to be remarkably comparable among propellers of the same diameter with varying pitch values, with chord being constant at each station while twist changed. It was also discovered via performance testing that increasing the pitch of a given diameter of propeller boosts non-dimensional performance and efficiency, while moving these features toward greater advance ratios. Similarly, higher propeller pitch improves thrust and power coefficients under static circumstances [5].

3.2 Wake Propagation

Wake propagation in multicopters refers to the behaviour of the air flow, or "wake," produced by the rotors of a multi-rotor unmanned air vehicle (UAV) during flight. In a forward flight mission, as the advance ratio (the ratio of forward speed to rotor speed) increases, the distance that the wake propagates below the UAV decreases. As the advance ratio rises, the flow above the UAV returns to freestream flow near the body. In ascending and descending vertical flight modes, there is substantial wake below the body of the multi-rotor vehicle in ascending flight, as well as modest disturbance above the body. In descending flight, there are flying circumstances in which the flow shifts from below the vehicle to above. Understanding wake propagation is critical for sensor location, data dependability, and avoiding proximity effects. Proximity effects are changes in aerodynamic performance that occur as a UAV approaches a surface or object. When a multi-rotor is near to the ground, drag decreases and lift increases.

A study on the wake propagation and flow development was gathered and analysed by Throneberry *et al.,* using Flow visualization and Particle Image Velocimetry method to capture multi-wake and flow development in a wind tunnel [37]. Experimental research in this sector has generally employed PIV experiments to get quantitative measures, with some also employing smoke visualisation techniques to improve wake visibility. Similarly, to CFD research, certain PIV investigations concentrate on vorticity dissipation [37]. Shukla *et al.,* used flow visualisation tools and PIV experiments to study coaxial rotors and a quadrotor [34]. The emphasis of the quad-rotor experiment was the influence of ducting around the rotors on rotor-to-rotor interactions. Flow visualisation techniques were originally employed for the coaxial rotor experiment to provide a clear visual of a vortex created by a coaxial rotor with a rotor diameter of 122 cm, but no insight into the propagation distance of the wake from the coaxial rotor was provided. PIV was used to examine the impact of adding a duct to a quadcopter. Fig.8. visualizes the velocity streamline for (a) unducted rotor and (b) ducted rotor.

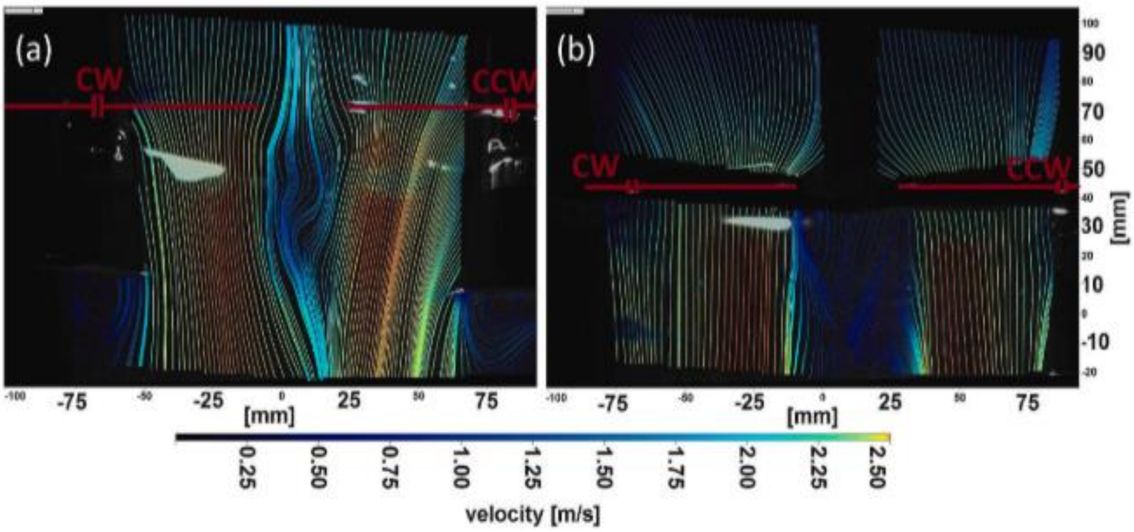

Fig.8. Velocity streamline for (a) unducted rotor and (b) ducted rotor [34]

Based on Figure 5, it can be observed that rotor-rotor interactions decrease significantly on ducted rotor as the wake propagates straight down. When ducting is added within the Field of Visual (FOV), the wake propagation distance remains unchanged. To quantify the results, Ramasamy *et al.*, evaluated a single rotor with a diameter of 17 cm and the vortices created using flow visualisation and PIV. The vortices' intensity increases soon after exiting the rotor before diminishing as they move downward. The vortices go a long distance away from the rotor [27]. Throneberry *et al.,* [39] used smoke visualisation and PIV tests to evaluate a quad-copter drone in a +configuration with an 18 cm (7.25 in) center-to-center distance and a 13cm (5 in) rotor diameter in several flying modes. The quadcopter is placed in a wind tunnel to study wake propagation and characteristics in forward, ascending, and descending flight simulations. Forward flight data revealed a distinct mixed zone just beneath the drone's fuselage, with significant jets of wake emanating from the fore and aft rotors. Strong wake jets are also emitted from the side rotors in the picture plane. In ascending flight, the bottom of the drone displayed a fully mixed zone with jets ejected from the bottom and top rotors in the photograph. This meant that the bottom of the drone should not be utilised for in-flight sensor positioning in any mode.

The impact of rotor velocity on the wake propagation in ascending flight was also studied by Throneberry *et al.,* [38]. The downstream findings demonstrated that greater rotor velocities result in higher velocity jets being released from the rotors. Except for certain higher velocity sections right above the drone, there is little disruption upstream from the drone, indicating that the top of the drone is a better site for in-situ sensor installation because there is less disturbance to the freestream flow. Further investigation was done by Throneberry *et al.,* [40] on changes in wake propagation as fight speed and rotor speed changes using smoke visualisation. The results indicated that when the flight speed increased in ascending flight, the jets released from the rotors propagated downstream more parallel to the background flow. The impact of prescribed angle of attack from the same multi-rotor in forward flight was also studied upon by Throneberry *et al.,* [40] . Although no quantitative data on the influence of angle of attack is presented in this study, the change in angle of attack does not appear to affect the strength of the wake from the multi-rotor.

3.3 Disk Angle of Attack

Serrano *et al.,* examined the aerodynamic performance of four 12-inch diameter propellers at various angle of attacks between 0 to 90 and advance ratios ranging from 0 to 0.55. A six-axis load cell is used to monitor aerodynamic loads. The experiment was done using a 1000 K_v brushless DC motor and 75 Hz electronic speed controller (ESC). Figure 9 shows the experimental setup of the power unit [32].

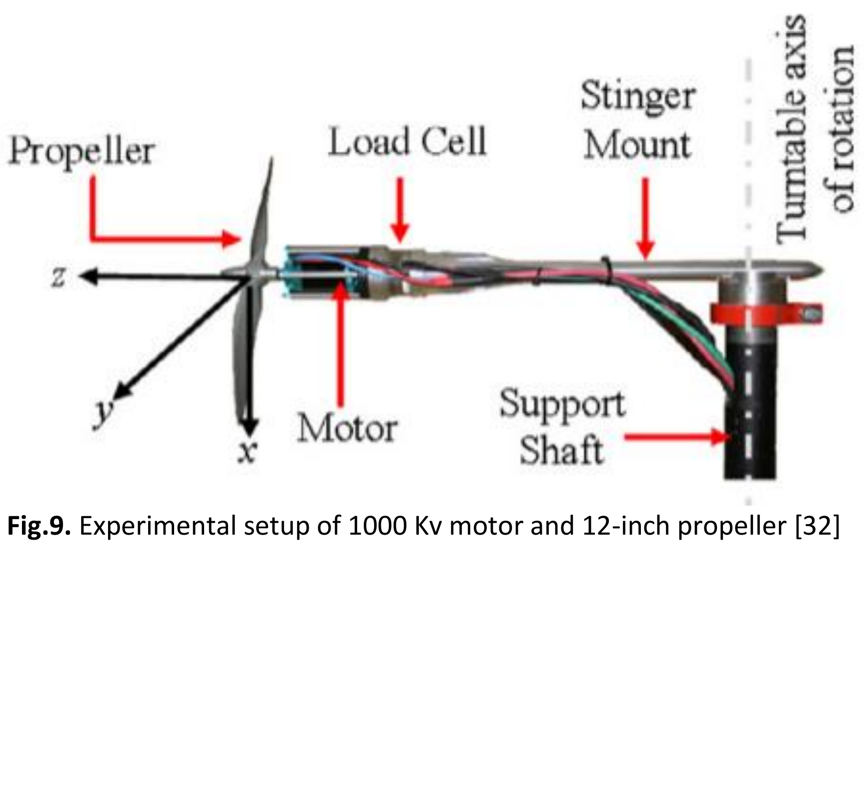

Fig.9. Experimental setup of 1000 Kv motor and 12-inch propeller [32]

The rotor's performance was predicted analytically using blade element theory. For all advance ratios tested, the thrust of all four propellers increased with increasing disc angle-of-attack. Power usage was less sensitive to changes in propeller angle of attack. The load differential between the advancing and retreating blades produced pitch and yaw moments, which grew as the propeller angle of attack rose. The thrust, power, and propulsive efficiency charts overlapping over the range of disc angle-of-attacks when plotted as a function of the inflow advance ratio.

3.4 Ducted Fan

Deng *et al.,* analysed the aerodynamic performance of a ducted drone based on force, pressure, and PIV parameters. Experiments were carried out on the UAV in both hover and forward flight modes. The in-ground impact was given special consideration since it is critical for the UAV's take-off and landing modes during flight. Variations such as the contra-rotating fan's rotational speed, incidence angle, forward flight speed, and exit-to-ground distance were investigated, providing for a thorough knowledge of the overall aerodynamic properties of the ducted fan UAV. Figure 10 shows the experimental setup of the ducted fan drone [6].

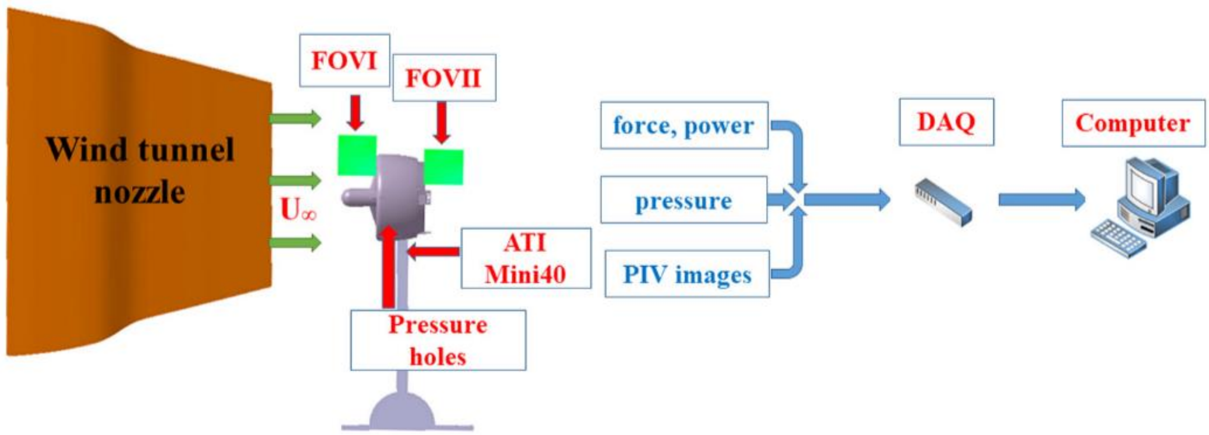

Fig.10. Ducted fan experimental setup [6]

Wind tunnel measurements have successfully defined the ducted fan UAV's first operation zone. The intake velocity distortion at the UAV's inlet during forward flight can significantly alter the inlet circumferential pressure distribution and hence, in theory, the overall aerodynamic performance. Figure 11 shows the lift performance of the ducted fan under the influence of ground effect and the power loading required to produce the corresponding lift.

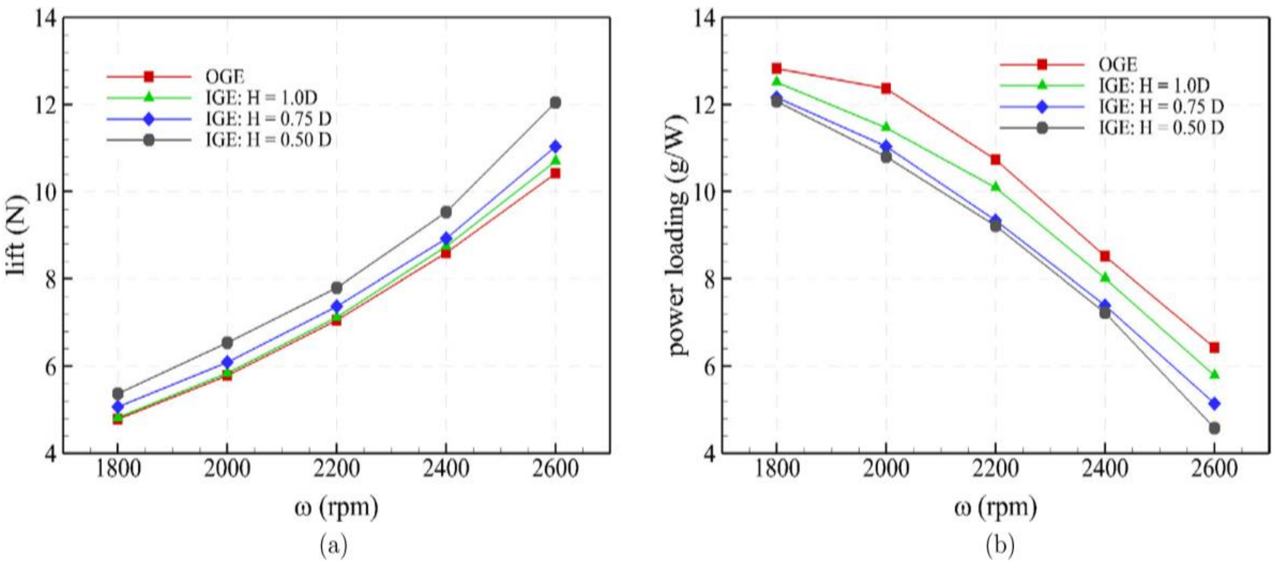

Fig.11. (a) Lift performance of ducted fan drone in ground effect; (b) power loading corresponding the rotation speed [6]

The presence of the ground during take-off and landing can increase overall lift generation while sacrificing propulsive efficiency significantly. Furthermore, while the UAV is flying close to the ground, the back pressure upon departure is enhanced, which reduces lift output [6].

3.5 Pitch Dynamics

Cyyz *et al.,* [4] researched on the experimental results of the aerodynamic performance of propellers with varying pitch values. A six-component force balance was used in the testing, which were carried out in a closed-circuit subsonic wind tunnel. The propellers under consideration were 12-inch diameter twin-blade propellers powered by a BLDC (brushless direct current) electric motor. The experiments were carried out in forced airflow settings. A strain gauge was used to measure the thrust and torque produced by the propeller. The study was carried out for various advance ratio values, which are the ratios of freestream fluid speed to propeller tip speed. A set of electrical parameters was also captured utilising the newly developed measuring method. A dimensional analysis was used to analyse the propeller performance. This approach allows for the generation of dimensionless coefficients, which are important for comparing propeller performance data. It was discovered that increasing pitch resulted in a progressive rise in thrust. The propeller with the greatest considered pitch produced the most thrust. Simultaneously, the rise in pitch caused the curve to move towards higher values of the advance ratio and thrust coefficient.

4. Numerical and Computational Simulation

Computational fluid dynamics (CFD) is a strong technique for investigating multicopter aerodynamic aspects. CFD simulations may offer researchers with a complete insight of the flow environment surrounding the drone, allowing them to optimise the design of multicopter drones. CFD simulations may also assist researchers in studying the impact of numerous elements on the flying characteristics of a drone, such as its size, shape, and weight, as well as the characteristics of the drone's propellers [36]. CFD simulations may also be used to investigate how different aerodynamic forces affect multicopter flying. CFD simulations, for example, may be used to investigate the effects of lift, drag, and thrust on multicopter flight. Researchers can increase the efficiency, stability, and manoeuvrability of multicopter flying by studying how these factors impact flight [35].

Creating CFD models for multicopters is a multi-step procedure. Figure 12 shows the procedure for creating CFD for multicopters.

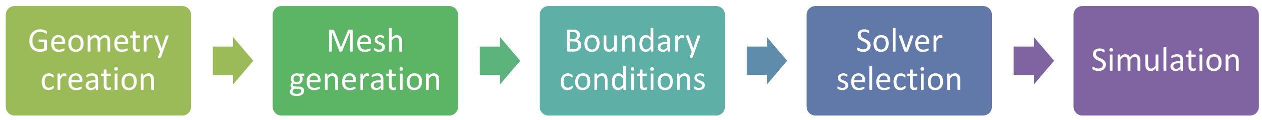

Fig.12. Procedure for the creation of CFD multicopter models.

i. Geometry creation – The first step in constructing a CFD model is to use computer-aided design (CAD) software to generate a 3D model of the drone's shape try to design illustrations that make good use of the available space—avoid unnecessarily large amounts of white space within the graphic;
ii. Mesh generation – The following step is to create a mesh, which separates the geometry into little cells. This enables modelling of fluid flow around the drone.
iii. Boundary conditions – The simulation's boundary conditions must be defined. This involves identifying the wall conditions as well as stating the velocity and pressure at the inlet and outflow borders.
iv. Solver selection – The suitable solution must be chosen based on the type of flow being simulated and the level of accuracy sought.
v. Simulation - After creating the CFD model, it may be utilised to simulate fluid flow around the drone. The simulation results may then be evaluated to get insight into the drone's aerodynamic performance

4.1 Tandem Distance

Rostami & Farajollahi [29] presented the new development made on new design and analysis of a twin-propeller with duct. the UAV design with Six distinct duct configurations is examined to determine the best duct design. In CFD simulations of flows around a moving rigid body, the Moving Reference Frame (MRF) approach is developed and investigated. Variations included propeller rotational speed and incidence angle, giving a thorough knowledge of the overall aerodynamic properties of this design. This study's findings are consistent with the experimental results. Lift and drag forces are investigated at various angles of attack. This study found that rear and front propeller designs with ducts boost efficiency by 6%, outperforming two-propeller (without duct) versions [29].

4.2 Wake Propagation & Flow Studies

Paz *et al.,* [24] tried to reproduce the flight of a drone over an obstacle with the use of computational simulations that employs a methodology based on dynamic meshes. The influence of ground proximity on drone performance was evaluated, as well as its interaction with flow around the body at various translational velocities. Because of the presence of the ground, the drag force decreased but the lift and forward pitch moment increased. The translational velocity magnifies these effects by deviating the flow created by the propellers and delaying the collision with the obstruction. Increases in pitch moment of up to 60% are seen while approaching and departing the obstruction. To ensure the stability and safety of the drone operation, these abrupt deviations must be adequately countered[24].

Paz *et al.,* [25] also furthered their investigation to access the performance in the 3D simulation using multiple reference frames (MRF) and sliding meshes. Consideration was made on the impact of ground effect. The findings for a single propeller demonstrated that both models were similar in terms of evaluating the ground effect, despite a substantial variation in thrust measurement. In the case of quadcopters, the relative location of the blades and the frame was shown to be a vital element. In the MRF example, similar rates of thrust change were attained by minimising the superposition of the blade across the body arms. However, the amplitude of the thrust varied by at least 11% at each simulated position. Assuming this variance, the MRF's much reduced computing cost makes it a highly appealing alternative. Finally, the effect of relative blade-to-blade location in the sliding simulation was investigated [25].

Heyong & Zhengyin [45] did a study to simulate the unsteady flows around forward flight helicopter with coaxial rotor based on unstructured dynamic overset grids using 3D unsteady Euler equation. It was found that the interaction of the coaxial rotors causes the downwash velocity at the bottom rotor plane to be substantially greater than the downwash velocity at the individual rotor plane, and the downwash velocity at the top rotor plane to be somewhat more than the individual rotor plane. Both helicopter types have upwash vortex flows on the top of their fuselages, and the coaxial rotor helicopter is weaker than the individual rotor helicopter. When the collective angle of the blade increases, so does the downwash velocity and thrust coefficient. When the rotor spacing increases, the thrust coefficients for the top rotor rise while decreasing for the bottom rotor, and the total thrust decreases somewhat[45].

Pasquali *et al.,* [23]investigated the link between experimental data and numerical simulations of the aerodynamics of a hovering rotor working in ground effect over parallel and inclined surfaces. A potential-flow, free-wake aerodynamic solver based on a boundary element technique formulation is thoroughly explored for its capacity to simulate in-ground-effect situations. In specifically, the bounded domain technique (BDM) and the mirror image method (MIM) for adding ground effect are described and contrasted. It was found that both techniques accurately represent the effects of ground on near tip vortex shape and thrust. However, the prediction of induced power is not slightly inaccurate for the BDM method. MIM does a better job in predicting the induced power and this was verified with experimental measurements.

Zhang *et al.,* [46]discussed the spatiotemporal distribution characteristics of airflow of the drone. The airflow field of a six-rotor plant protection drone was simulated using the lattice Boltzmann method (LBM) based on a mesoscopic kinetic model. The airflow field of a drone in hover and at various flight speeds (1.0-5.0 ms^{-1}) and altitudes (1.5-3.5 m) was studied. The numerical investigation of airflow separation, airflow coverage equivalent area, and "steep" impact. The results show that flight speed and altitude had a significant influence on the dispersion of the airflow field. When the drone was flying forward, the wake of the airflow field had a significant backward tilt, thus when the flight speed was 4.0 ms^{-1} and 5.0 $m\ s^{-1}$, the wake of the airflow field rose off the ground, whilst the transverse separation showed as horseshoe vortices. The distribution of V_{-Y} was most uniform at flight speeds of 3.0 $m\ s^{-1}$ and altitudes of 3.0 m [46].

4.3. Rotor & Fixed Wing Optimization

Zadeh & Sayadi [19]developed a novel optimization strategy for an efficient multi-fidelity model building approach to decrease computational costs for dealing with aerodynamic shape optimization based on high-fidelity simulation models. Figure 13 shows meshing section used in 2D space.

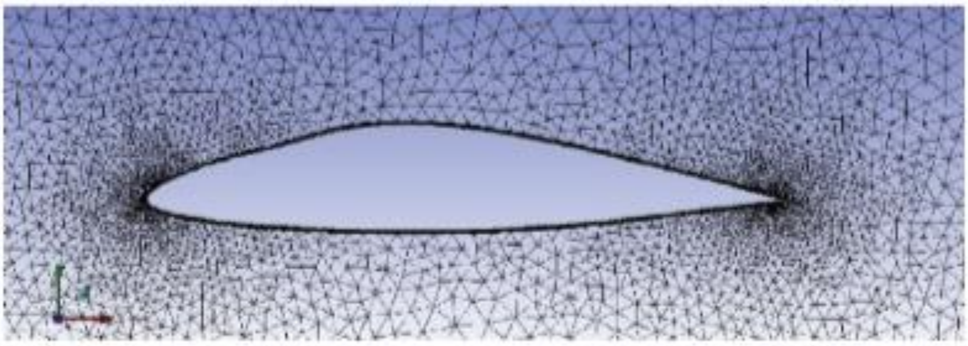

Fig.13. Mesh section in 2D space [19]

Modelling 3D (high-fidelity) and 2D (low fidelity) models, generating global meta-models from notable factors rather of all variables, and finding durable optimal form associated with modifying local meta-models were all carried out. It was found that despite very little modifications in the aerodynamic geometry of sections and total size of the aircraft, the drag coefficient is significantly lowered.

Zhu *et al.,* [48] devised a hybrid methodology that combines textbook methodologies, computational fluid dynamics (CFD), and verification tests to improve the aerodynamic efficiency and performance of low-speed subsonic octocopter drones. Figure 14 shows the eight- rotor configuration used.

Fig.14. Eight rotor configuration drone [48]

It is discovered that the new and coaxial configurations may create higher thrust because they allow bigger rotors to be deployed in a specific fuselage planar space. The novel configuration design is also shown to have improved aerodynamic performance due to less rotor-rotor interactions. Larger rotor blades perform better aerodynamically, but rotor-rotor interactions reduce aerodynamic efficiency. Because rotor-rotor interactions rise with rotor blade size, the ideal design cannot meet the highest aerodynamic performance and efficiency at the same time. Total drone thrust increases significantly with rotor blade size, but rotor-rotor interactions rise at a considerably slower pace, since the new configuration reduces rotor-rotor interactions, which is a more desirable consequence [48].

Kapsalis *et al.,* [12] discussed the layout optimization of a tactical, fixed-wing UAV, during the early process of preliminary design. Figure 15 presents the Blended-Wing-Body configuration used for this study

Fig.15. BWB configuration [12]

The optimization is carried out utilizing the Taguchi experimental design approach and Computational Fluid Dynamics (CFD). The essential design parameters are defined as aspect ratio, taper ratio, and sweep angle. The influence of those factors on the maximum velocity, takeoff runway, and gross takeoff weight, which serve as performance criteria, is investigated using a L_9 orthogonal array. Combinations that optimize peak speed, reduce takeoff runway length, and maximise gross takeoff weight are extracted. In addition, an Analysis of Variance (ANOVA) is performed to evaluate the contribution of each design feature to the performance criterion. When compared to a complete factorial "experiment," the Taguchi approach reduces the number of needed "experiments" (computational analyses) by over 70%. The maximum velocity and takeoff runway are mostly controlled by, whereas the GTOW is primarily impacted by aspect ratio. The suggested technique is applicable to any other layout, allowing for quick optimization trade studies [12].

4.4 Rotor Configurations

There are various configurations that are available for a multicopter. This degree of freedom is possible to the flexible nature of the motor- propulsion positioning of the multicopter. Figure 16 shows the conventional configurations used by the industry and researchers.

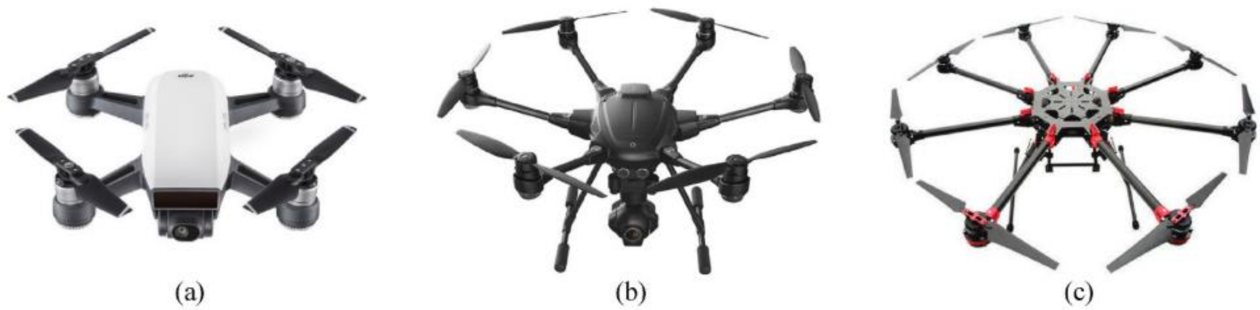

Fig.16. Conventional multicopter configurations. (a) quadcopters, (b) hexacopter, (c) octacopter [37]

Idrissi *et al.,* [9]worked on a novel structure of a quadrotor UAV with the purpose of changing the dynamics during flight. The proposed structure is presented in Figure 17.

The suggested mechanism is described, which comprises of extensible plates that move along horizontal axes from the body frame.

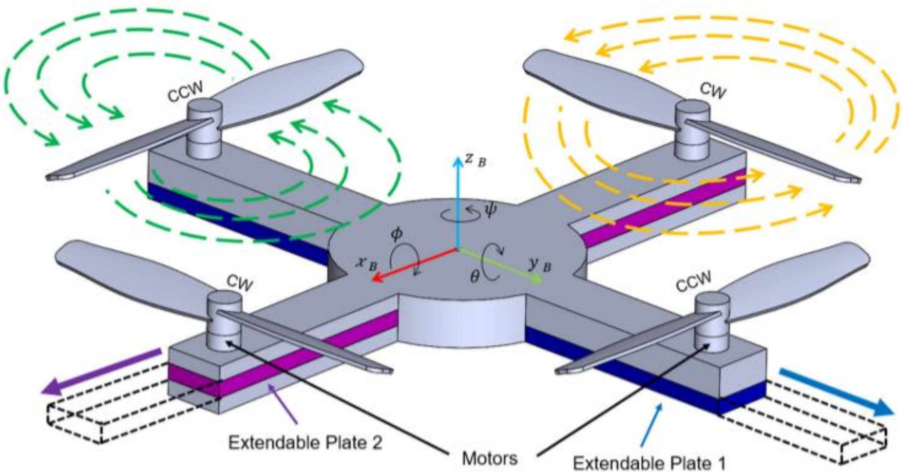

Fig.17. Novel quadrotor structure [9]

To show the concept and analyse the vehicle behaviour as the structure changes during flight, basic PID controllers were constructed. A physical modelling programme is also used to investigate rigid body multi-body interactions as well as dynamic response. To show the concept and analyse the vehicle behaviour as the structure changes during flight, basic PID controllers were constructed. A physical modelling programme is also used to investigate rigid body multi-body interactions as well as dynamic response [9].

Tolba & Shirinzadeh [41]provides a nonlinear mathematical model and an adaptive control approach for imbalanced MUAV configurations in which the vehicle's centre of gravity is arbitrarily positioned. The MUAV dynamics model and the MUAV mapping matrices comprise the model. Two innovative MUAV classification algorithms, as well as a new set of MUAV geometric descriptive characteristics, are provided to define the structure and values of these mapping matrices for every MUAV configuration. Following that, a configuration-adaptive controller that adjusts to the MUAV configuration types is designed and applied to three distinct MUAV configurations using nonlinear simulations. The simulation results demonstrated the efficacy of the general method used as a design and analysis tool enabling designers/researchers to easily model, control, simulate, and compare various MUAV configurations for a specific application [41].

Wang & Zhou [43] presented and examined a hand-launched solar-powered unmanned aerial vehicle (UAV) with flying wings. The flow with a low Reynolds number (LRN) is quasi-steadily simulated by solving the full three-dimensional Reynolds Averaged Navier-Stokes (RANS) governing equations coupled with the k_T -k_L- ω transition model, while propeller performance is evaluated using the multiple-rotating reference frame (MRF) method. Both the cruising and low-speed takeoff aerodynamic evaluations are detailed, including the aerodynamic force analysis and the propeller/wing integrated flow mechanism study. The results show that the current UAV can fulfil the high-efficiency cruise criteria very well while also having the capacity to take off at a low-speed hand-launched condition and a relatively low Reynolds number by making efficient use of the energy injected into the flow field by the propeller rotation [43].

Mohamed *et al.,* [18] outlines the design, microfabrication, and testing of a revolutionary Micro-Aerial Vehicle (MAV) that is modelled after a genuine locust. Actual locust bug attributes are utilised to develop a micro-scale MAV that can replace standard versions that resemble dragonflies and birds. According to the results, the innovative MAV's critical factors for take-off under regular locust performance characteristics include its weight and strength. Computational Fluid Dynamics (CFD) simulations are run at 10°, 20°, and 30° angles of attack with flapping frequencies of 19 Hz, 24 Hz, 30 Hz, 35 Hz, and 40 Hz to examine and optimise the aerodynamic performance of this proposed MAV. The proposed MAV could raise its own weight at a frequency greater than 35 Hz. Furthermore, at flap- ping frequencies of 35 Hz, the MAV will be able to hover [18].

4.5 Hover & Forward Flight

Yongjie *et al.,* [33] tried to predict the unsteady aerodynamic flow around helicopter rotors in hover and forward flight based on a hybrid of Euler wake method. It was found that the hybrid approach utilised is faster than the usual CFD method and will become more efficient as the number of blades increases. A conventional hover case can save around 46.4 percent of CPU time, while a forward-flight scenario can save more than 70 percent of CPU time, and the process becomes more efficient as the number of blades rises [33].

4.6 Actuator Method

Kim *et al.,* [13] evaluated the practically of using actuator method to carry out aerodynamic analysis of two aircraft with multiple propellers. The forces and moments generated by the propellers are discovered to render the QTP UAV's longitudinal and directional stabilities unstable. It was found that actuator techniques have significant promise for aerodynamic analysis since they are computationally efficient in terms of cost, time, and accuracy [13].

4.7 Transition Prediction

Chen *et al.,* [3]suggested a transition prediction method based on the coupled Michel transition Criterion and intermittency factor (γ) for aerodynamic analysis be carried out on low-speed fixed-wing UAVs. To calculate the transition momentum thickness Reynolds number $Re_{\theta t}$, the Michel transition criteria is used. The critical momentum thickness Reynolds number $Re_{\theta c}$ and the length of the transition zone F_{length} are then calculated using an empirical relationship. Finally, using the FLUENT platform, the improved transition model is linked with Reynolds Averaged Navier-Stokes (RANS) equations to perform an aerodynamic study. The approach is proven using the SD7032 airfoil and the FX 63-137 wing. Results on various angle of attacks can be seen in Figure 18(a) and 18(b).

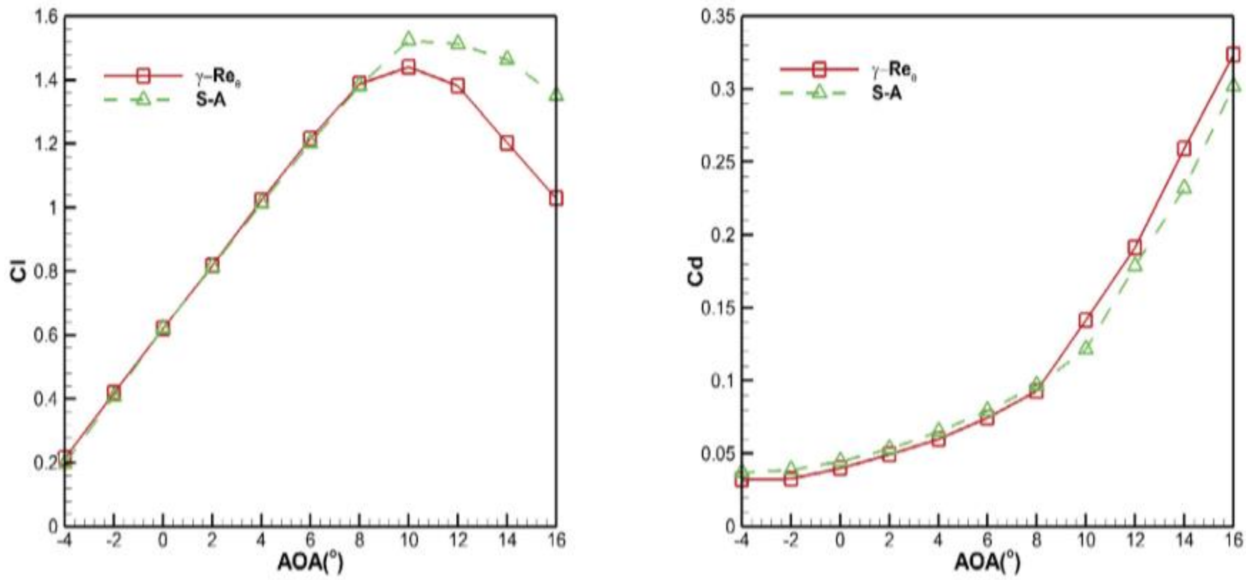

Fig.18(a). Lift coefficient [3] **Fig.18(b).** Drag coefficient [3]

When the angle of attack is less than 8, the lift coefficient of the UAV varies linearly with the angle of attack. The drag coefficient varies significantly across all angles of attack. When the drag coefficient determined by the S-A model is greater than that calculated by the transition model, the inaccuracy exceeds 12 percent at = 0 and 8.3 percent at = 4. When the angle of attack exceeds 8, the excessive loss generation of the laminar-transition separation bubble outweighs the beneficial impact of lower losses in the linked laminar boundary layer, resulting in increased drag by transition model [3].

4.8 Low Fidelity Study

Loureiro *et al.,* [42]employed Blade Element Momentum theory (BEMT) and CFD for the analysis of an APC propeller with a dimension of 14 x 7e. Geometric modelling was done with a 3D scanner, and simulations were done with BEMT and CFD. Two formulations were used in the BEMT model analyses. The first examined a linear lift coefficient up to the stall limits but did not provide post-stall lift coefficients. The second includes three-dimensional flow equilibrium effects and better mimics post-stall situations. Two techniques for the compatibility of the revolving and stationary domains were tested in the CFD models: the stationary frozen rotor (FR) and the transient arbitrary mesh interface (AMI). The turbulence model k SST was used. The Gamma Theta transitional model was also studied to investigate the influence of the transition laminar-turbulent boundary layer. Fig. 19 shows difference between models for K_t and K_p along the advance ratio [42].

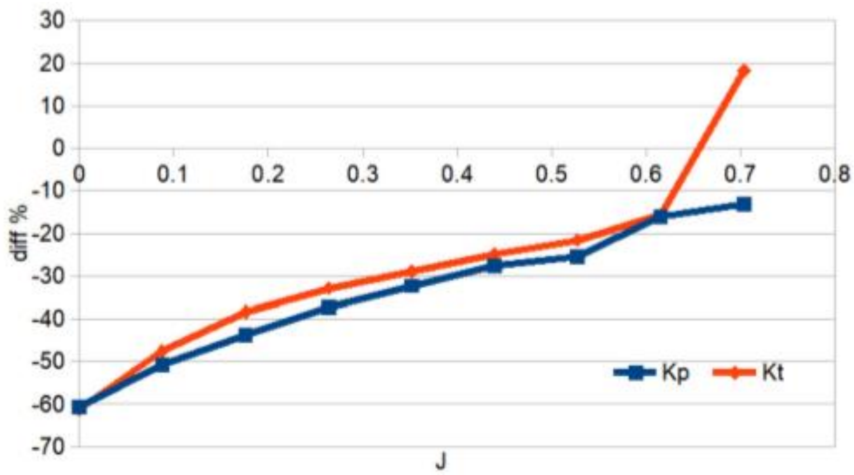

Fig.19. Difference between FR and AMI [42]

The CFD-AMI model, on the other hand, produces better results at higher advanced ratio velocities but is computationally more costly. It was discovered that the suitable analytical technique selection had a substantial association with the Reynolds number. The BEMT models produced the greatest results for low advanced ratio velocities. BEMT linear model overestimated power and efficiency for high advance ratio, however BEMT with Tri dimensional flow equilibrium produced consistent findings at a cheap computational cost[42].

4.8 Energy Dynamics

Michel *et al.,* [16] create a system-level model by merging sub-models of diverse physical dynamics, such as rotor-propeller aerodynamics, electro-mechanical dynamics of the motor and motor controller, electrical dynamics of the battery, and rigid body dynamics of the airframe. The model, which has been parameterized and verified by component and vehicle tests, can capture crucial system variables and their mutual influences during flight. The model generates the link between battery voltage and key propulsion parameters under various PWM actuation orders. This is shown in Figure 20(a), 20(b) and 20(c).

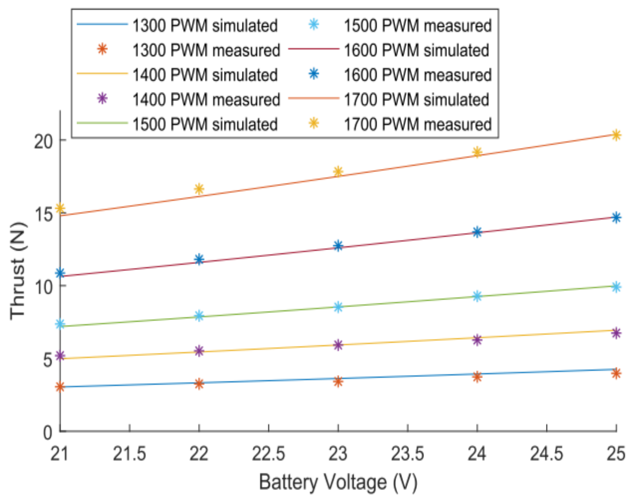

Fig.20. (a) Thrust[16]

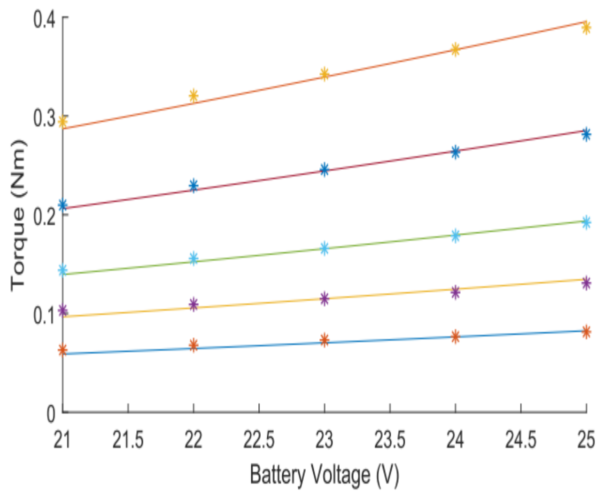

Fig.20. (b) Torque[16]

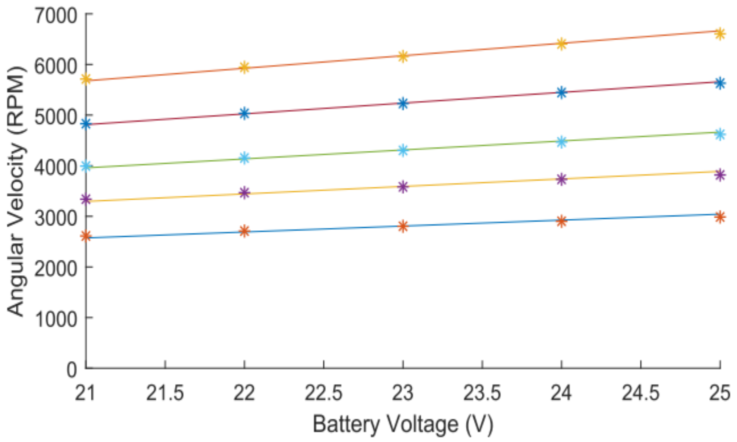

Fig.20. (c) Angular velocity [16]

There is an average loss of 24.8 percent, 23.5 percent, and 13.4 percent in propeller thrust, torque, and rotor angular velocity across the entire PWM range, with maximum decreases of 26.5 percent, 26.2 percent, and 14.4 percent in each. It was found that the reduction in battery voltage causes the multicopter to have a limited flight duration as compared to when battery health is conserved. The connection of the dynamics of the battery, ESC, motor, and propeller can explain this result [16].

5. Conclusions

The rising popularity of multicopters has increased interest in increasing efficiency and optimizing the UAVs. This has become a key motivation for researchers. Extensive work on aerodynamics would give rise to better multicopters and further increase its appeal to key industries. Researchers have done studies involving various angles of attacks of small propellers. Different performance parameters have also been studied. Ducted multicopters have been assessed in a wind tunnel to further increase the understanding from an aerodynamics standpoint. Wake propagation and flow visualization have been carried out using CFD work. However, few of the wake propagation studies involve wind tunnel tests. Additionally, more studies need to be done on uncommon but rather important configurations so that these can have a beneficiary effect on the multicopter industry.

Most small propeller studies done by researchers have focused on a single motor- propeller unit or a single coaxial motor arm and does not carry out a detailed aerodynamic performance on a complete multicopter setup involving the many propulsion units and the frame of a multicopter. This is crucial since it has been proven that interaction between propulsion units in a multicopter does significantly affect its aerodynamic performance. The tandem distance between each motor arm is to be investigated in a controlled environment such as a wind tunnel test. This is particularly significant involving a coaxial motor since there would be flow interactions between propellers on the same arm and the motor arm in parallel to it.

Even studies done on a single motor arm do not often involve ground or wall effect studies. Researchers have mainly done ground effect studies using CFD work due to its varied advantages. However, this simulation work needs to be verified with data from a wind tunnel test of a similarly small multicopter.

Future wind tunnel tests also need to involve hover and off- hover conditions. The flight aspect of the multicopter in a wind tunnel needs to be looked at since numerous studies have been carried out on flight aerodynamics. The study of flight aerodynamics on a wind tunnel can pave the way for it to be a benchmark for cost effective solutions rather than involving expensive flight controllers and algorithms. The titling of the propeller unit would be able to simulate flight characteristics of the UAV and therefore studies could be done in a wind tunnel and reliable data could be obtained due to the controlled environment facilitated by the wind tunnel.

Extensive work has been undertaken by researchers in the past using CFD. Scope of studies ranging from thrust generation to wake propagation have been carried out. Nevertheless, very few studies involve a complete multicopter setup. This is due to its complex nature and the high computing power needed to accurately carry out the simulation.

More configurations of the multicopter also need to be studied using CFD work. Most previous work done has involved the commonly used configurations of a quadrotor. Some uncommon setups serve a specific purpose far better than a quadcopter. An H-configured hexacopter would be able to carry greater payload and of bigger size compared to quadcopter.

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References

[1] NC, Ajay Vishwath, Arvind R. Yadav, Deep Mehta, Jatin Belani, and Ravi Raj Chauhan. "A guide to novice for proper selection of the components of drone for specific applications." *Materials Today: Proceedings* 65 (2022): 3617-3622. https://doi.org/10.1016/j.matpr.2022.06.187.

[2] Azarov, Andrey V., Fedor K. Antonov, Mikhail V. Golubev, Aleksey R. Khaziev, and Sergey A. Ushanov. "Composite 3D printing for the small size unmanned aerial vehicle structure." *Composites Part B: Engineering* 169 (2019): 157-163. https://doi.org/10.1016/j.compositesb.2019.03.073.

[3] Chen, Lili, Zheng Guo, Xiaolong Deng, and Zhongxi Hou. "Aerodynamic performance and transition prediction of low-speed fixed-wing unmanned aerial vehicles in full configuration based on improved γ− Reθ model." *Aerospace Science and Technology* 107 (2020): 106281. https://doi.org/10.1016/j.ast.2020.106281.

[4] Czyż, Zbigniew, Paweł Karpiński, Krzysztof Skiba, and Mirosław Wendeker. "Wind tunnel performance tests of the propellers with different pitch for the electric propulsion system." *Sensors* 22, no. 1 (2021): 2. https://doi.org/10.3390/s22010002.

[5] Dantsker, Or D., Marco Caccamo, Robert W. Deters, and Michael Selig. "Performance Testing of APC Electric Fixed-Blade UAV Propellers." In *AIAA AVIATION 2022 Forum*, p. 4020. 2022.

[6] Deng, Shuanghou, Siwei Wang, and Zheng Zhang. "Aerodynamic performance assessment of a ducted fan UAV for VTOL applications." *Aerospace Science and Technology* 103 (2020): 105895. https://doi.org/10.1016/j.ast.2020.105895.

[7] Franzmann, Christian, Friedrich Leopold, and Christian Mundt. "Low-interference wind tunnel measurement technique for pitch damping coefficients at transonic and low supersonic Mach numbers." *Aerospace* 9, no. 2 (2022): 51. https://doi.org/10.3390/aerospace9020051.

[8] Hu, Haitao, Yannian Yang, Yu Liu, Xiaomin Liu, and Yong Wang. "Aerodynamic and aeroacoustic investigations of multi-copter rotors with leading edge serrations during forward flight." *Aerospace Science and Technology* 112 (2021): 106669. https://doi.org/10.1016/j.ast.2021.106669.

[9] Idrissi, Moad, Mohammad Salami, and Fawaz Annaz. "Modelling, simulation and control of a novel structure varying quadrotor." *Aerospace Science and Technology* 119 (2021): 107093. https://doi.org/10.1016/j.ast.2021.107093.

[10] Jo, Daeil, and Y. Kwon. "Vertical takeoff and landing wing developed for long distance flight and stable transit flight." *International Journal of Mechanical Engineering and Robotics Research* 8, no. 5 (2019). https://doi.org/10.18178/ijmerr.8.5.797-802.

[11] Jody Dascalu. 2022. “Aerodynamics of Multirotor Drones.” GlobalSpec. March 8, 2022.

[12] Kapsalis, S., P. Panagiotou, and K. Yakinthos. "CFD-aided optimization of a tactical Blended-Wing-Body UAV platform using the Taguchi method." *Aerospace Science and Technology* 108 (2021): 106395. https://doi.org/10.1016/j.ast.2020.106395.

[13] Kim, Dahye, Yebin Lee, Sejong Oh, Youngmin Park, Jaehoon Choi, and Donghun Park. "Aerodynamic analysis and static stability analysis of Manned/unmanned distributed propulsion aircrafts using actuator methods." *Journal of Wind Engineering and Industrial Aerodynamics* 214 (2021): 104648. https://doi.org/10.1016/j.jweia.2021.104648.

[14] Lauren Nagel. 2023. “Types of Wind Tunnels and How They Work 2023.” TYTO ROBOTICS. February 15, 2023.

[15] Liu, Peiqing. "Aerodynamic Characteristics of Flow Over Low-Speed Airfoils." In *Aerodynamics*, pp. 493-575. Singapore: Springer Nature Singapore, 2022. https://doi.org/10.1007/978-981-19-4586-1_8.
[16] Michel, Nicolas, Peng Wei, Zhaodan Kong, Anish Kumar Sinha, and Xinfan Lin. "Modeling and validation of electric multirotor unmanned aerial vehicle system energy dynamics." *eTransportation* 12 (2022): 100173. https://doi.org/10.1016/j.etran.2022.100173.
[17] Mishra, Aadya, Sourav Pal, and Prabhat Singh. "Design and analysis of an Eight Rotor Co-Axial UAV using carbon fiber composites." *Materials Today: Proceedings* 68 (2022): 1011-1015. https://doi.org/10.1016/j.matpr.2022.08.206.
[18] Mohamed, Mohamed A., Talal Maksoud, Rodney J. Santos, Mohamed Hefny Salim, and Mohamed FC Esmail. "Numerical simulation of the aerodynamic performance of a novel micro-aerial vehicle mimicking a locust." *Ain Shams Engineering Journal* 12, no. 3 (2021): 2935-2945. https://doi.org/10.1016/j.asej.2021.01.022.
[19] ZADEH, Parviz MOHAMMAD, and Mohsen Sayadi. "An efficient aerodynamic shape optimization of blended wing body UAV using multi-fidelity models." *Chinese Journal of Aeronautics* 31, no. 6 (2018): 1165-1180. https://doi.org/10.1016/j.cja.2018.04.004.
[20] Nancy Hall. "Closed Return Wind Tunnel". NASA. May 13, 2021.
[21] Nancy Hall. "Types of Wind Tunnels". NASA. May 13, 2021.
[22] Panza, Simone, Davide Invernizzi, Mattia Giurato, and Marco Lovera. "Design and characterization of the 2DoF Drone: a multirotor platform for education and research." *IFAC-PapersOnLine* 54, no. 12 (2021): 32-37. https://doi.org/10.1016/j.ifacol.2021.11.006.
[23] Pasquali, Claudio, Jacopo Serafini, Giovanni Bernardini, Joseph Milluzzo, and Massimo Gennaretti. "Numerical-experimental correlation of hovering rotor aerodynamics in ground effect." *Aerospace Science and Technology* 106 (2020): 106079. https://doi.org/10.1016/j.ast.2020.106079.
[24] Paz, C., E. Suárez, C. Gil, and C. Baker. "CFD analysis of the aerodynamic effects on the stability of the flight of a quadcopter UAV in the proximity of walls and ground." *Journal of Wind Engineering and Industrial Aerodynamics* 206 (2020): 104378. https://doi.org/10.1016/j.jweia.2020.104378.
[25] Paz, C., E. Suárez, C. Gil, and J. Vence. "Assessment of the methodology for the CFD simulation of the flight of a quadcopter UAV." *Journal of Wind Engineering and Industrial Aerodynamics* 218 (2021): 104776. https://doi.org/10.1016/j.jweia.2021.104776.
[26] Raja, Vijayanandh, Senthil Kumar Solaiappan, Parvathy Rajendran, Senthil Kumar Madasamy, and Sunghun Jung. "Conceptual design and multi-disciplinary computational investigations of multirotor unmanned aerial vehicle for environmental applications." *Applied Sciences* 11, no. 18 (2021): 8364.. https://doi.org/10.3390/app11188364.
[27] Ramasamy, Manikandan, Timothy E. Lee, and J. Gordon Leishman. "Flowfield of a rotating-wing micro air vehicle." *Journal of aircraft* 44, no. 4 (2007): 1236-1244. https://doi.org/10.2514/1.26415.
[28] Rohacs, Jozsef. "Goal-and Object-Oriented Models of the Aerodynamic Coefficients." *Flight Physics: Models, Techniques and Technologies* (2018): 159. https://doi.org/10.5772/intechopen.71419.
[29] Rostami, Mohsen, and Amir hamzeh Farajollahi. "Aerodynamic performance of mutual interaction tandem propellers with ducted UAV." *Aerospace Science and Technology* 108 (2021): 106399. https://doi.org/10.1016/j.ast.2020.106399.
[30] Sanwale, Jitu, and Dhan Jeet Singh. "Aerodynamic Parameters Estimation Using Radial Basis Function Neural Partial Differentiation Method." *Defence science journal* 68, no. 3 (2018). https://api.semanticscholar.org/CorpusID:21671529.
[31] Sebbane, Yasmina Bestaoui. *A first course in aerial robots and drones*. CRC Press, 2022. https://doi.org/10.1201/9781003121787.
[32] Serrano, David, Max Ren, Ahmed Jawad Qureshi, and Sina Ghaemi. "Effect of disk angle-of-attack on aerodynamic performance of small propellers." *Aerospace Science and Technology* 92 (2019): 901-914. https://doi.org/10.1016/j.ast.2019.07.022.
[33] Yongjie, Shi, Zhao Qijun, Fan Feng, and Xu Guohua. "A new single-blade based hybrid CFD method for hovering and forward-flight rotor computation." *Chinese Journal of Aeronautics* 24, no. 2 (2011): 127-135. https://doi.org/10.1016/S1000-9361(11)60016-2.
[34] Shukla, Dhwanil, Nandeesh Hiremath, Sahaj Patel, and Narayanan Komerath. "Aerodynamic interactions study on low-Re coaxial and quad-rotor configurations." In *ASME International Mechanical Engineering Congress and Exposition*, vol. 58424, p. V007T09A023. American Society of Mechanical Engineers, 2017. https://doi.org/10.1115/IMECE2017-71005.
[35] Shukla, Dhwanil, and Narayanan Komerath. "Multirotor drone aerodynamic interaction investigation." *Drones* 2, no. 4 (2018): 43. https://doi.org/10.3390/drones2040043.
[36] Spalart, Philippe R., and V. Venkatakrishnan. "On the role and challenges of CFD in the aerospace industry." *The Aeronautical Journal* 120, no. 1223 (2016): 209-232. https://doi.org/10.1017/aer.2015.10

[37] Throneberry, G., C. M. Hocut, and A. Abdelkefi. "Multi-rotor wake propagation and flow development modeling: A review." *Progress in Aerospace Sciences* 127 (2021): 100762. https://doi.org/10.1016/j.paerosci.2021.100762.

[38] Throneberry, Glen, Christopher M. Hocut, Fangjun Shu, and Abdessattar Abdelkefi. "Multi-rotor wake propagation investigation for atmospheric sampling." In *AIAA Aviation 2019 Forum*, p. 3604. 2019. https://doi.org/10.2514/6.2019-3604.

[39] Throneberry, Glen, Adam Takeshita, Christopher M. Hocut, Fangjun Shu, and Abdessattar Abdelkefi. "Experimental investigation on the drone-wake interaction of multi-rotor systems in forward flight." In *AIAA Scitech 2021 Forum*, p. 0938. 2021. https://doi.org/10.2514/6.2021-0938.

[40] Throneberry, Glen, Adam Takeshita, Christopher Hocut, Fangjun Shu, and Abdessattar Abdelkefi. "Experimental investigations on multi-rotor wake development and propagation." In *AIAA AVIATION 2020 FORUM*, p. 2741. 2020. https://doi.org/10.2514/6.2020-2741.

[41] Tolba, Mohamed, and Bijan Shirinzadeh. "Generic modeling and control of unbalanced multirotor UAVs." *Aerospace Science and Technology* 121 (2022): 107394. https://doi.org/10.1016/j.ast.2022.107394.

[42] Loureiro, Eric Vargas, Nicolas Lima Oliveira, Patricia Habib Hallak, Flávia de Souza Bastos, Lucas Machado Rocha, Rafael Grande Pancini Delmonte, and Afonso Celso de Castro Lemonge. "Evaluation of low fidelity and CFD methods for the aerodynamic performance of a small propeller." *Aerospace Science and Technology* 108 (2021): 106402. https://doi.org/10.1016/j.ast.2020.106402.

[43] Wang, Kelei, and Zhou Zhou. "An investigation on the aerodynamic performance of a hand-launched solar-powered UAV in flying wing configuration." *Aerospace Science and Technology* 129 (2022): 107804. https://doi.org/10.1016/j.ast.2022.107804.

[44] Wang, Ruochen, Guoxin Zhang, Pei Ying, and Xiaoping Ma. "Effects of key parameters on airfoil aerodynamics using co-flow jet active flow control." *Aerospace* 9, no. 11 (2022): 649. https://doi.org/10.3390/aerospace9110649.

[45] Heyong, X. U., and Y. E. Zhengyin. "Numerical simulation of unsteady flow around forward flight helicopter with coaxial rotors." *Chinese Journal of Aeronautics* 24, no. 1 (2011): 1-7. https://doi.org/10.1016/S1000-9361(11)60001-0.

[46] Zhang, Hao, Lijun Qi, Yalei Wu, Elizabeth M. Musiu, Zhenzhen Cheng, and Pei Wang. "Numerical simulation of airflow field from a six–rotor plant protection drone using lattice Boltzmann method." *Biosystems Engineering* 197 (2020): 336-351. https://doi.org/10.1016/j.biosystemseng.2020.07.018.

[47] Zhu, Hang, Zihao Jiang, Hang Zhao, Siyu Pei, Hongze Li, and Yubin Lan. "Aerodynamic performance of propellers for multirotor unmanned aerial vehicles: Measurement, analysis, and experiment." *Shock and Vibration* 2021 (2021): 1-11. https://doi.org/10.1155/2021/9538647.

[48] Zhu, He, Hong Nie, Limao Zhang, Xiaohui Wei, and Ming Zhang. "Design and assessment of octocopter drones with improved aerodynamic efficiency and performance." *Aerospace Science and Technology* 106 (2020): 106206. https://doi.org/10.1016/j.ast.2020.106206.