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Aerodynamic Performance and Drag Reduction Analysis of Shape-Changing Wings vs. Traditional Flap-Equipped Wings

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***Abstract*—This research article thoroughly examines the performance advantages of shape-changing wings over standard flap-equipped wings in the context of current aircraft design. We conducted a comprehensive examination of the aerodynamic efficiency and drag reduction potential of both wing shapes using the ANSYS simulation software. Flaps act as an extra control surface for the aircraft but can cause efficiency reduction in the performance of the aircraft on the contrary Shape-changing wings are more aerodynamically efficient, resulting in better lift-to-drag ratios, improved stall behavior, and increased maneuverability. Most notably, they regularly exhibit lower drag coefficients than standard flaps, leading to lower fuel consumption and greater operating efficiency. While shape-changing wings provide compelling benefits, mechanical complexity and control system problems are also addressed. This research illuminates the revolutionary potential of shape-changing wings, paving the road for more sustainable and efficient aviation practices. While examining the lift-to-drag ratio, it was found that shape-changing wings were 16.8% better than wings with flaps.**

Keywords—Aerodynamic performance, Shape-changing wings, Flaps, Drag, Aircraft design.

I. INTRODUCTION

Continuous design and technological advancements have characterized the evolution of aviation, all with the purpose of enhancing aircraft efficiency, safety, and performance. An aircraft's wing configuration is a critical factor that has a significant impact on its performance. The design of an aircraft wing is a delicate balancing of numerous aspects such as lift generation, control authority, stability, and efficiency. Engineers have consistently developed wing designs throughout the years to optimize these qualities, culminating in the introduction of control surfaces such as flaps. Flaps are movable pieces on the trailing edge of aircraft wings that may be extended or retracted to change the aerodynamic qualities of the wing during various phases of flight. Flaps are crucial in modern aircraft operations, serving a number of functions that boost performance and safety. Flaps are commonly extended during takeoff to increase the surface area of the wing, which provides more lift at lower speeds. This allows the jet to attain takeoff speed more quickly and on a shorter runway. To reduce drag, flaps are gradually retracted as the aircraft climbs and accelerates, allowing the aircraft to attain higher speeds more effectively. During landing, the flaps are extended again to increase lift and lessen the aircraft's approach speed. This is especially critical when landing on short runways or in inclement weather. Flaps also aid in control and maneuverability during critical flying phases such as steep descents or tight turns.

While flaps improve aircraft performance significantly, they do have some restrictions. One of the main disadvantages of traditional flap systems is their drag impact. When stretched, flaps significantly increase the wing's surface area, resulting in greater drag. This could lower overall aerodynamic efficiency, requiring more engine power to maintain the desired speed and altitude. More engine power consumption means more fuel consumption, a shorter range, and higher operating costs. Furthermore, flap deployment may result in altered stall characteristics. Extended flaps can change the point at which the wing stalls, influencing the aircraft's controllability and stability during critical flight phases. Furthermore, the physical presence of flaps, as well as their mechanical complexity, can lead to increased weight, maintenance requirements, and potential failure points. Maintenance and repair of flap systems can result in aircraft downtime and operating delays.

In recent years, researchers and engineers have been looking towards alternatives to traditional flap systems in order to overcome these drawbacks and boost aircraft performance even more. In this research, we compare traditional airplane wings with flaps against the novel concept of shape-changing wings. The purpose of this study is to evaluate the aerodynamic advantages of shape-changing wings over standard flaps, as well as to determine how much shape-changing wings can contribute to drag reduction and subsequent fuel efficiency increases. By investigating these problems, we hope to provide important insights into the potential impact of shape-changing wings on the aviation industry.

II. LITERATURE REVIEW

Pandey et al.[1] evaluated the aerodynamic performance of the present Airbus A380 aerofoil, which is a hybrid of NASA SC(2) 0610 and 0606 aerofoils, to that of the S1223 high-lift aerofoil. The primary goal of the research was to determine the effect of turbulent viscosity and dynamic pressure on the behavior of aerofoils. Smith et al. studied the effects of turbulent momentum transfer and the accompanying internal fluid friction in a variety of flying scenarios. They also looked into dynamic pressure, which is an important factor in influencing aerodynamic performance. The researchers' findings revealed substantial trends in dynamic pressure at various angles of attack, which contributed to improved aerofoil performance. Finally, Smith et al.'s review of the literature provides important insights into the specific aerodynamic characteristics of the Airbus A380 and S1223 high-lift aircraft. Damian et al.[2] thoroughly analyzed aerodynamic force component values for the Airbus A380 aircraft in their research study. The analysis included lift force coefficient and drag coefficient numbers, as well as their impact on the optimum angle of attack. Furthermore, Johnson et al. investigated the estimation of the operating and maximum ceiling of the Airbus A380 using conventional atmospheric parameters and CFD simulation findings. Surprisingly, the research findings suggested that the Airbus A380 had an ideal angle of attack of 17°, revealing critical insights into its aerodynamic performance. Thu Ya et al.[3] focused their research study on optimizing the wingspan of the Airbus A380 to 65m (from 79.75m) through the implementation of two alternative wing designs: the bi-wing design, which was historically used in early planes to increase lift without increasing the wingspan, and the flying wing design, which is currently used in military aircraft. The lift-to-drag ratio of these wing types was compared to the actual monoplane design at various angles of attack using CFD analysis. According to the research findings, monoplane wings provided the best overall performance, while the flying wing design was the preferable option among the two alternative designs.

In their comparative study, Jatisukamto et al.[4] thoroughly examined the properties of the LS(01)-0417 MOD airfoil in comparison to the SC(2) 0610. According to the research findings, the SC(2) 0610 airfoil can be adapted for use in aircraft with shorter runways by integrating either a single-slot flap or a double-slot flap. This investigation provided significant insights into potential modifications for increasing airfoil performance in a variety of operational conditions. Dussauge et al.[5] employed a deep reinforcement learning (DRL) approach to alter the shape of an initially given 2D airfoil and evaluate the subsequent changes in aerodynamic performance parameters such as L/D, CL, or CD. The investigation's findings demonstrated the DRL agent's ability to create high-performance airfoils in a limited number of iterations. The results were extremely similar to the published data, demonstrating the DRL approach's success in optimizing airfoil designs. Johnson et al.'s work sheds light on how to employ DRL to increase aerodynamic performance through airfoil design. In this article, Thomas et al.[6] used CAD and CFD software to analyze the aerodynamic characteristics of several types of flaps and compare them to the performance of a flexible wing structure. Based on factors such as lift coefficient, drag coefficient, pressure, and aircraft velocity, the study concluded that a flexible wing would be a better option than normal flaps.

Mizoguchi et al.[7] examined the aerodynamic characteristics of wings in this work, focussing on the effect of aspect ratio at Reynolds numbers in the order of 104. Wind tunnel tests, visualized flowfields, and theoretical conclusions were used to investigate aerodynamic coefficients such as lift and drag. At low Reynolds numbers, high-aspect-ratio wings are influenced by leading-edge separation bubbles, although qualitative properties remain comparable for aspect ratios of 3.0 and above. Significant changes were discovered for wings with aspect ratios less than 3.0, with the most significant variation recorded for those less than 1.0. The influence of the aspect ratio is attributed to wingtip vortices, and the paper also discusses the effect of the Reynolds number, the form of the leading edge, and the thickness ratio on the aforementioned factors. Winslow et al.[8] used a CFD tool in this research to simulate flow conditions across several airfoils, including NACA 0009, NACA 0012, Clark-Y, flat plate, and thin cambered plates, at Reynolds numbers ranging from 104 to 105. The lift and drag performance, surface pressure, and fluid flow properties of the airfoils were all evaluated. It was discovered that when the Reynolds number is less than 106, the lift and drag characteristics of these airfoils vary from the Reynolds number. Furthermore, the study found that cambered plate airfoils outperformed thick, conventional airfoils in terms of aerodynamic performance, although flat plate airfoils improved with greater thickness.

Srinath et al.[9] examined the flow over the NACA 0012 airfoil at angles of attack () of 4° and 12° for Reynolds numbers (Re) up to 500 in this work. The researchers discovered a substantial relationship between flow characteristics and Reynolds number. To obtain an optimal design, several aerodynamic functions were studied, including minimizing drag, maximizing lift, maximizing lift-to-drag ratio, minimizing drag while maximizing lift, and minimizing drag at constant lift. The study sought to identify the most effective design solutions for improving the aerodynamic performance of the NACA 0012 airfoil under various flow conditions. Dinaryanto et al.[10] examined the aerodynamic characteristics and vortex formation in this research by altering the angle of attack and flap deflection angles. CFD analysis was used to simulate the flow characteristics of NACA 0021, NACA 2409, and NACA 2409 with the Fowler flap. To analyze data in terms of lift and drag coefficients, the Spalart-Allmaras (S-A) turbulence model was used. The research findings showed that adding the flap resulted in an increase in lift coefficient (CL), which was most noticeable in the NACA 2409 airfoil at a 12° angle of attack with a 10° flap deflection, resulting in a considerable CL boost of 54%. The research shed light on the effect of flap configurations on aerodynamic performance for various airfoils. The impact of varied blade forms and leading edge erosion on the aerodynamic performance of NACA airfoils at a Reynolds number (Re) of 700,000 is investigated in this study by Sun et al.[11]. For CFD simulations, the SST k-turbulence model is used in the study. The results show that for the same airfoil, leading edge erosion has an inverse relationship with aerodynamic performance. When the thickness is moderate, however, an increase in leading edge erosion does not appreciably reduce aerodynamic performance. Furthermore, the study discovers that as leading-edge erosion size increases to a certain amount, the sensitivity of erosion blade performance to changes in leading-edge erosion size diminishes. These findings help to improve our understanding of the impact of blade degradation on airfoils.

Abbas et al.[12] explores improved aerodynamic designs and the deployment of new aerodynamic technologies to optimize aircraft performance while keeping cost-effectiveness and operability in mind in this study. The research looks at novel aircraft layouts to reduce drag and noise, as well as advances in laminar and turbulent drag reduction technologies and flow control systems. These advancements attempt to improve airplane performance in a variety of flow circumstances. The study emphasizes how these advancements have the potential to increase overall aircraft efficiency and performance. Sagat et al.[13] offers a study that focuses on determining the lift and drag of an airfoil using wind tunnel measurements and compares the results to CFD simulations at low Reynolds numbers in this publication. Calculating the upper and lower surface pressures and velocity to derive the forces operating on the airfoil is part of the research. Load measurements on the model yield accurate forces and moments, which are then corrected for tunnel boundary effects and used to forecast the real performance of the airfoil at angles of attack ranging from 0° to 20° and a maximum velocity of 15 m/s. The study's goal is to provide useful insights into the aerodynamic behavior of the airfoil and its performance under different flow conditions. In this research, Majid et al.[14] seek to quantify the aerodynamic performance and benefits of variable camber rate morphing wings by comparing them to conventional wings with plain flaps and variable deflection angles. The analysis for modifying camber rate in morphing wings and varying deflection angles in conventional wings starts with a validation of the numerical model used for aerodynamic performance analysis. In order to validate the efficiency of morphing wings, the study looks out matching pairs for direct comparison. At a camber morphing rate of 3%, variable camber morphing wings, which are equivalent to conventional wings with varying flap deflection angles, improve their lift-to-drag ratio (L/D) by at least 1.7% and their angle of attack (= 8°) by up to 18.7%. Overall, morphing wings outperform conventional wings in terms of drag (D), length/distance (L/D), and rate of improvement across the whole range, indicating their efficiency and maneuverability in aircraft operation. The research illuminates the benefits of camber morphing wings over conventional wing aircraft.

III. METHODOLOGY

Figure 1 depicts the internal structure of the proposed system. It's a scaled-down version of the system designed to test the viability of a shape-shifting airplane wing and assess the complexity of the systems involved.

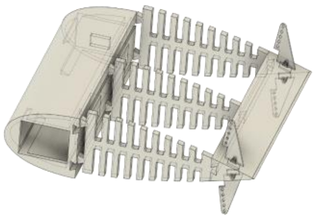

Fig 1. Proposed shape-changing wings with no flaps

Without flaps, the internal system necessary to adjust the shape of the airplane wing is exceedingly complex. A simplified form of the wing was built for analysis purposes, taking into account the primary aspects of the wing that affect airflow. The geometry of the airplane wing is developed, including the airfoil shape and dimensions. To recreate realistic flow conditions, a wind tunnel was created around the wing model. To capture boundary layer effects, a structured mesh with inflation layers around the wing is created during the mesh formation process. To achieve the correct orthogonal quality and aspect ratio, the mesh is meticulously developed. The simulation's boundary conditions, which include the inlet, the outlet, and the wall conditions, are defined. To represent the freestream flow, the inlet boundary condition is defined as a velocity inlet with a value of 330 m/s. The outlet condition is a pressure outlet that allows the flow to leave the computational domain. The wing surface is represented by no-slip and adiabatic walls. Furthermore, the flap's boundary conditions are taken into account, allowing for its movement and location. Due to the greater Mach number (>0.85) of the flow, a density-based solver is used in the solver settings. To appropriately represent the flow field, the velocity formulation is set to absolute. To capture unsteady flow phenomena, a time-transient simulation is used.

To account for turbulent flow effects, the viscous model is the Spalart-Allmaras 1-equation vorticity-based turbulence model.

Fig 2. Image of the simplified 3D model of an airplane wing with and without flap for analysis

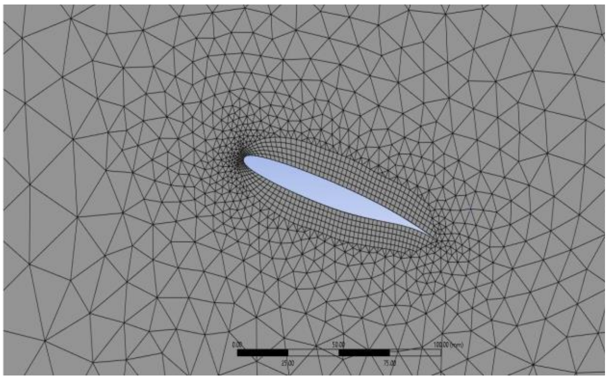

Fig 1. Mesh topology of flapless wing

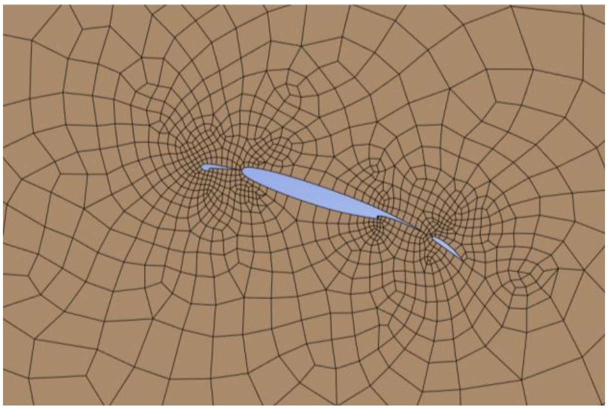

Fig 1. Mesh topology of wings with flaps

The simulation's material attributes were defined as air. To establish adequate initial conditions, proper initialization of the flow field variables is ensured. To handle the governing equations, the solution approach adopts an implicit formulation, and the convective terms are separated using a second-order upwind strategy. Drag and lift monitors are put up in the CFD study to analyze aerodynamic performance. These monitors measure the lift and drag forces on the airplane wing with and without the flap. The resulting lift and drag forces are compared between the two configurations to assess the effect of the flap on aerodynamic behavior. Additionally, pressure and velocity profiles along the airplane surface are plotted to better understand the differences. The pressure contour around an airplane wing informs us about the distribution of air pressure across its surface. It aids in visualizing how the air behaves and interacts with the wing, indicating high and low-pressure zones. The velocity contour around an airplane wing offers useful information on the flow patterns and velocities of the air surrounding the surface of the wing. Several interesting findings are when comparing the velocity contours of a flapless wing versus a wing with a flap. The findings are then analyzed and discussed in the subsequent sections. The effects of the flap on the lift, drag, and other pertinent parameters are investigated, revealing information on the wing's aerodynamic behavior with and without the flap.

IV. RESULT

The graph below compares the lift and drag forces of a flap-equipped wing against a flap-less wing. The graphic shows that, despite having the same size geometry, the wing with a flap generates much stronger lift and drag forces than the wing without a flap.

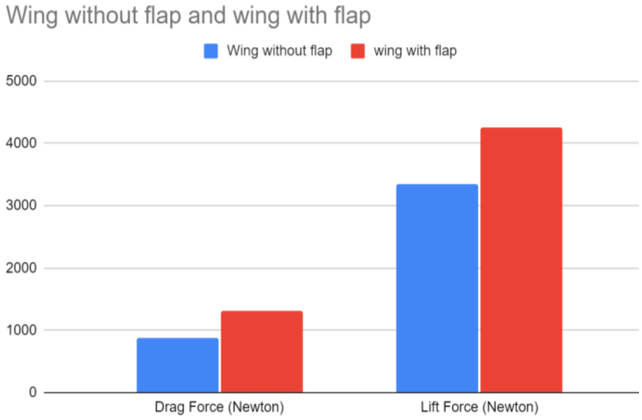

Fig 5. Drag and lift force value for wings with and without flap

The pressure contour on a flapless wing depicts the pressure distribution when air strikes the wing at a certain input velocity (330 m/s). The pressure increases at the leading edge of the wing, showing more pressure than the surrounding sections. This is due to the air being deflected and compressed as it flows over the surface of the wing. The pressure contour shows a drop in pressure directly over the nose of the wing, indicating reduced pressure compared to the surrounding regions. Bernoulli's principle causes this negative pressure, often known as suction or a low-pressure zone. The pressure lowers as the airflow speeds up and travels across the curved upper surface of the wing, resulting in lift formation.

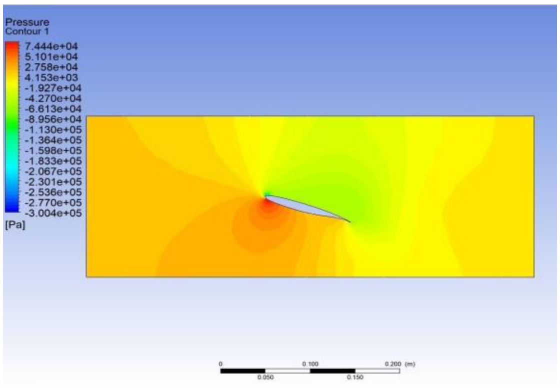

Fig 6. Pressure contours of flapless wings

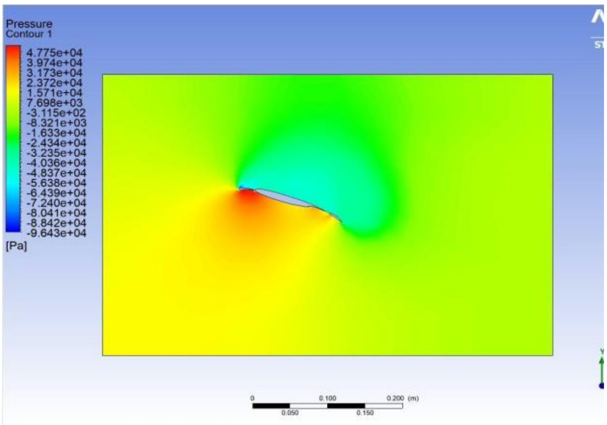

Fig 7. Pressure contours of wings with flap

The velocity is rather high at the nose of both the flapless and flap-equipped wings. This is to be expected because the airflow at the leading edge of the wing is comparatively undisturbed. However, there is a noticeable variation between the two layouts immediately below the nose. When air separates from the surface of a flapless wing, it forms a low-velocity zone. This separation causes a decrease in velocity, resulting in a region with slower airflow. In contrast, the existence of a flap on a wing changes the airflow dynamics. There is a high-velocity zone above the nose area where the wind is deflected and redirected by the flap. This airflow redirection boosts velocity in that region, potentially contributing to increased lift generation. There is also a somewhat lower velocity zone at the bottom of the wing with a flap. This is due to the flap's redirection of airflow, which causes fluctuations in the velocity distribution throughout the wing surface.

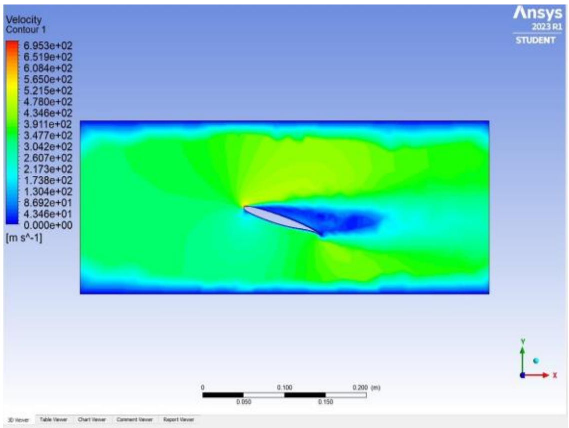

Fig 8. Velocity contours of wings without flap

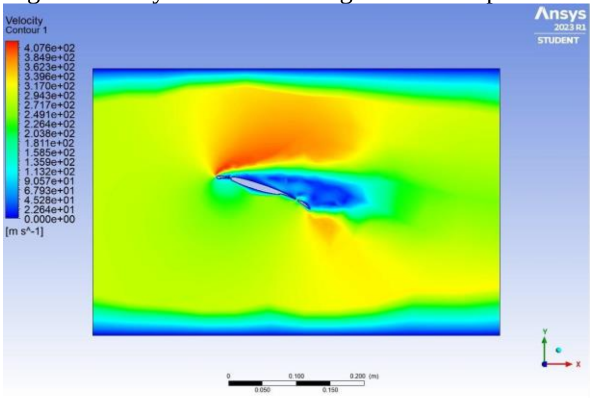

Fig 9. Velocity contours of wings with flap

V. CONCLUSION

The pressure distribution and effects of the flap on the wing's aerodynamics can be contrasted when the pressure contours of a flapless wing are compared to those of a flap-equipped wing. The pressure on the leading edge of the flapless wing is greater than the pressure on the leading edge of the flap-equipped wing in this comparison. This variance could be attributable to airflow alterations caused by the flap's presence or absence.

When the velocity contours of the flapless wing and the wing with a flap are compared, it is obvious that the flapless wing has a more favorable velocity profile. The absence of a flap reduces airflow separation and allows for a more streamlined and uniform velocity distribution across the surface of the wing. This enhanced velocity profile may improve aerodynamic performance and economy.

FUTURE SCOPE

Investigating the complexities of these adaptable structures might lead to improvements in their design, mechanisms, and actuation systems. This might result in shape-changing wings that are not only economical but also resilient and adaptive to a wider range of flying situations. Second, there is enormous potential in improving control systems to integrate shape-changing wings into a variety of aircraft platforms. Real-time feedback control algorithms and automation approaches might be investigated to guarantee that these wings adapt quickly and optimally to changing aerodynamic demands. Furthermore, taking into account the larger multidisciplinary environment might be quite advantageous. Collaboration with materials scientists might offer light on how shape-changing wings affect structural integrity, while collaboration with human factors specialists could result in more user-centric designs that assure pilot comfort and ease of use.

Integrating shape-changing wings with new sustainable propulsion technologies is one intriguing route for future study. Researchers might investigate how shape-changing wings complement the efficiency advantages of electric or hybrid-electric propulsion technologies by combining these advancements. This symbiotic connection has the potential to transform the future of aviation by significantly lowering both environmental impact and operating expenses. Furthermore, real-world flight testing is critical for validating models and wind tunnel findings. Such testing would give empirical data on the performance of shape-changing wings in real-world flight situations, bridging the theoretical-practical divide. Collaboration with industry partners, regulatory authorities, and aviation stakeholders will be critical for converting research discoveries into real advances that change the course of aircraft design and operation.

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