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Alula Effect on Aerodynamic Performance of Small UAVs Wing Configuration

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Abstract. The application range of small UAVs for civil purposes such as aerial imaging, agricultural pest control and, corps management as well as drone delivery has been increasing throughout recent years. Promising results are observed from recent studies which support the effectiveness of the bio-inspired approach in improving the aerodynamic efficiency of small UAVs. However, very limited studies have investigated the effect of Alula on the aerodynamic performance of wing geometries. This research investigates the effects of employing Alula on the aerodynamic efficiency of the wing to overcome the challenge of small UAVs efficiency degradation. Numerical and experimental investigations are conducted on 6 different Alula configurations. The findings of the investigations shows a reduction in drag for wings and an increase in aerodynamic efficiency by 9% for wings with Alula compared to the conventional wing. It is observed that using Alula configuration helps in delaying flow separation by adding momentum into the flow which resulted in total drag reduction without having a significant effect on the lift. Consequently, the aerodynamic efficiency is increased, and this can be utilized in drone industry to increase the endurance of the flight.

1. Introduction

Unmanned aerial vehicles (UAVs) were initially designed and deployed for military purposes. However with the advancements in Mini-UAVs (MUAVs) and Micro UAVs (MAVs), the applications of UAVs have been extended from military purposes only to civil applications such as aerial imaging, environmental monitoring, search and rescue, agriculture, etc. [1]. The aircraft are equipped with cameras and sensors to obtain live and recorded aerial images as well as corresponding data based on the mission requirements. In order to obtain clear and reliable recordings, low speed flight of the small UAVs is desired due to low altitude flight and limitations in cameras frame rate and sensitivity of different sensors; thermal, humidity, gas, noise and motion sensors namely [2]. Various small UAVs such as Black Widow, SENDER, MITE, etc., have been built and flown throughout the past decade. However, the endurance of these vehicles is significantly less than other flying vehicles which reduce

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the feasibility and reliability of small UAVs [3]. Hence, it is crucial to enhance the aerodynamic efficiency of small UAVs to improve the operational capacity of these vehicles.

Small UAVs operate at chord Reynolds number ranging from 103 to 105 due to their low operating speed (v < 19 m/s) and the aerodynamic efficiency of airfoils is drastically deteriorated in this operating Reynolds number as it is evident in figure 1 [4]. The degradation in aerodynamic performance of airfoils in this sensitive Reynolds number range is caused by dominant viscous forces which extends the laminar characteristics of the flow over airfoil until the flow is opposed by an adverse pressure gradient resulting in early laminar boundary layer separation. Susceptible shear layer characteristics to external disturbance results in laminar turbulent transition and energizing the turbulent shear layer [5]. Consequently the flow reattaches to the airfoil surface resulting in in formation of laminar separation bubble (LSB) at leading and/or trailing edge of the airfoil [6–9]. Formation of LSB results in aerodynamic performance degradation due to increase in drag and/or reduction in generated lift. The length of LSB and the extent of its negative effect on aerodynamic performance depends on the shape of the airfoil, Reynolds number, wing geometry discontinuities and flow disturbance [10].

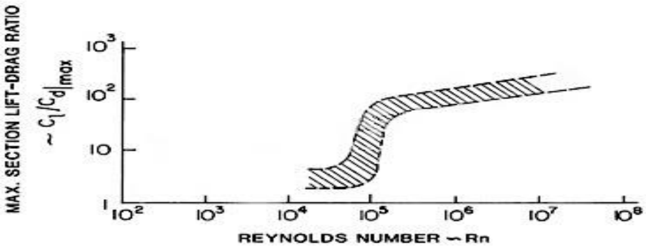


Figure 1. Effect of Re on Airfoil's aerodynamic performance [3]

The aerodynamic performance of different bio-inspired wing geometries was experimentally investigated by Lazos [11]. A planar elliptic wing model was designed as the base model as well as a wing planform with a sinusoidal leading edge (SLE). Three wing designs were inspired by the soaring seagull (GULL), figure 2(c), seagull in high-speed gliding (HECS), figure 2(d), and white shark (SHARK), figure 2(e). Evaluation of the results shows that the best aerodynamic efficiencies among the investigated wings belong to SHARK and HECS swept wing models with a maximum lift-to-drag ratio of 22.43 and 21.36 respectively which is higher than the corresponding ratio of the baseline model by 9.2% and 4.0%. Improvements in aerodynamic efficiency would equate to enhanced endurance and the authors suggest that utilizing bio-inspired wing configurations have a significant contribution to the performance enhancement of low-speed aircrafts.

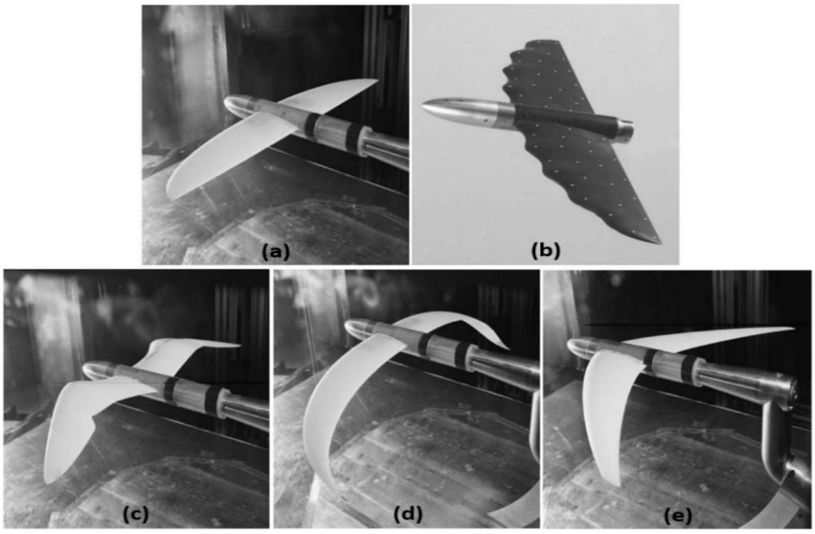


Figure 2. Elliptical wing (a), WLE (b), GULL (c), HECS (d) and SHARK (e) [11]

A flow control like device inspired by bird's wing Alula was investigated by Lee et al. experimentally [12]. Alula is known as the thumb of the wing and birds use it to actively control the flow over the wing at different phases of their flight, especially during soaring and landing. Investigations were conducted on four jouvenile captive magpies using wind tunnel and Particle Image Velocimeter (PIV) to examine the flow behavior around the wing configuration. The findings of the study shows that Alula generates vortices over the wing which helps in the delay of the flow separation (figure 3). As a result, the aerodynamic efficiency is improved.

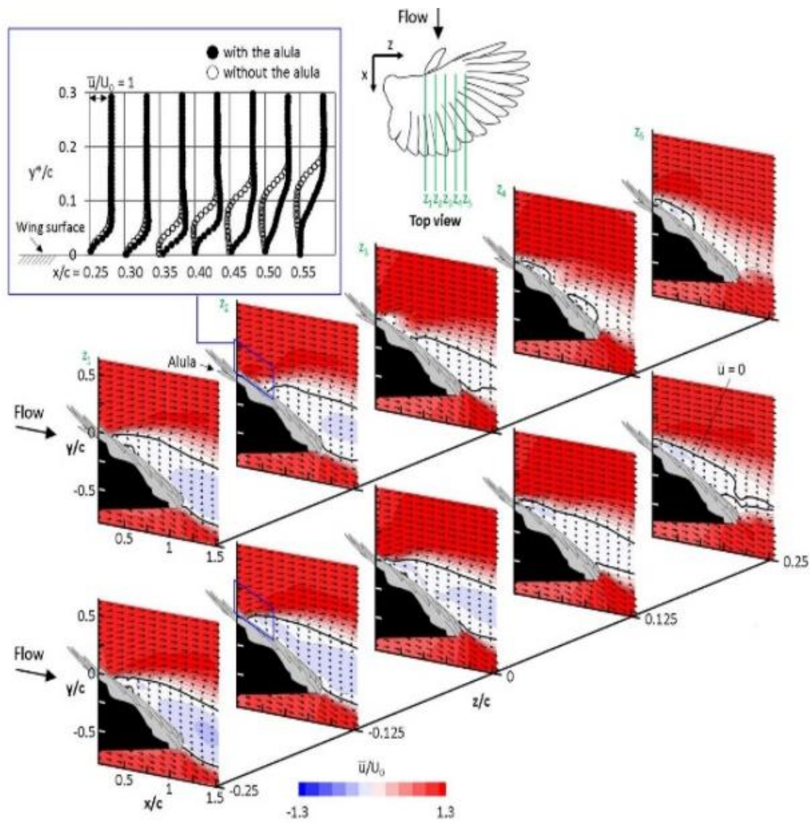


Figure 3. Vortices Generated by Alula [12]

A number of studies have recently investigated the design and application of innovative bioinspired wingtips [13], serrated trailing edges [11,14] as well as Alula configuration [12,15]. Promising results are observed that support the effectiveness of the bio-inspired approach in improving the aerodynamic efficiency of small UAVs. However, very limited studies have investigated the effect of Alula on the aerodynamic performance of wing geometries.

The objectives of this research are aimed to investigate and employ Alula as a bioinspired feature to design an innovative wing configuration to overcome the challenge that aeronautical industries are facing with the efficiency degradation of small UAVs.

The manuscript is organized as follows. The methodology utilized in the investigations including numerical simulations and experiments is described in section 2. The results obtained from the investigations are presented and the effectiveness of Alula on aerodynamic efficiency enhancement is discussed in section 3 and the concluding statements are given in section 4.

2. Methodology

2.1. Numerical Simulation

The aerodynamic characteristics of wing configurations are predicted using numerical simulation. A total of 6 different Alula configurations with straight and raked trailing edges and Alula to wingspan ratios of 7%, 10%, and 15% are investigated. ANSYS FLUENT 19.0 is utilized to conduct the simulations on wing models prepared using SOLIDWORKS 18.0. A C-Type boundary domain is identified as the efficient method for fluid domain generation and the domain boundaries are located 12 chords away from the wing as shown in figure 4 to allow the flow development around the wing. A grid independence study was then conducted to obtain an efficient mesh with a first layer Y+ less than 5. The quality of the mesh is controlled by adjusting the grid sizing and surface inflation of the wing surface.

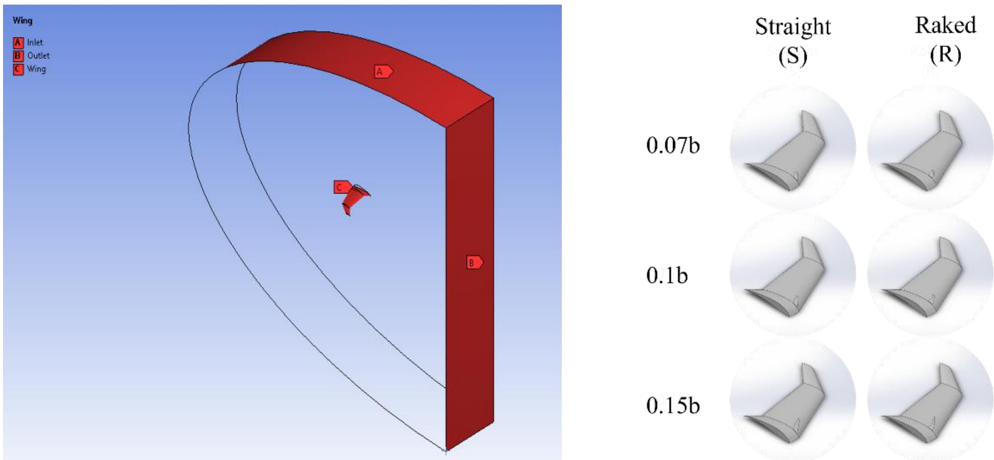


Figure 4. Fluid Domain around the Wing (Left) and Wing Configurations (Right)

The low speed of small UAVs under investigation in the research lends the flow regime to incompressible flow since the Mach number is less than 0.3. Therefore, a pressure-based solver and k-ω SST turbulence model are used for numerical simulations with fluid properties presented in Table 1.

Table 1. Fluid Properties Assumptions for Simulations

Fluid Properties			
Fluid	Temperature (°C)	Density ($\frac{Kg}{m^3}$)	Viscosity ($\frac{Kg}{ms}$)
Air	15 to 25	1.225	1.7894×10^{-5}

For a valid aerodynamic characteristic comparison of different wing configurations, it is required to achieve similar boundary conditions and physical similarity by maintaining a constant Reynolds number throughout the investigations. The corresponding flow speed (V) for different wing configurations is calculated using Eq. (1) based on the mean aerodynamic chord length of the wing (cMAC). The mean aerodynamic chord corresponds to chord of the wing for rectangular wings while for non-rectangular wings it is calculated using Eq. (2).

$$Re = \frac{\rho V c_{MAC}}{\mu} \quad (1)$$

$$c_{MAC} = \frac{2\times[C_r{}^2+(C_r\times C_t)+C_t{}^2]}{3\times(C_r+C_t)} \quad (2)$$

where C_r and C_t are the root and tip chord length of the wing respectively.

2.2. Experimental Method

The new wing's aerodynamic characteristics obtained from numerical simulations are validated by conducting wind tunnel experiments on wing models. The experiments are conducted using Taylor's University Wind Tunnel (TUWT) shown in figure 5, which is an open subsonic wind tunnel with a rectangular test section (0.303 m × 0.303 m × 0.885 m).

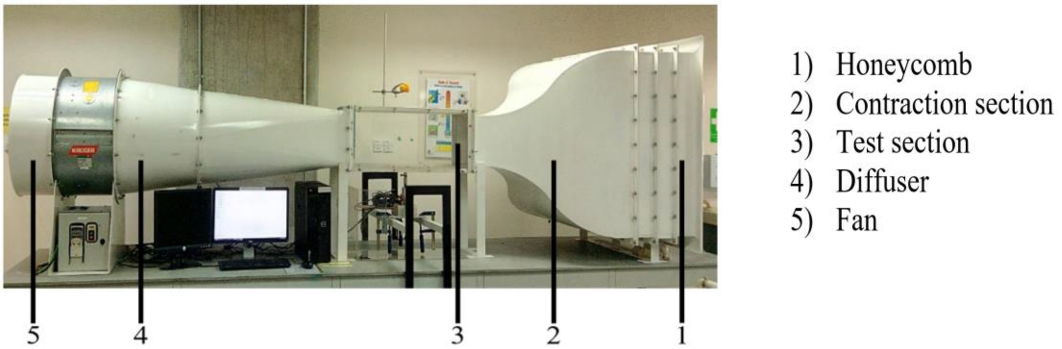


Figure 5. Taylor's University Subsonic Wind Tunnel

The aerodynamic forces and moments acting on the test models are measured using a force measurement mechanism (figure 6) consisting of the following components: Heavy base (1), Tool side fixture shaft (2), 6-axis transducer (3), Model mounting adaptor (4), Rotary mechanism (5), Model mounting strut (6), and Base stand (7) equipped with an ATI GAMMA F/T transducer. The transducer is a 6-axis transducer model of ATI GAMMA FT/T connected to a DAQ card model of NI-PCI6220, which converts the signals received from the sensors to six-axis forces and moments using the ATI data acquisition software installed on the computer.

The wing models are prepared using Taylor's University 3-D printing machine and smooth finishing is conducted using fine sandpaper and primer paint to obtain test models with a smooth surface. However, to prepare test models with a small scale of serration and fins (in millimeter scale) Taylor's University CNC machine is utilized to manufacture high-precision test models. In the final step of the wing preparation process, the prepared test models are compared with printed technical drawings of the wings to confirm the accuracy of the manufactured wing configurations.

The test models are then mounted on the model mounting strut inside the test section to measure the aerodynamic forces acting on the test model. The corresponding coefficients for lift (C_L), drag (C_D) and pitching moment (C_M) are calculated using Eqs. (3), (4) and (5) based on the lift (L), drag (D), and moment (M) readings obtained from the transducer. The same density (ρ) as shown in Table. 1 is used for the calculations and the flow speed (v) is adjusted based on the MAC of the wing models.

$$L=C_L\frac{1}{2}\rho v^2A \quad (3)$$

$$D=C_D\frac{1}{2}\rho v^2A \quad (4)$$

$$M = C_M \frac{1}{2} \rho v^2 A \qquad (5)$$

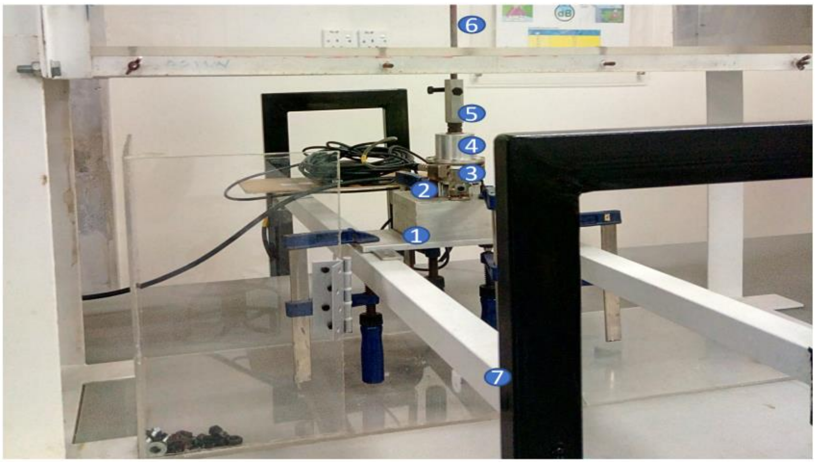


Figure 6. Force Measurement Mechanism

3. Results and Discussion

3.1. Mesh Efficiency and Numerical Results Validation

Mesh efficiency investigation is crucial in order to obtain accurate numerical results. Five cases with cell count ranging from 11.5 (case 1) to 13.5 (case 5) million. As it is shown in figure 7, the lift and drag coefficient values are almost consistent for cases 3, 4 and 5. Also it is observed in figure 8 that the Y+ value is reduced by 10% per case after case 3. However, convergence time for case 3 is 27% faster compared to case 5. Therefore case 3 is selected.

The accuracy of numerical results is examined through wind tunnel simulations and finding of the investigations shows that numerical and experimental results complement each with a minimum accuracy of 92% (figure 9).

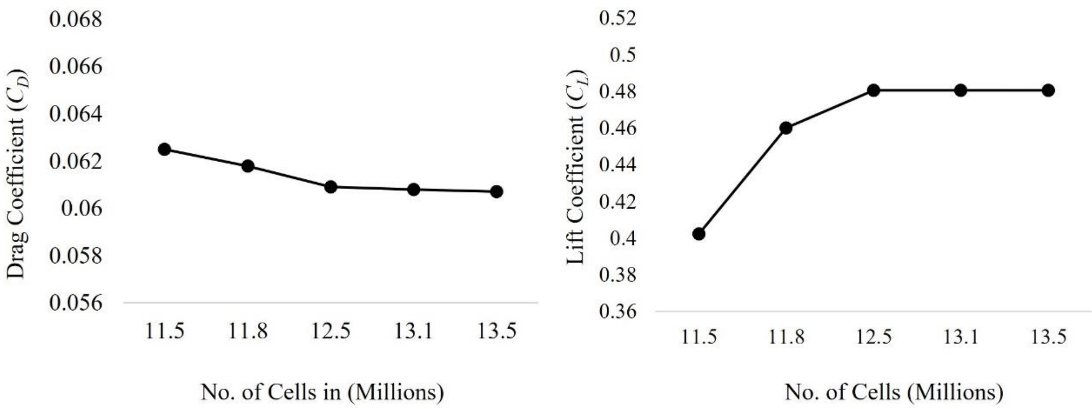


Figure 7. Lift (Left) and Drag (Right) Coefficient Change with Mesh Cell Number

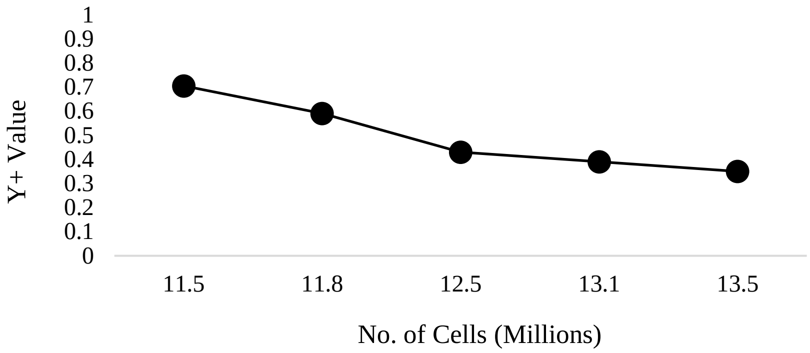


Figure 8. Y+ Value with Mesh Cell Number

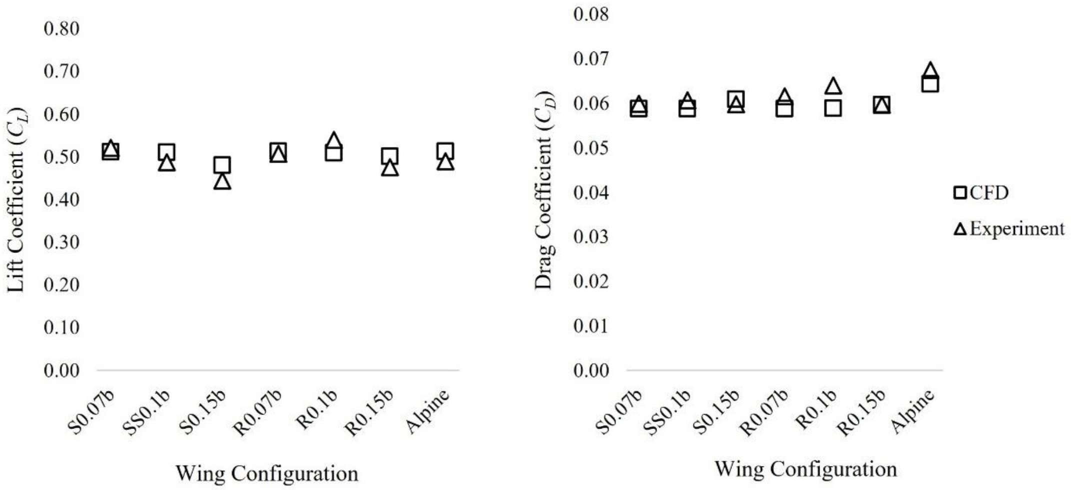
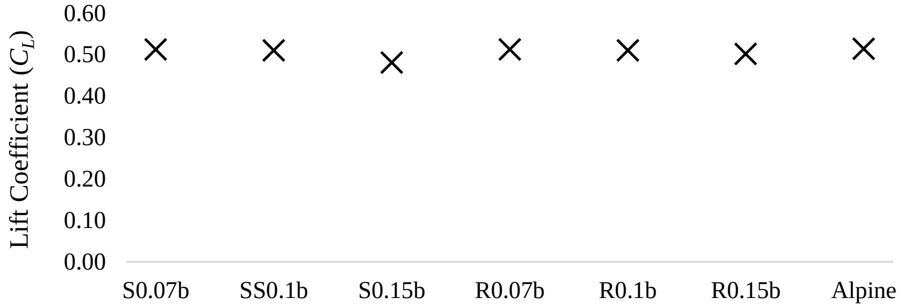


Figure 9. Lift (Left) and Drag (Right) Coefficient Validation

3.2. Alula Effect

The lift and drag coefficients for the investigated wings are shown in figure 10. It is observed that the lift coefficient for configurations with a 7% span ratio is almost the same as the Alpine wing [16]. Also, it is observed that increasing the Alula span results in a gradual reduction in lift and this can be explained by the higher pressure generated between Alula and the wing surface. However, the drag coefficient trend shows that drag for all wings with Alula is lower than for the clean wing. A drag reduction of 9% is observed for wings with a 7 and 10% span ratio. Hence, it is observed that Alula helps in achieving a compromise between the lift and drag coefficients in order to enhance the aerodynamic efficiency of the wing. As it is shown in figure 10, the aerodynamic efficiency of all the wing configurations with Alula is increased by 9% except for the 15% span ratio Alula with straight trailing edge.



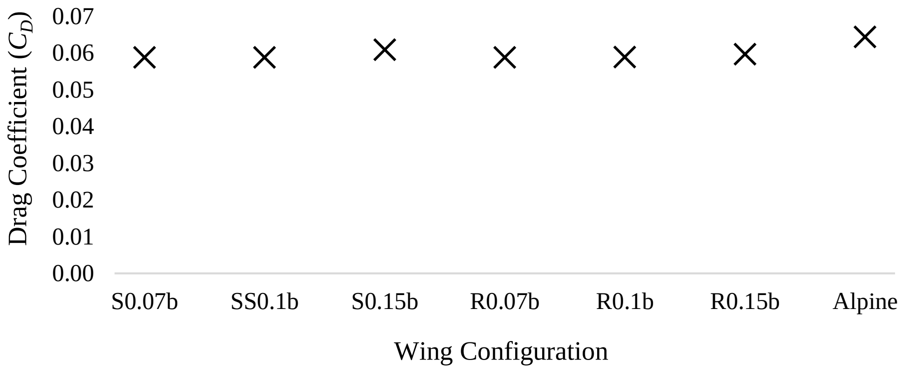


Figure 10. Wing Configurations Lift (Up) and Drag (Down) Coefficient

The flow behavior around the clean wing and wing with Alula can be observed from the flow stream around the wing at 3, 4, and 5 cm from the wing to the root (figure 11). The regions in green color represent the near to zero to negative velocity of the stream on the wing and the flow on the clean wing starts separating in upstream of the flow prior to the mid-chord. While for cases with Alula, the separation point is observed to be pushed back toward the trailing edge instead. Delaying the flow separation helps in reducing the total drag. As it was discussed earlier, the results of the investigation show a lower total drag for cases compared to the clean wing. It is important to take note that total drag is made from two main components of friction drag and form drag. For cases with Alula which has more surface area the friction drag is higher, however despite the increase in friction drag we observed a reduction in total drag which explains significant reductions in the form drag because of the delay in flow separation.

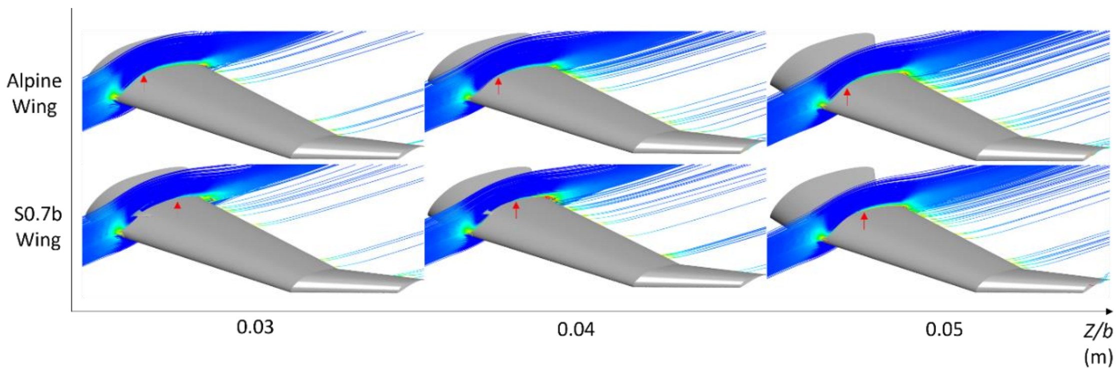


Figure 11. Flow Stream Around the Wings

4. Conclusion

The bio-inspired approach is proven to help in having a better understanding of nature flyers and their wing anatomy. It is observed that using the Alula configuration helps in delaying flow separation by adding momentum into a flow which resulted in total drag reduction by a maximum of 9% without having a significant effect on the lift. Consequently, the aerodynamic efficiency is increased, and this can be utilized in the drone industry to increase the endurance of the flight. Further investigations on the effect of Alula configurations having different deflection angles at different spanwise locations of the wing could result in having a more in-depth understanding of the flow behavior around wings with Alula and utilize this bio-inspired feature as an active flow control mechanism for small UAVs.

5. Conclusion

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