DESIGN AND DEVELOPMENT OF DELTA WING WITH LOITERING CAPABILITY

Loh Yi Rui[1]
[1]Raffles Institution (Junior College), 1 Raffles Institution Lane, Singapore 575954

Abstract

The aim of this study is to redesign delta wings for low-speed loitering flight by capitalising on its strong leading-edge vortices (LEV) developed over the wing. Existing methods such as leading-edge flaps to enhance the strength and persistence of LEV were reviewed. Various combinations and configurations of existing methods such as Gurney flaps, apex flaps, leading-edge vortex flaps and saw-tooth shaped leading-edges were explored to enhance the aerodynamic characteristics of the delta wing under subsonic conditions. The delta wing with leading-edge vortex flaps, Gurney flap and apex flap deflection of 5° was the best choice to maximise range and endurance.

Nomenclature

C_D = drag coefficient
C_L = lift coefficient
α = angle of attack of delta wing

Introduction

With an evolving security landscape, modern warfare will see an increase in the usage of Unmanned Combat Aerial Vehicles (UCAVs) due to their increased capabilities to meet operational demands, the elimination of loss of lives and lower costs (Eng, 2021, pp. 4-5). These UCAVs are required to perform extreme manoeuvres at high speeds [1]. To meet this criterion, UCAVs can be equipped with swept wings or delta wings. Comparing both types of wings built for supersonic flight, delta wings allow UCAVs to maintain the same aspect ratio while experiencing a low wing loading, resulting in better turn performance. Delta wings are also able to generate greater lift as their wing surface area is greater. Thus, the more practical option is to equip UCAVs with delta wings.

Delta wings are beneficial for supersonic flights to reduce wave drag, which occurs only in supersonic flow. However, the large wing area of delta wings produces higher viscous drag, resulting in poorer aerodynamic efficiency. Furthermore, due to their short wingspans and large chord length, the aspect ratio of such wings is low and will cause aircraft to face low lift and high induced drag. This results in poorer aerodynamic performance and higher fuel burn. This becomes problematic under subsonic conditions such as take-off, landing and low-speed loitering flight [2]. As such, new approaches must be implemented to generate greater lift during low-speed flight. One characteristic of the delta wing, its strong leading-edge vortices (LEV), can be exploited to achieve greater lift generation. In an experiment conducted by Lee & Ho (1990), it was found that LEV are capable of contributing up to 40% of the total lift [3]. The airflow separates at the sharp leading edge as a result of the boundary-layer effect. Instead of breaking down into turbulent airflow, strong vortices are formed, helping UCAVs armed with delta wings to generate a huge amount of additional lift when placed at a high angle of attack.

This paper aims to implement modifications on delta wings for low-speed loitering flight by capitalising on its strong LEV developed over the wing. The paper will explore different design modifications adopted to maximise the additional lift generated by strengthening the core of the LEV.

Rao (1979) realised that the use of leading-edge vortex flaps (LEVFs) improved the L/D ratio of sharp leading-edge delta wings at the C_L range of interest [4]. This was due to the strengthening of the persistence and stability of LEV along the flap length by the LEVFs as well as a large reduction of lift-dependent drag of up to 40% relative to a sharp leading-edge delta wing. Hence, using LEVFs is a promising method to improve loitering capability.

Gu et al. (1993) discovered that applying steady blowing, steady suction, or alternate suction-blowing tangentially along the leading edge of a delta wing is able to significantly delay vortex breakdown and stall [5]. They also found that the use of alternate suction-blowing changes the vortex structure from a fully stalled condition to immensely coherent LEV. While leading-edge injection is a viable method to enhance LEV, the design of the injection slit is complex and is thus not the most optimal method from an engineering perspective.

Zhan & Wang (2004) found that the use of both Gurney flaps and apex flaps increases C_L of the delta wing [6]. While the Gurney flap significantly increases C_L, C_D increases as well. As for the apex flap, it is able to reduce C_D at certain angles of attack. Delta wings with apex flaps also have increased camber, causing the effective α to be lower than the wing's absolute α, thereby affecting LEV and delaying vortex breakdown. Using both flaps is advantageous over each flap alone by mitigating the drag caused by the Gurney flap with apex flaps and capitalising on delayed vortex breakdown. It was found that the maximum relative increment of L/D ratio with the combination of both flaps was 88%. Implementing Gurney flaps and apex flaps is thus a possible way to improve aerodynamic efficiency.

Ramakrishna et al. (2019) found that leading-edge shapes could influence the vortex behaviour of delta wings [7]. Comparing plane, saw-tooth and sinusoidal delta wings, the L/D ratio for plane and sinusoidal delta wings faced a decline beyond $\alpha = 30°$, whereas the L/D ratio of the saw-tooth delta wing continued to increase until $\alpha = 40°$. At $\alpha = 40°$ and Re = 2.5×10^5, the saw-tooth delta wing had an L/D ratio of 13.5 as compared to that of the plane delta wing at 11. Based on computational fluid dynamics (CFD) analysis, saw-tooth delta wings are able to maintain an attached low pressure region on the wing surface at such high α, they are able to delay vortex breakdown by increasing the stability of the LEV, thus improving the aerodynamic performance of aircraft with saw-tooth delta wings under subsonic conditions.

No existing literature discusses the effect of Gurney and apex flaps used in conjunction with LEVFs or saw-tooth-shaped leading-edges. This study thus aims to compare the characteristics of delta wings with and without modifications, as well as variations of the modifications implemented. Experiments were conducted to investigate the optimal combination for the best loitering capability.

Materials and Methods

CAD software Onshape was used to design four types of cropped delta wings: Delta A, Delta B, Delta C and Delta D. The deltas were modelled after the W280 indoor remote-control paper plane. All deltas have a wingspan of 280mm, root chord length of 240mm, flat plate thickness of 5mm and sweep angle of 56°. Delta A and B have masses of 0.0250kg while Delta C and D have masses of 0.0243kg. Delta A is a basic delta with no modifications.

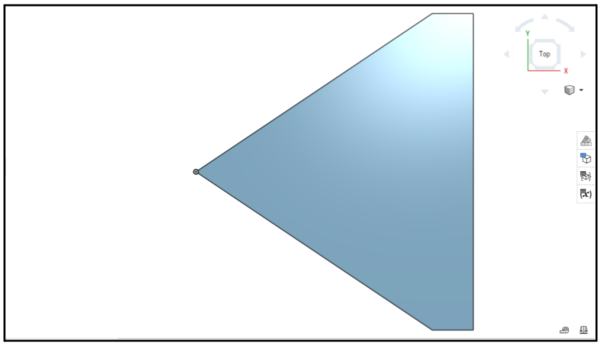

Figure 1: Top view of Delta A

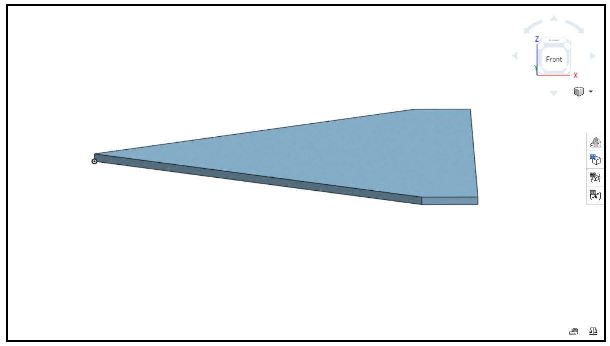

Figure 1.1: Side view of Delta A

Both Delta B and C have Gurney flaps of height 8.6mm and apex flaps deflected by 5° from the plane of the wing. Delta B has LEVFs attached while Delta C has a saw-tooth-shaped leading-edge. This was done by removing three identical right angled triangles of base 11.9mm and height 30.6mm along the leading-edges of the basic delta beyond the apex flap.

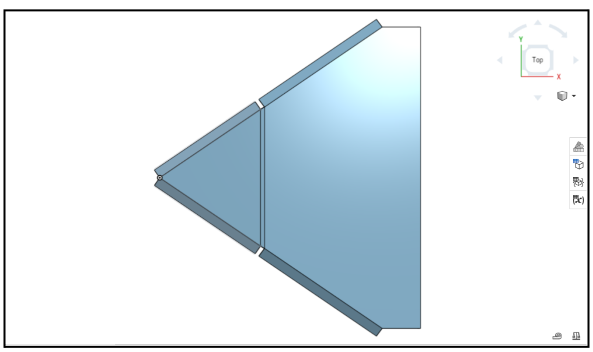

Figure 2: Top view of Delta B

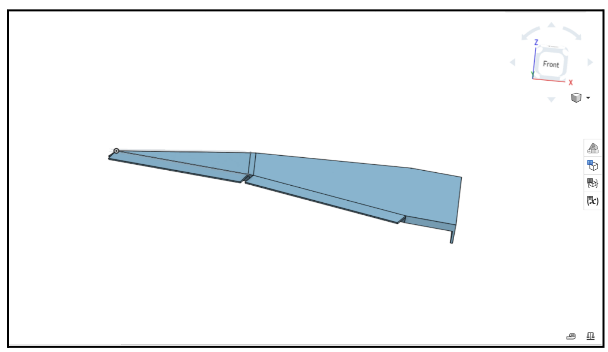

Figure 2.1: Side view of Delta B

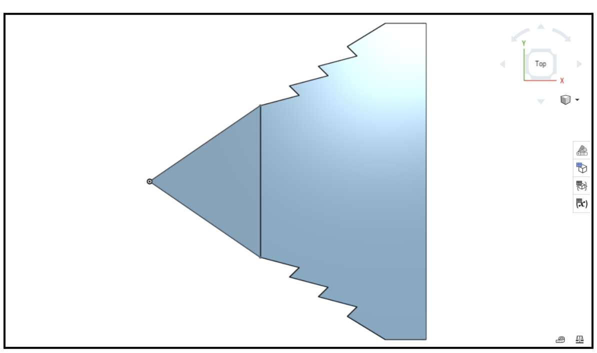

Figure 3: Top view of Delta C

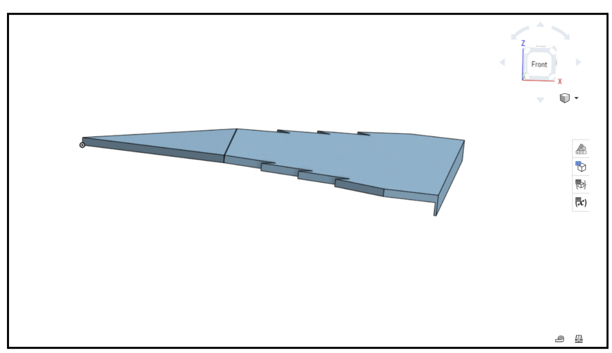

Figure 3.1: Side view of Delta C

Delta D has a Gurney flap of height 8.6mm, a saw-tooth-shaped leading-edge and apex flap deflected by 25° from the plane of the wing.

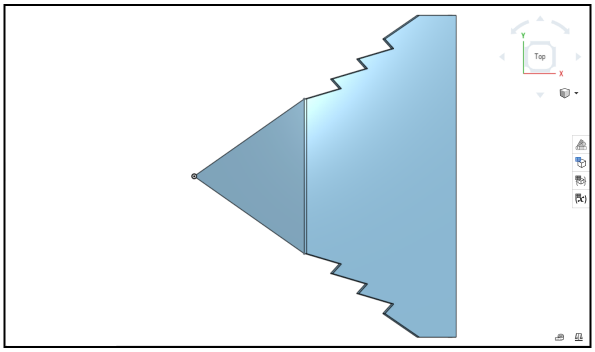
Figure 4: Top view of Delta D

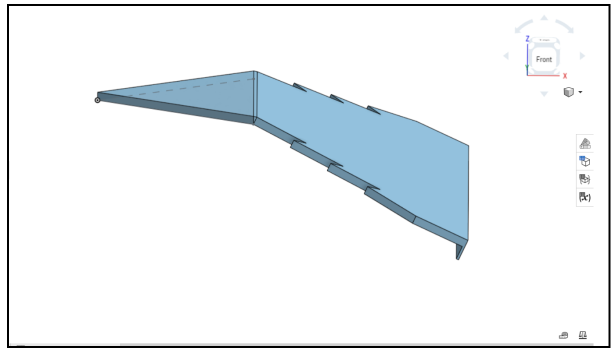
Figure 4.1: Side view of Delta D

ANSYS FLUENT student version was used to conduct CFD analysis. Freestream velocity was set at 15 m/s for subsonic flow. Turbulent intensity of 1% was used. The K-epsilon turbulence model was chosen to investigate the aerodynamic characteristics of the wings under turbulent flow conditions. The materials for fluid and solid were air and aluminium respectively. It is to be noted that mesh sensitivity was not achieved, since there was a maximum mesh count of 512k for the ANSYS FLUENT student version.

Results

Delta A

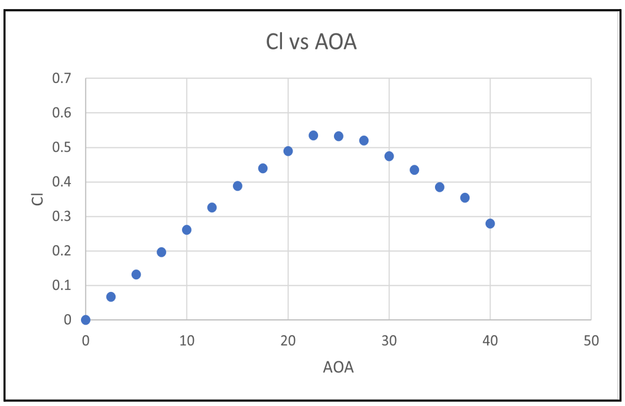

Figure 5: Lift coefficient vs angle of attack

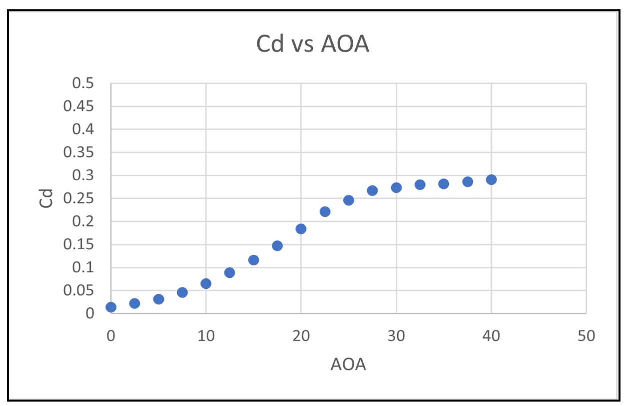

Figure 5.1: Drag coefficient vs angle of attack

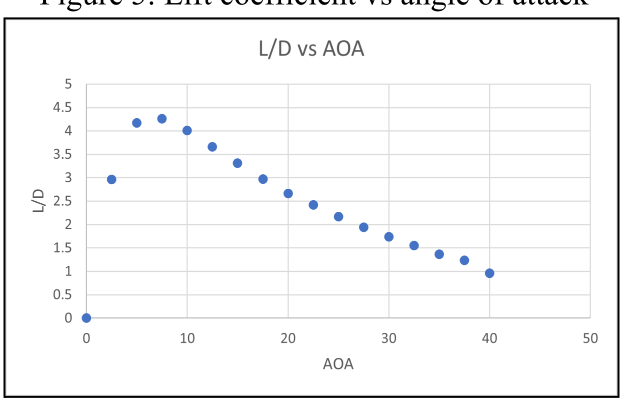

Figure 5.2: Lift-to-drag ratio vs angle of attack

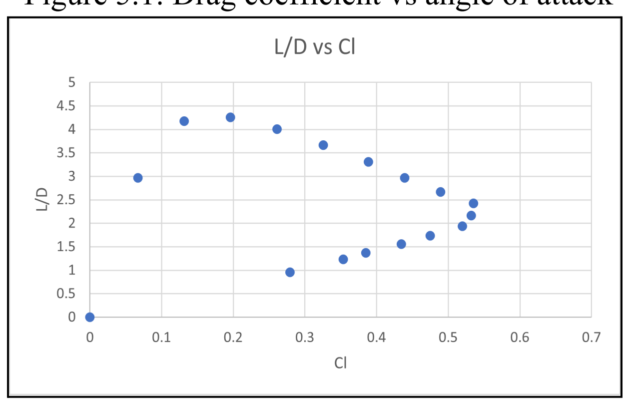

Figure 5.3: Lift-to-drag ratio vs lift coefficient

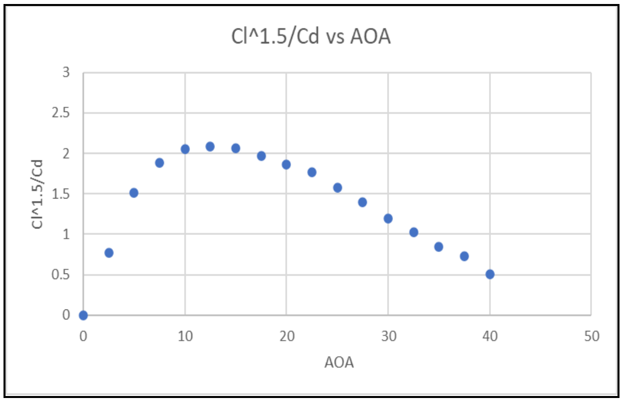

Figure 5.4: $C_L^{3/2}/C_D$ vs angle of attack

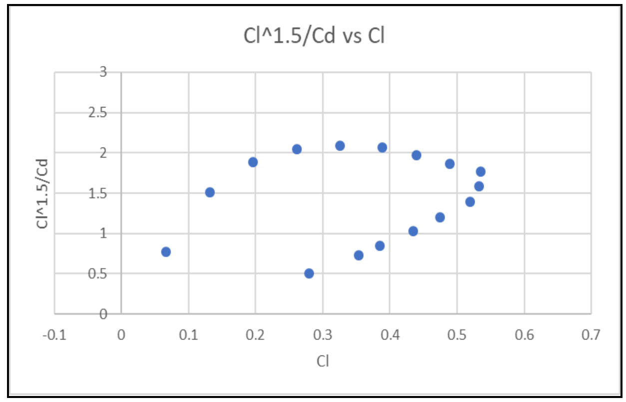

Figure 5.5: $C_L^{3/2}/C_D$ vs lift coefficient

Delta B

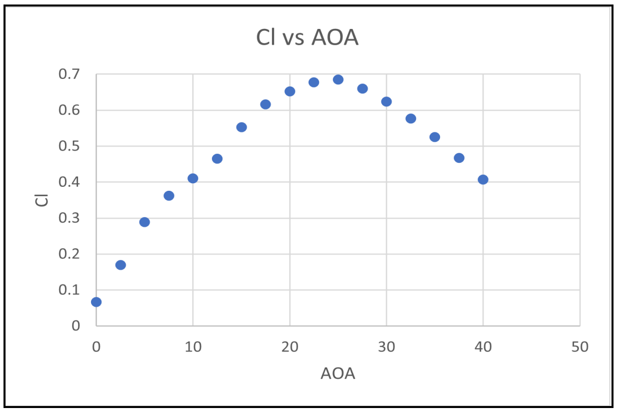

Figure 6: Lift coefficient vs angle of attack

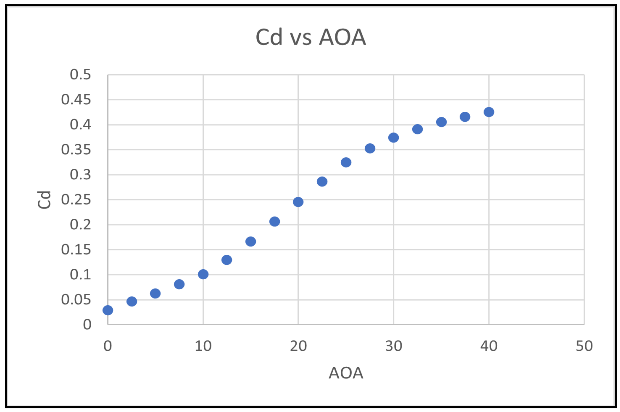

Figure 6.1: Drag coefficient vs angle of attack

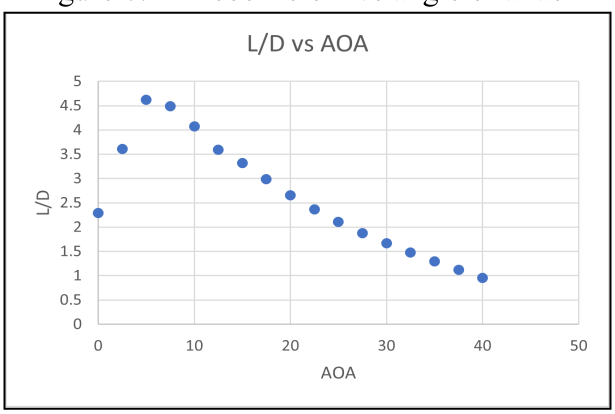

Figure 6.2: Lift-to-drag ratio vs angle of attack

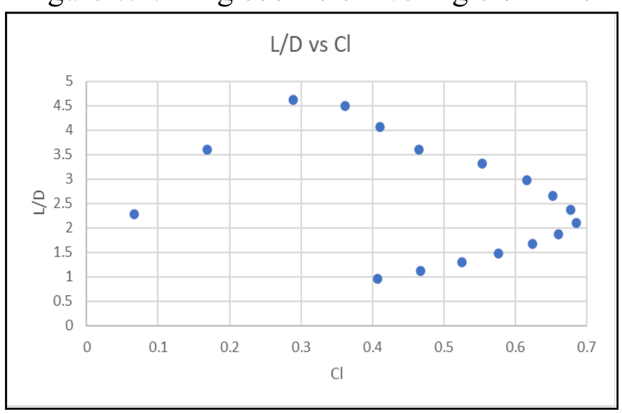

Figure 6.3: Lift-to-drag ratio vs lift coefficient

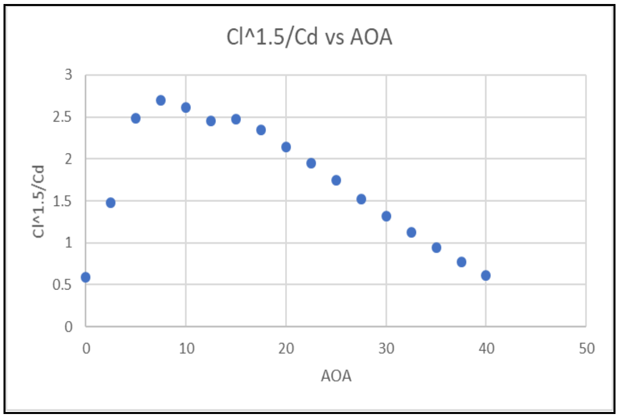

Figure 6.4: $C_L^{3/2}/C_D$ vs angle of attack

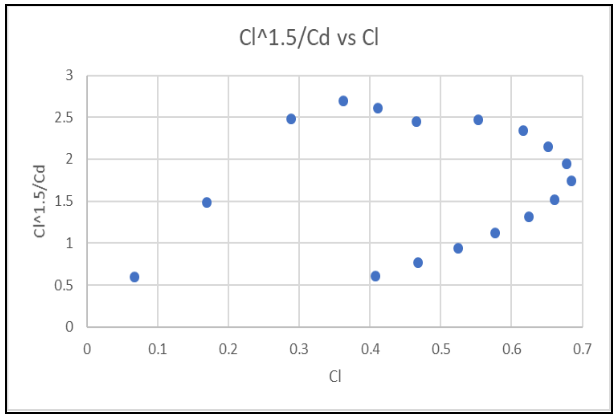

Figure 6.5: $C_L^{3/2}/C_D$ vs lift coefficient

Delta C

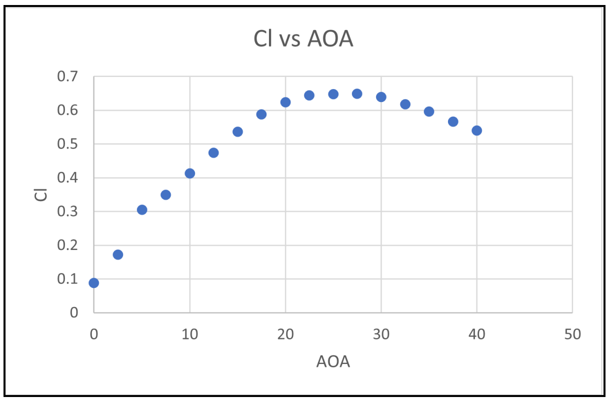

Figure 7: Lift coefficient vs angle of attack

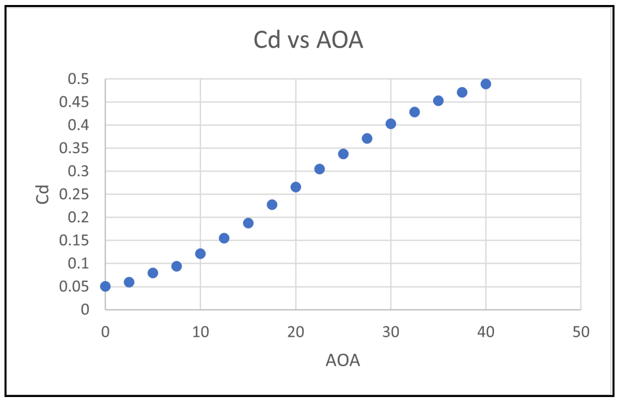

Figure 7.1: Drag coefficient vs angle of attack

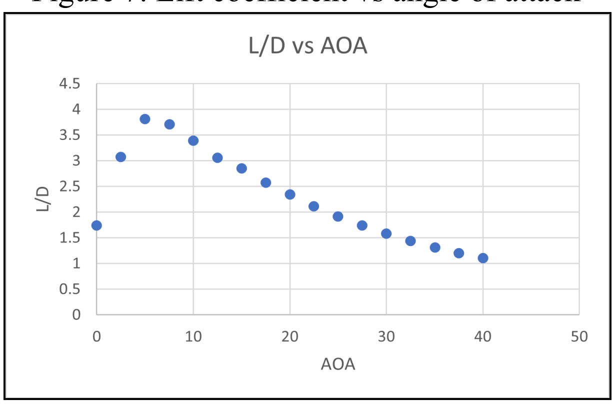

Figure 7.2: Lift-to-drag ratio vs angle of attack

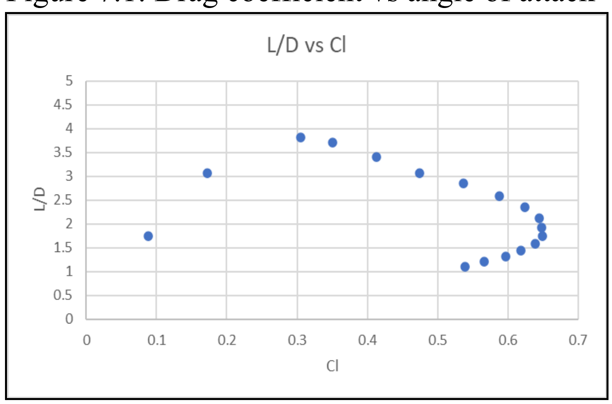

Figure 7.3: Lift-to-drag ratio vs lift coefficient

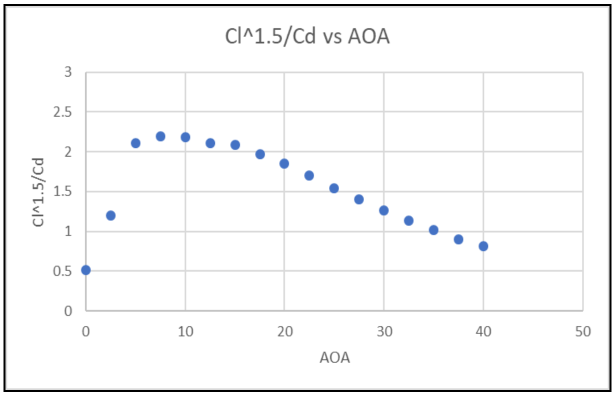

Figure 7.4: $C_L^{3/2}/C_D$ vs angle of attack

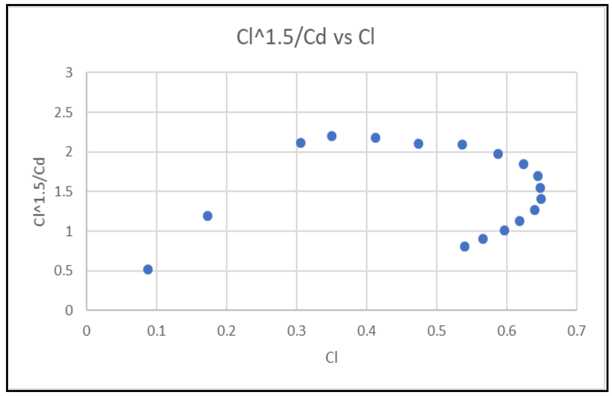

Figure 7.5: $C_L^{3/2}/C_D$ vs lift coefficient

Delta D

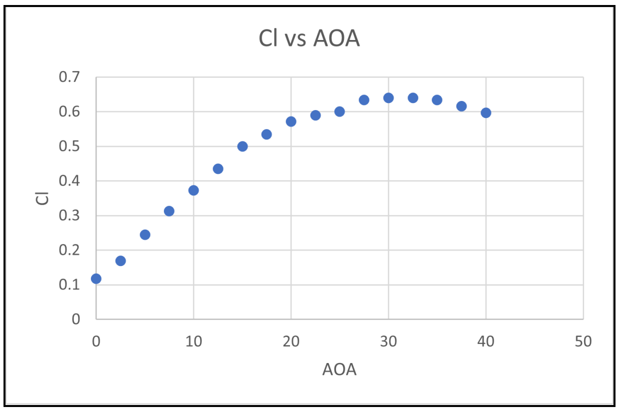

Figure 8: Lift coefficient vs angle of attack

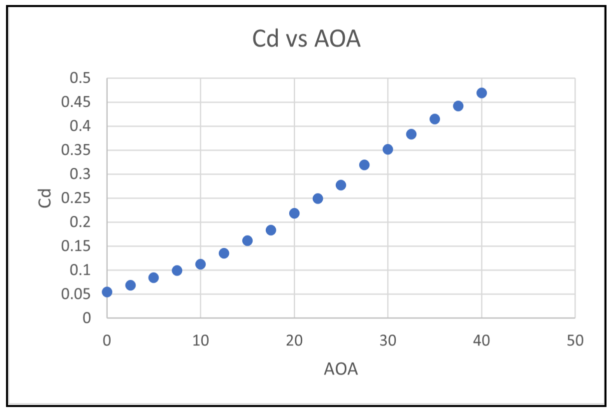

Figure 8.1: Drag coefficient vs angle of attack

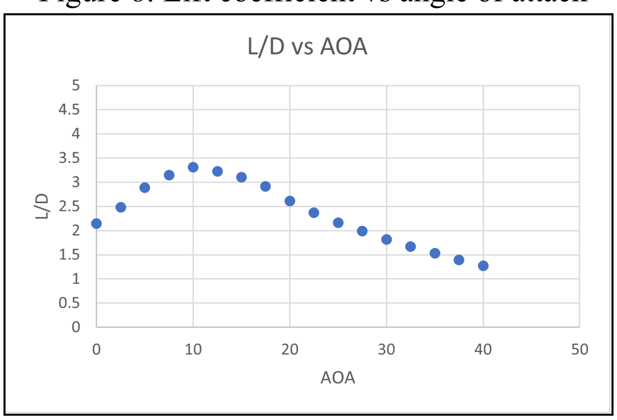

Figure 8.2: Lift-to-drag ratio vs angle of attack

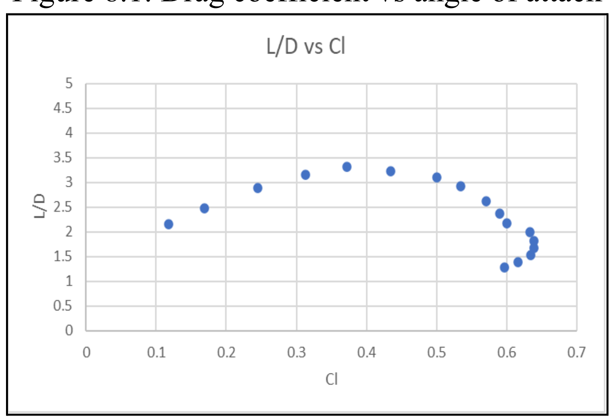

Figure 8.3: Lift-to-drag ratio vs lift coefficient

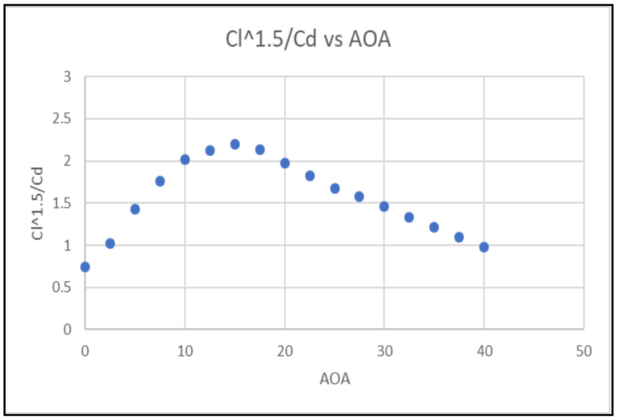

Figure 8.4: $C_L^{3/2}/C_D$ vs angle of attack

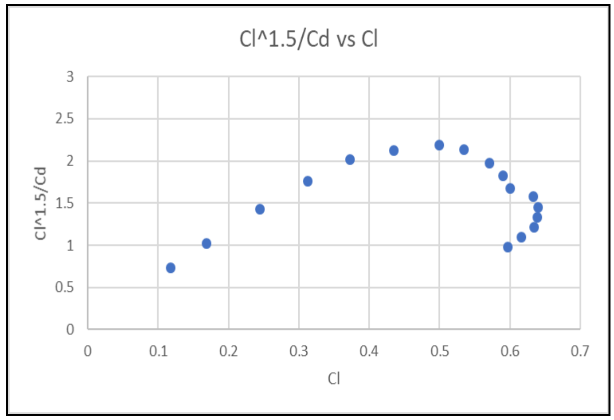

Figure 8.5: $C_L^{3/2}/C_D$ vs lift coefficient

Comparison between Delta A, Delta B, Delta C and Delta D

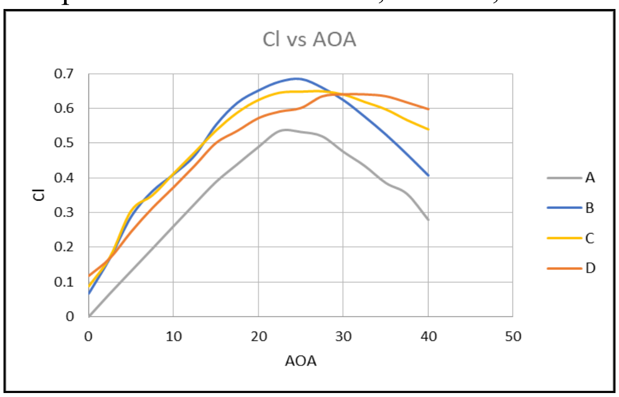

Figure 9: Lift coefficient vs angle of attack

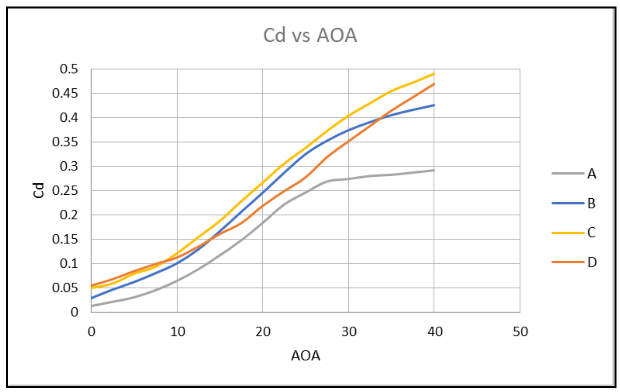

Figure 9.1: Drag coefficient vs angle of attack

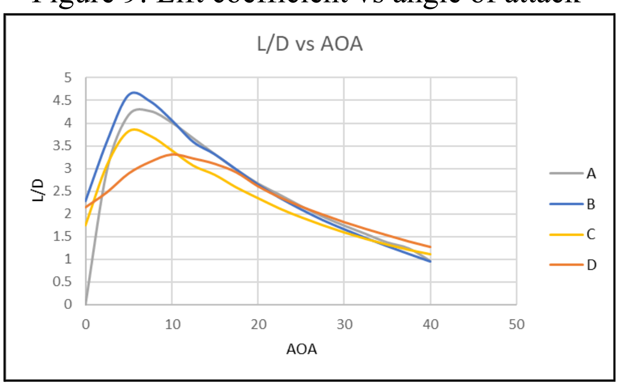

Figure 9.2: Lift-to-drag ratio vs angle of attack

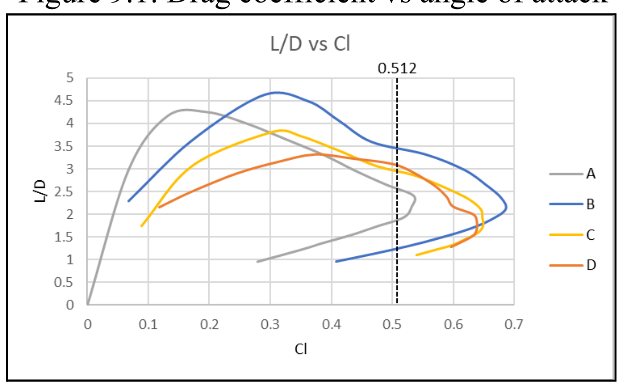

Figure 9.3: Lift-to-drag ratio vs lift coefficient

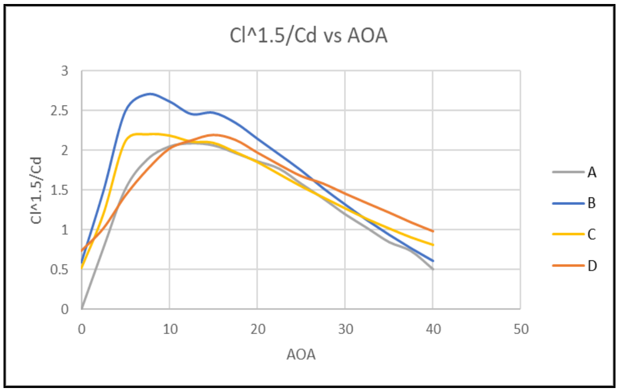

Figure 9.4: $C_L^{3/2}/C_D$ vs angle of attack

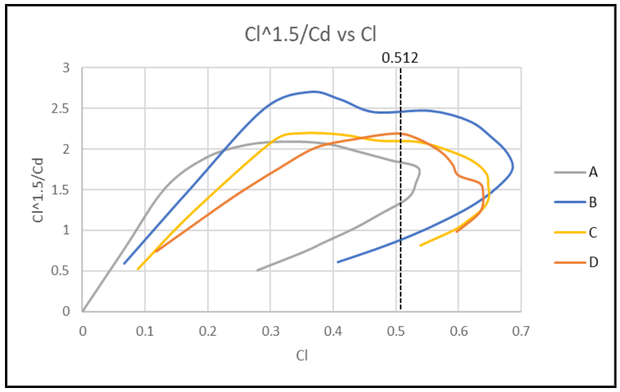

Figure 9.5: $C_L^{3/2}/C_D$ vs lift coefficient

Discussion

Deltas B, C and D achieved higher C_L values than Delta A as shown in Figure 9, suggesting that the modifications generated more lift. This is likely due to the strengthening of the LEV on the delta wing. As seen in Figures 6 and Figure 7, Delta B has a greater C_{Lmax} = 0.685 than the C_{Lmax} = 0.649 of Delta C. While it can be inferred that LEVFs were able to strengthen LEV to a greater extent than saw-toothed-shaped leading-edges on Delta C, the geometry of the saw-tooth could have affected the strength of vortices formed and thus investigating the effects of different saw-tooth shapes might be a potential area of research interest. Comparing the effects of apex flap deflection of 5° and 25°, Delta C reaches C_{Lmax} at $\alpha = 27.5°$ while Delta D achieves C_{Lmax} at $\alpha = 30°$. This is because the camber of the wing increases as a result of the apex flap, and since the effective α is less than the wing absolute α, the onset of vortex breakdown is delayed. Thus, a greater drooping apex flap angle of 25° helps to postpone vortex breakdown longer than 5°. This also can be seen when comparing the point of vortex breakdown between Delta A and Deltas B and C, whose apex flap is deflected by 5°. Delta A achieves C_{Lmax} at $\alpha = 22.5°$ while Deltas B and C reach C_{Lmax} at $\alpha = 25°$ and C_{Lmax} at $\alpha = 27.5°$ respectively as shown in Figures 6 and 7. This further reinforces the idea of drooping apex flaps delaying vortex breakdown. As for the difference in α at which vortex breakdown occurs between Deltas B and C, this might be due to the saw-tooth-shaped leading-edge being able to maintain an attached low pressure region at higher α than a basic delta, as found by Ramakrishna et. al (2019). As such, vortex breakdown occurs at a higher α for Delta C than Delta B.

The value of C_D for Deltas B, C and D is significantly higher than that of Delta A as shown in Figure 9.1. This is due to the Gurney flap on Deltas B, C and D, and this is supported by Zhan & Wang's (2004) findings that Gurney flaps increase C_D across all α. Moreover, the flap might not have been submerged in the local boundary layer, leading to a further increase in the drag generated. Deltas C and D generally have greater C_D values than Delta B. This is because the saw-tooth-shaped leading-edge increases the surface area of the wing normal to the airflow, causing an increase in parasite drag produced. Another possible reason is that the LEVFs reduced lift-dependent drag as found by Rao (1979). Additionally, Delta C generally has a higher C_D value than Delta D, likely because of the extent to which the apex flap is deflected. Zhan & Wang (2004) found that deflected apex flaps were able to achieve a lower C_D value at certain α as compared to no deflection. It can be thus inferred that the greater degree of apex flap deflection led to an increase in the reduction of C_D for Delta D.

Delta B has the highest L/D ratio of 4.63 (Figure 6.2), followed by Delta A with 4.26 (Figure 5.2), then Deltas C and D with 3.82 (Figure 7.2) and 3.22 (Figure 8.2) respectively. Delta B has a higher L/D ratio than Delta A likely because of the lack of drag penalty that comes about from the parasite drag for Deltas C and D. While the Gurney flap on Delta B led to a higher C_D value across all α as compared to Delta A, the increase in C_L was greater than the increase in C_D, causing the maximum L/D ratio to be higher than that of Delta A. Meanwhile, Deltas C and D had a less significant increase in lift generated than Delta B, and the drag penalty from the Gurney flap and the parasite drag led to an overall decrease in the L/D ratio when compared with Delta A. Therefore, Delta B is the most aerodynamically efficient and has the greatest range.

Figure 9.4 shows that Delta B achieved the highest value of $C_L^{3/2}/C_D$ amongst all deltas. In Breguet's equation for propeller aircraft, the $C_L^{3/2}/C_D$ parameter is proportional to the endurance of the plane. This suggests that out of all the tested deltas, Delta B has the best endurance.

The weights of Delta A and B and Delta C and D are 0.245N and 0.238N respectively. Taking the flight speed of the W280 indoor remote-control paper plane to be 4.5 m/s, the value of C_L to maintain level flight where the lift is equal to weight is 0.512 for all deltas. At $C_L = 0.512$, Delta B, C and D have higher L/D and $C_L^{3/2}/C_D$ values than Delta A as seen in Figures 9.3 and 9.5, implying that the modifications improved range and endurance. Delta B achieved both the highest L/D value and $C_L^{3/2}/C_D$ value at $C_L = 0.512$. It can be thus inferred that Delta's B configuration is the optimal choice for both maximum range and endurance, making it the best candidate for improving the loitering capability of delta wings.

Conclusion

CFD analysis was conducted to determine the effect of the Gurney flap, apex flap and LEVF/saw-tooth shaped leading-edge on the aerodynamic characteristics of a cropped delta with sweep angle of 56°. This paper found that the modifications were able to strengthen LEV and increase the overall C_L across all α. When used with apex and Gurney flaps, LEVFs were able to achieve a higher C_L and attain a lower C_D than saw-tooth-shaped leading-edges. Delta B also achieved the highest maximum L/D ratio and $C_L^{3/2}/C_D$ value out of the four models. Consequently, Delta B is the best model to maximise loitering capability, and UCAVs of similar configuration will be able to sustain low-speed loitering flight for a longer period of time. Due to time constraints, experiments on a delta wing with LEVFs, Gurney flap and apex flap deflected by 25° were not conducted. It is likely that it will achieve a smaller C_D value than Delta B due to the drag reduction from the larger apex flap deflection angle, thus improving the loitering capability of the delta wing. Further research on this area should be conducted to further enhance the aerodynamic characteristics of the delta wing.

Acknowledgements

I would like to thank my mentor, Mr. Jonathan Lim Zhi Wei, for his invaluable support and guidance throughout the project, as well as those who have helped me in one way or another.

References

[1] Gursul I., Gordnier R. and Visbal M. 2005. Unsteady aerodynamics of nonslender delta wings. Progress in Aerospace Sciences. 41 (7): 515-557

[2] Zheng, Y., Ahmed, N.A. and Zhang, W. 2014. Enhancing subsonic performance of delta wing at low angles of attack. Advances and Applications in Fluid Mechanics. 16: 31-56

[3] Lee, M., and Ho, C. 1990. Lift Force of Delta Wings. American Society of Mechanical Engineers. 43(9): 209–221.

[4] Rao, D.M. (1979). Leading edge vortex-flap experiments on a 74 deg. delta wing.

[5] Gu, W., Robinson, O. & Rockwell, D. 1993. Control of Vortices on a Delta Wing by Leading-Edge Injection. Aerospace Research Journal. 31(7): 1177-1186

[6] Zhan, J.-X. & Wang, J.-J. 2004. Experimental Study on Gurney Flap and Apex Flap on a Delta Wing. Aerospace Research Journal. 41(6): 1379-1383

[7] Ramakrishna, M., Kumar, C.S. & Venkatesh, B. (2019). Influence of leading edge shapes on vortex behaviour of delta wing. J. Phys.: Conf. Ser. 1276