DESIGN AND DEVELOPMENT OF DELTA WING WITH LOITERING CAPABILITY

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ABSTRACT

Around the world, military operations increasingly rely on advanced technology, such as Unmanned Aerial Vehicles (UAVs). For UAVs to operate efficiently on the battlefield, they will have to possess great loitering and manoeuvring capabilities. This can be achieved by using a delta wing, which maximises their agility, range, and endurance allowing for use in diverse environments. However, delta wings are optimally designed to fly at transonic and supersonic speeds, but not at subsonic speeds. Hence, this project aims to develop and implement modifications onto the main delta wing, as well as the aircraft itself, to improve the aerodynamic characteristics of the UAV. Using Computational Fluid Dynamics software to simulate the model's aerodynamic capabilities, the aim is to increase the $\frac{C_L}{C_D}$ and $\frac{C_L^{1.5}}{C_D}$ ratio, and delay the stall angle of the aircraft. Modifications such as the sweep angle of winglets, addition of canards and subsequently varying its angle and height were studied. Winglets improved $\frac{C_L}{C_D}$ of the plane while not delaying stall angle. The addition of canards proved to be unsuccessful in improving $\frac{C_L}{C_D}$, but did slightly delay stall. However, the increase in stall angle was unable to compensate for the decrease in $\frac{C_L}{C_D}$. The study found that winglets were useful in improving a delta wing aircraft's loitering capability, while canards were found to be ineffective.

INTRODUCTION

In an ever-changing global security landscape increasingly driven by modern technology, Unmanned Aerial Vehicles (UAVs) play a pivotal role in intelligence, surveillance and reconnaissance [1]. By reducing human risk on the battlefield, UAVs offer a competitive advantage over traditional methods of warfare [2]. Among UAV designs, delta wings stand out for their higher manoeuvrability and delayed stall angles, making them effective for tactical operations [3]. At low subsonic speeds, delta wings become aerodynamically inefficient due to generating low lift while producing significant drag. This inherently poses a significant challenge for UAVs tasked with missions requiring prolonged loitering times, such as persistent surveillance, search-and-rescue operations, among many more. The aircraft's loitering capability, which is a critical performance metric for such missions, is defined by its ability to remain airborne for extended durations while travelling great distances efficiently. As a result, the range and endurance of UAVs, especially those with delta wing configurations, must be optimized to improve its aerodynamic capabilities and enhance its effectiveness. Assuming constant velocity and atmospheric pressure, Breguet's

Range equation for propellor planes:

$$R = \frac{\eta}{SFC}\frac{C_L}{C_D}\ln\left(\frac{W_{initial}}{W_{final}}\right); \tag{1}$$

and Endurance equation for propeller planes:

$$E = \frac{\eta}{SFC}\frac{C_L^{1.5}}{C_D}\sqrt{2\rho_\infty S}\left(\frac{1}{\sqrt{W_{initial}}} - \frac{1}{\sqrt{W_{final}}}\right); \quad (2)$$

can be used, where:

η	=	Propulsion Efficiency of Propeller
SFC	=	Specific Fuel Consumption
C_L	=	Lift Coefficient
C_D	=	Drag Coefficient
ρ_∞	=	Pressure of Atmosphere
S	=	Reference Wing Area
$W_{initial}$	=	Initial Weight of Plane
W_{final}	=	Final Weight of Plane [4]

From equations (1) and (2), it can be seen that Range $\propto \frac{C_L}{C_D}$, and Endurance $\propto \frac{C_L^{1.5}}{C_D}$. To maximise the aircraft's range and endurance, the highest C_L and lowest C_D should be achieved. The paper explores various designs to the delta wing, optimising its performance for extended loitering flight by maximising its $\frac{C_L}{C_D}$ and $\frac{C_L^{1.5}}{C_D}$ ratio while still capitalising on its strengths. An increase in C_L and $\frac{C_L}{C_D}$, by extension means that $\frac{C_L^{1.5}}{C_D}$ will increase as well.

Canards and winglets have been studied on delta-wing aircraft to increase the lift generated, to maximise its $\frac{C_L}{C_D}$ and $\frac{C_L^{1.5}}{C_D}$ ratio. Furthermore, discussions surrounding the aerodynamic characteristics of these factors on low-speed delta wings are relatively limited in existing literature. Therefore, this study aims to provide a comprehensive analysis of how these factors influence performance in the low-speed regime. It is hypothesised that the addition of winglets and canards will increase both the $\frac{C_L}{C_D}$ and $\frac{C_L^{1.5}}{C_D}$ ratio, as well as delay the stall angle of the aircraft.

MATERIALS AND METHODS

CAD software *Onshape* was used for the design of the plane models. NACA 2408 airfoil was used for the main delta wing, with dimensions as shown in Fig. 1. This standard design was used for all models. As a baseline, Model A is a basic delta wing model with no modifications.

ANSYS 2024 R2 Student Version (Fluent with Fluent Meshing) was used to conduct CFD analysis. The SST k-omega model was used to simulate turbulent flow, with a subsonic freestream velocity of Mach 0.05 and a turbulent intensity of 1%. Ideal Gas was used as the fluid domain, using Sutherland's law for viscosity.

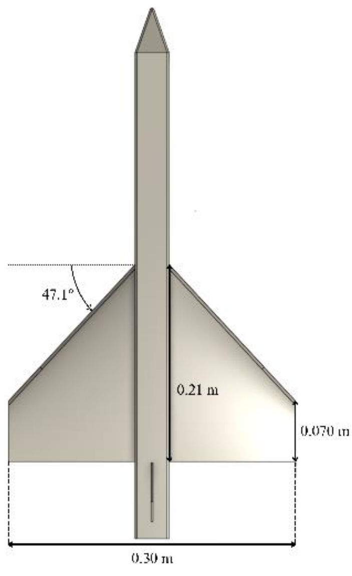

Figure 1: Top view of Model A

Modification 1: Addition of winglet to main wing

Winglets are proven to reduce drag by up to 20% through weakening wingtip vortices [5]. At lower Mach numbers, the loss of lift from winglets at higher lift coefficients are also shown to be less significant [6]. Furthermore, winglets increase lateral stability, providing better manoeuvrability — a critical characteristic of delta wing aircrafts [7,8]. Thus, winglets can be effective to increase the $\frac{C_L}{C_D}$ ratio of delta aircraft at low speeds, aiding in its loitering capability.

To Models B1-B10, sweep angles of the winglets on the main wing were varied, as shown in Figure 2.1 and Table 2.2.

Model	Sweep Angles of Winglets/°
B1	0
B2	+10.0
B3	+20.0
B4	+30.0
B5	+40.0
B6	+50.0
B7	+60.0
B8	+70.0
B9	+80.0
B10	+90.0

Table 2.2: Overview of Models B1-B10

Modification 2: Addition of canards

An efficient delta wing aircraft requires good manoeuvrability at high angles of attack (AOA) to carry out its operations. Canards direct airflow to the main wing, reducing turbulence-induced drag. Canards have shown to be effective in increasing lift and providing added pitch control at subsonic speeds [9]. Canard-induced airflow delays vortex breakdown and flow separation in the main wing, decreasing the amount of drag experienced [9,10] Mochizuki & Yamada [11] showed that canards also can delay the stall angle of the aircraft.

Thus, the second modification was made, as seen in Figure 3.1, 3.2 and Table 3.3. Canards were added at 0 m vertical height and 0 m horizontal distance to the main wing. Effect of vertical height of canard and horizontal distance between the canard and main delta wing were to be studied. Initial analyses using *XFLR5* showed that using canards of NACA 4606 airfoil, with a root chord of 0.12 m, wingspan of 0.03 m and sweep angle of 67° produced the best $\frac{C_L}{C_D}$. Further modifications were made to determine the most effective positioning of canards.

Model	Sweep Angles of Winglets/°
C1	0
C2	+10.0
C3	+20.0
C4	+30.0

C5	+40.0
C6	+50.0
C7	+60.0
C8	+70.0
C9	+80.0
C10	+90.0

Table 3.3: Overview of Models C1-C10

Modification 2a: Horizontal Distance of Canard

To Models D1-D6, canards were added at varying horizontal lengths from the main delta wing with a vertical height of 0 m and tilt angle of 0°, as shown in Figure 4.1 and Table 4.2.

Model	d/m
D1	0
D2	0.02
D3	0.04
D4	0.06
D5	0.08
D6	0.10

Table 4.2: Overview of Models D1-D6

Modification 2b: Vertical Height of Canard

To Models E1-E5, canards were added at various vertical heights in front of the main wing, with a horizontal distance of 0 m and tilt angle of 0°, as shown in Figure 5.1 and Table 5.2.

Model	d/m
E1	0
E2	+0.002
E3	+0.004
E4	+0.006
E5	+0.008

Table 4.2: Overview of Models E1-E5

RESULTS AND DISCUSSION

Baseline Model

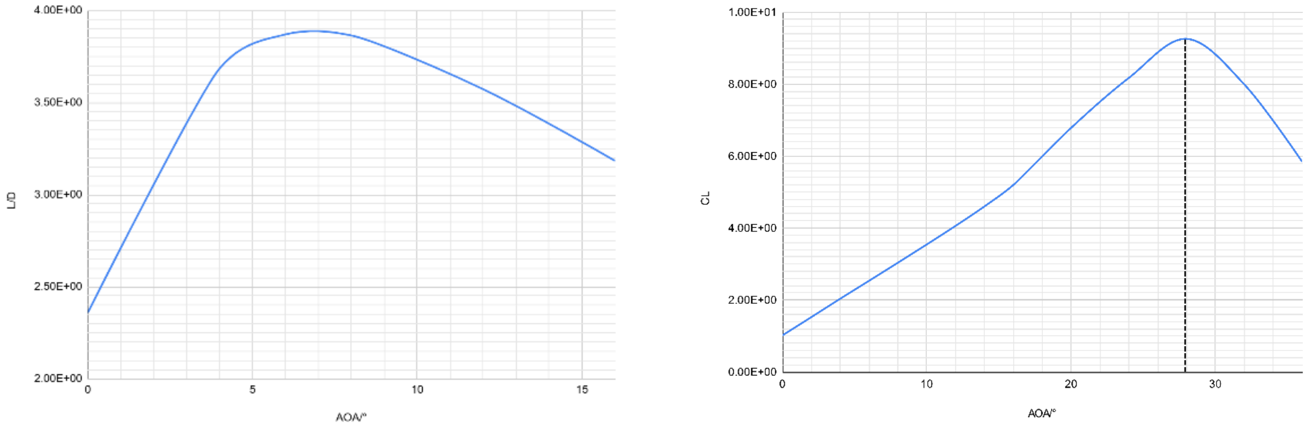

Figure 6: Graph of $\frac{C_L}{C_D}$ (left), and C_L (right) against AOA/° for Model A.

Model A achieved a peak $\frac{C_L}{C_D}$ ratio of 3.89, while stalling at an AOA of 28°. Model A is a bare delta wing, so wingtip vortices tend to form more readily near the trailing edge of the wing at higher AOA, leading to increased induced drag on the aircraft. Additionally, the wing experiences greater airflow separation, which further contributes to increased drag experienced by the aircraft. Wingtip vortices and flow separation must be reduced such that both $\frac{C_L}{C_D}$ and $\frac{C_L^{1.5}}{C_D}$ of the aircraft can be improved.

Modification 1: Addition of winglet to main wing

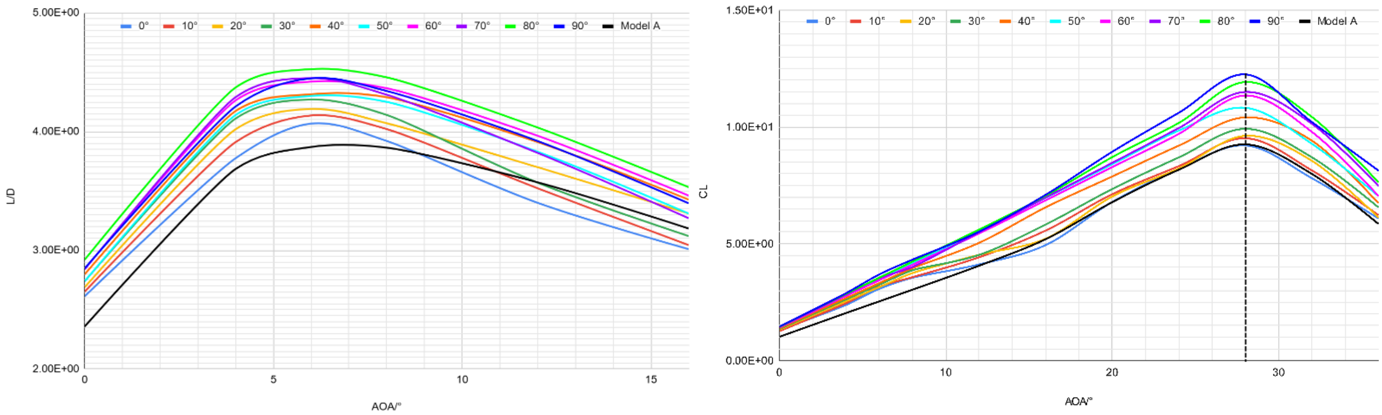

Figure 7: Graph of $\frac{C_L}{C_D}$ (left), and C_L (right) against AOA/° for Models B1-B10.

It was observed that as the sweep angle of the winglet increases from 0° to 80°, the maximum $\frac{C_L}{C_D}$ achieved by the aircraft increased significantly from 3.89 to 4.54. The enhancement in $\frac{C_L}{C_D}$ was a sign of winglets being effective in enhancing lift generation and reducing wingtip vortex formation, in turn reducing induced drag, an observation supported by Bargsten & Gibson [12]. However, a 90° winglet, effectively acting as an extension of the main delta wing, produced a lower $\frac{C_L}{C_D}$ ratio when compared to the 80° winglet. This may be due to the winglet and the main wing having different sweep angles. The non-continuous leading edge of the wing produced greater drag, while insufficiently compensating with a lower increase in lift.

While the addition of winglets helped to increase the lift generated by the wings, the aircraft still faced the issue of stall angles not being delayed, remaining approximately at 28° for all models. Since winglets with a sweep angle of 80° gave the highest $\frac{C_L}{C_D}$ ratio, it was used in all future models.

Modification 2: Addition of Canard

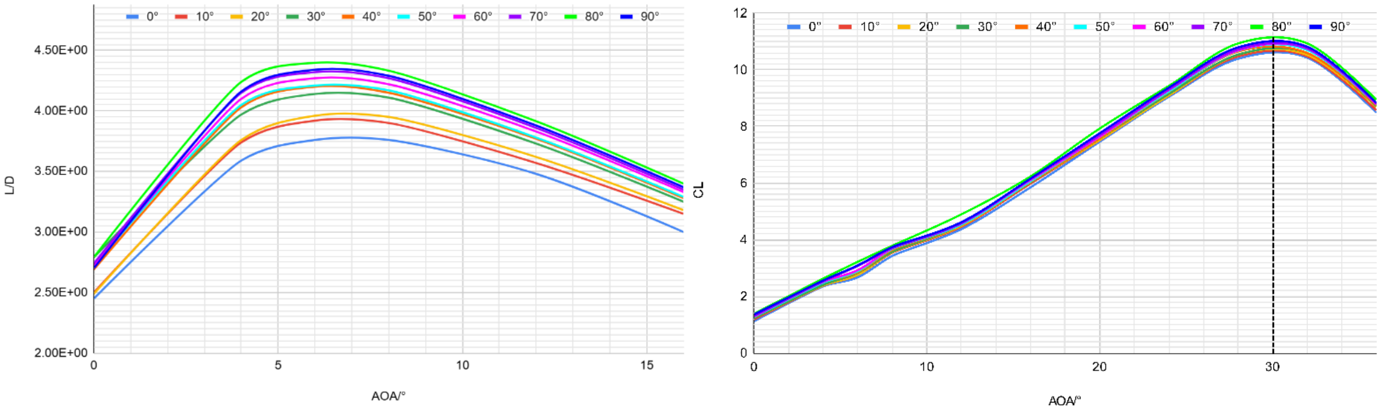

Figure 8: Graph of $\frac{C_L}{C_D}$ (left) and C_L (right) against AOA/° for Models C1-C10.

Canards were observed to slightly delay the stall angle of the aircraft, as supported by Mochizuki and Yamada [11], increasing it by 2° to 30°. Then, to further improve the aerodynamic characteristics of the canards, the effect of horizontal distance and vertical height were studied.

Modification 2a: Horizontal Distance of Canard

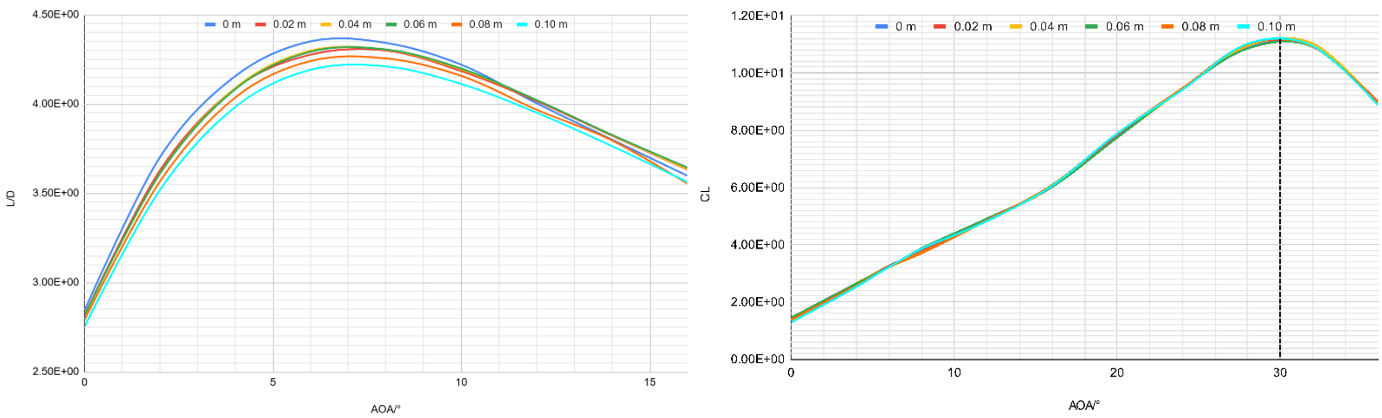

Figure 9: Graph of $\frac{C_L}{C_D}$ (left) and C_L (right) against AOA/° for Models D1-D6.

It was observed that increasing the horizontal distance between the canard and main wing worsened the aircrafts $\frac{C_L}{C_D}$ ratio, while the stall angle remained the same at 30°. As C_L remained fairly constant across the various distances, it can be deduced that increasing the canard distance by a maximum of 0.10 m was likely to have an insignificant effect on the airflow across the canard and main wing. Since the canard with 0 m distance to the main wing gave the highest $\frac{C_L}{C_D}$ ratio relative to other horizontal distances between the canard and the main delta wing, it was used in future models.

Modification 2b: Vertical Height of Canard

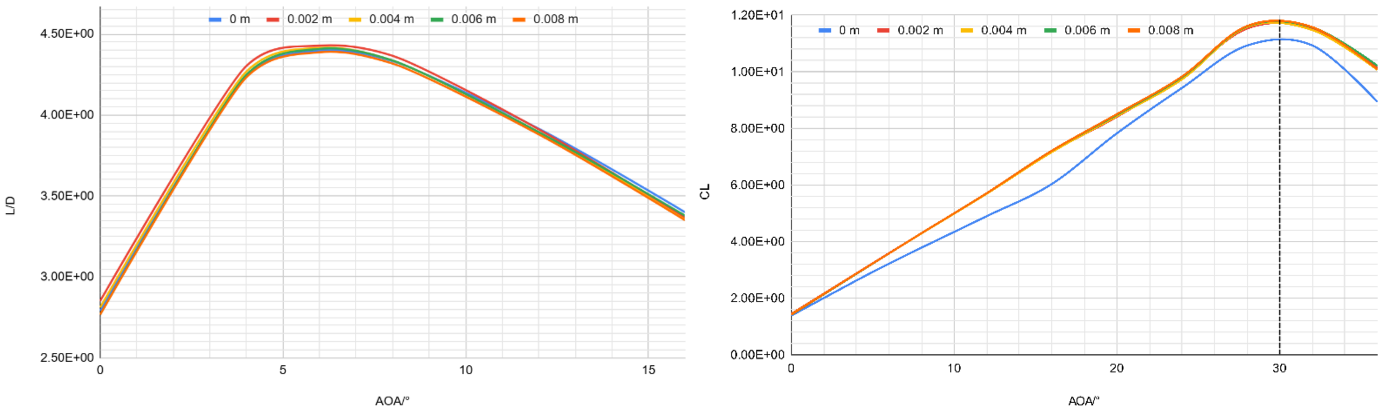

Figure 10: Graph of $\frac{C_L}{C_D}$ (left) and C_L (right) against AOA/° for Models E1-E5.

It was observed that increasing the canard's vertical height from 0 m to 0.008 m had minimal impact on the aircraft's $\frac{C_L}{C_D}$ ratio, remaining relatively constant. Stall angle remained constant at 30°. While raising the canard helps direct airflow toward the upper surface of the wing, the physical limitations of the fuselage height limited how much the canard height could be varied. As such, the canard's low vertical height may have been insufficient in redirecting enough airflow to create the pressure differential necessary for generating additional lift. Therefore, $\frac{C_L}{C_D}$ ratios of the aircraft with varying vertical heights of canards were kept relatively constant.

Overall, the addition of canards proved ineffective in increasing the ratio of the aircraft. It was suggested that the canard's ineffectiveness was due to the aircraft's relatively low angle of attack and low flight speed. These factors could have caused the canards to generate more drag than lift, as canards have often found to be effective only at higher angles of attack. At these conditions, downwash is particularly detrimental as it reduces the effective angle of attack experienced by the main wing, leading to a decrease in its lift production. The resultant increase in drag due to downwash effects and vortex formation ultimately leads to a scenario where canards may produce more drag than lift, highlighting their dependence on higher AOA for optimal performance., as canards have often been found to be effective only at higher angles of attack by exploiting increased airflow separation and vortex generation to enhance lift over the main wing. However, possibly due to the operating conditions of low flight speed used, the delay in stall angle caused by the canards was less significant than expected. The marginal delay in stall angle was deemed insufficient to offset the decrease in, to justify the addition of canards onto Models B1-B10.

Final design

The final design of the plane based on the highest $\frac{C_L}{C_D}$ ratio, while maintaining a stall angle that is not too low. Model B9, the addition of 80° winglet onto the main delta wing, gave the highest $\frac{C_L}{C_D}$ ratio of 4.54 while having a stall angle of 28°, thus being chosen as the final design. The velocity vectors and pressure contours of Model B9 are shown below.

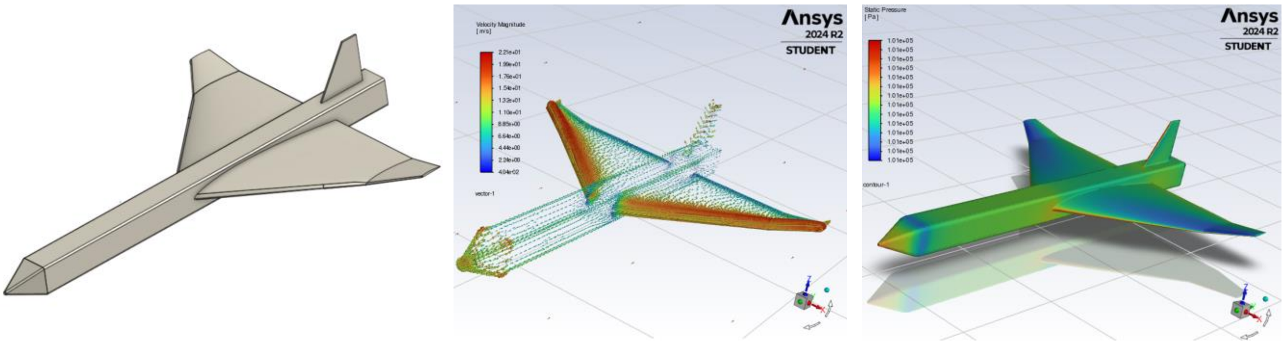

Figure 11: Model Design (left), Velocity Vectors (middle) and Pressure Contour (right) of final Model B9.

CONCLUSION

In this study, it was observed that winglets improved the C_L, $\frac{C_L}{C_D}$, and then $\frac{C_L^{1.5}}{C_D}$ ratios of the aircraft, but did not delay the stall angle. However, canards were disadvantageous as they failed to delay the stall angle of the aircraft without decreasing its $\frac{C_L}{C_D}$ and $\frac{C_L^{1.5}}{C_D}$ ratios. At low flight speeds, the lift generated by the canards and their subsequent modifications was insufficient to compensate for the increased induced drag experienced by the aircraft. In real life, delta-winged UAVs can benefit from winglets to increase its loitering capabilities and manoeuvrability.

An experimental limitation was due to the maximum cell count limit of 1 048 576 cells in *ANSYS Student Version.* There were limitations to the refinement of the mesh generated, such as the maximum mesh size. This may have affected the precision of obtained results.

Future work should explore varying the aspect ratios (ARs) of the canard and main wing. Current studies suggest that higher ARs improve the $\frac{C_L}{C_D}$ ratio of the delta wing aircraft operating at low speeds [13]. Wings of higher AR reduce induced drag caused by wingtip vortices, lowering power requirements and enhancing loitering capability of the aircraft. Increased ARs also improve manoeuvrability, enabling operations in diverse environments [14]. Further studies on the benefits of higher ARs for delta wings in subsonic conditions could further improve loitering and manoeuvrability capabilities of delta wing UAVs.

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APPENDIX

Figure 1

Top View of Model A

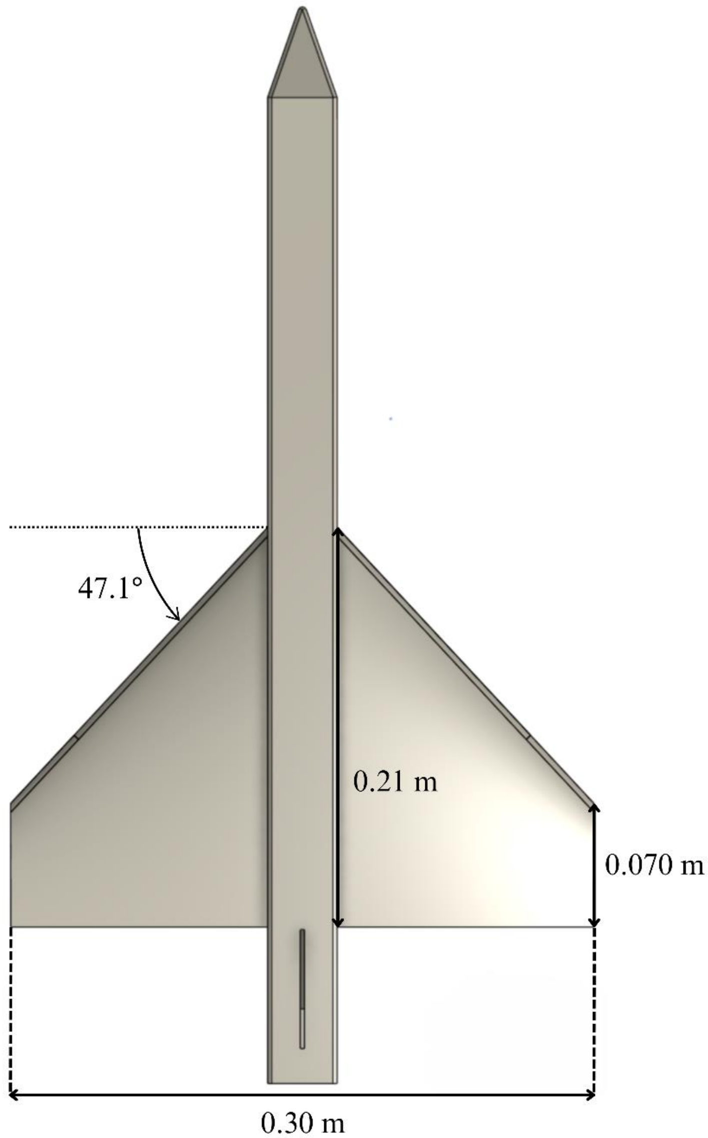

Figure 2.1

Sweep angle of winglet on main wing as θ/ °

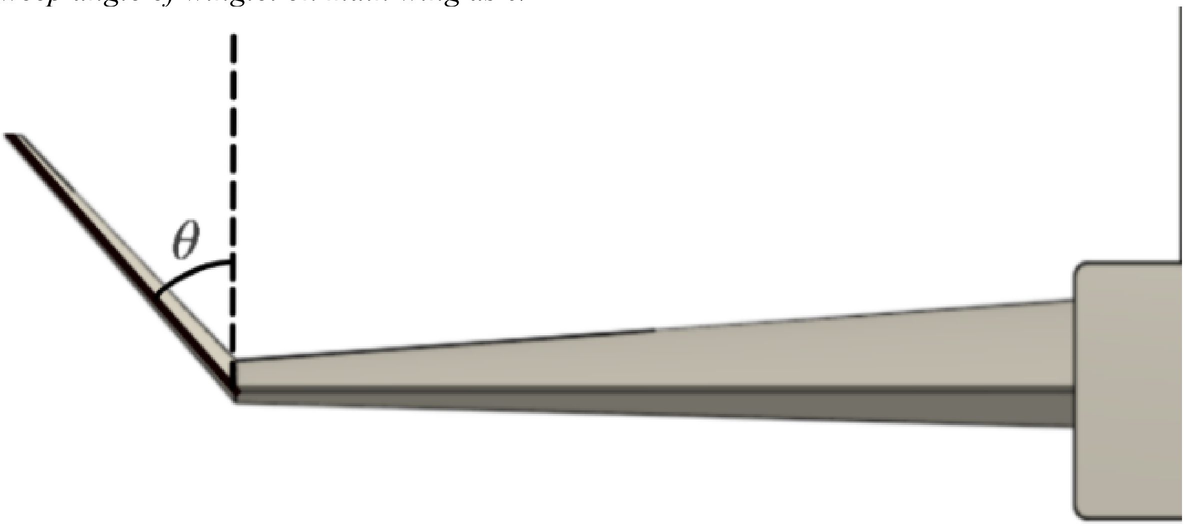

Figure 3.1

Addition of Canards onto Plane with Winglets on Main Wing for Models C1-C10

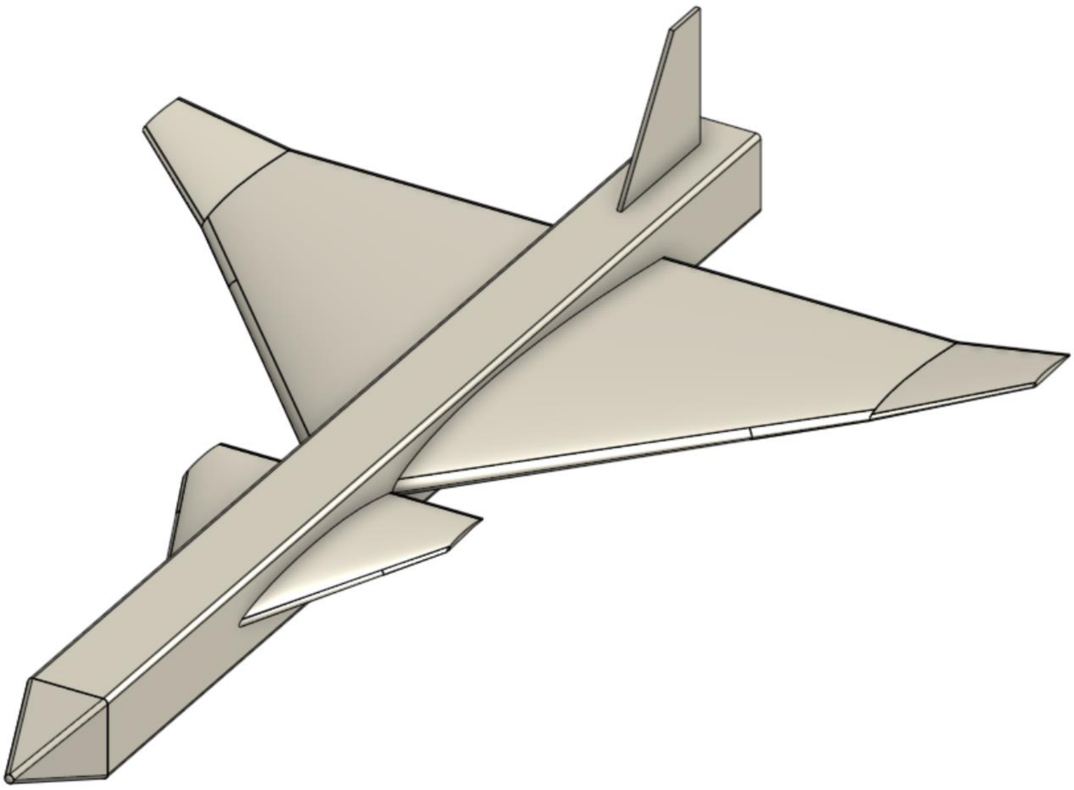

Figure 3.2

Side View of Addition of Canards onto Plane with Winglets on Main Wing for Models C1-C10

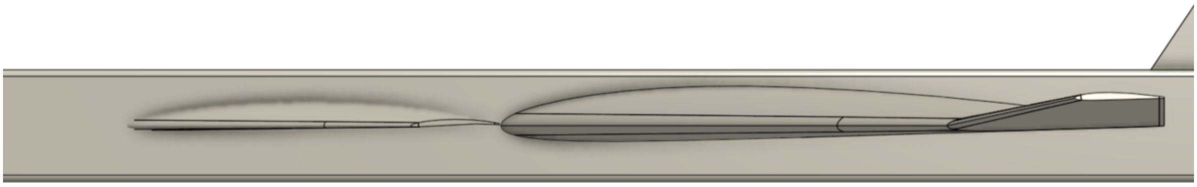

Figure 4.1

Horizontal Height of Canard as d/m

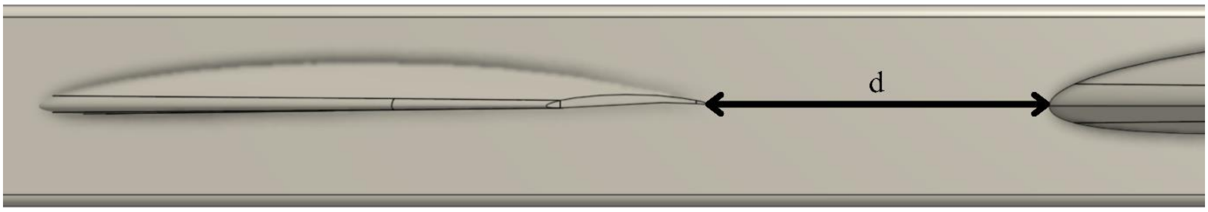

Table 4.2

Overview of Models D1-D6

Figure 5.1

Vertical Height of Canard as d/m

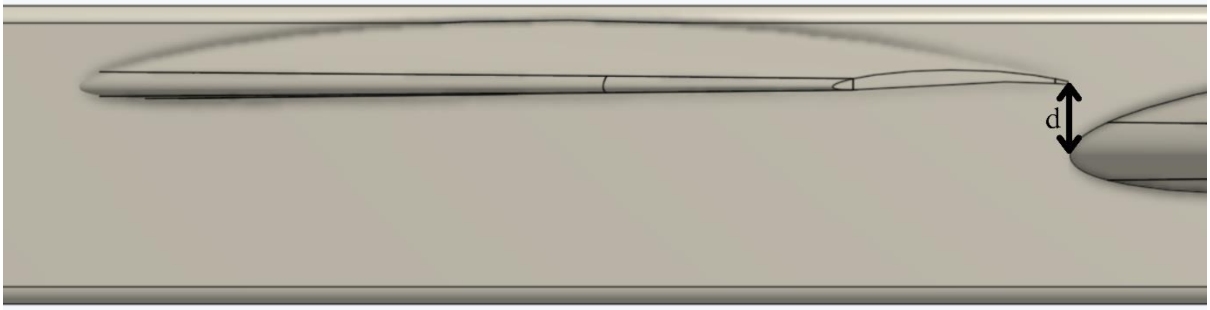

Table 5.2

Overview of Models E1-E5

Model	d/m
E1	0
E2	+0.002
E3	+0.004
E4	+0.006
E5	+0.008