Autonomous MAV aerofoil solution Investigation

Table of Contents

Table of Figures

Introduction

The following document outlines findings from an investigation into the effects of aerofoil profile and aspect ratio on aerodynamic characteristics under set operating conditions and design requirements. These requirements (See Table 1) arise from the physical constraints of an electric Autonomous MAV to be used in a smart city for detailed video surveillance. The effect of aspect ratio on lift induced drag is analysed assuming an elliptical lift distribution and the effect on Re is calculated using the chord length for each aspect ratio. Analysis of the 2D aerodynamic effects was undertaken with a software 'XFoil 6.99' where varying NACA 4-Digit aerofoil profiles were loaded, and the pressure distribution solved using a high-order panel and viscous interaction method at varied angles of attack. From this pressure distribution, drag and lift coefficients could be calculated and thus conclusions made on the suitability of the aerofoil.

Design Specification

Design Specification	**Value**
Altitude	Sea level condition ($\rho_{\text{air}} = 1.225kg/m^3$)
MAV speed	11 m/s
MAV Mass	0.51 (Weight 5N)
Wing area	0.13 m^2

TABLE 1 – TABLE DISPLAYING DESIGN SPECIFICATION CONSTANTS SET BY PROBLEM STATEMENT

Wing Aspect Ratio

Wing aspect ratio (AR) was chosen to balance the desirable effects of a lower induced drag coefficient from a larger AR and the un-desirable effects, being a decreased lift curve slope (a) and decreased Reynolds number, which would introduce flow separation from the wing and vastly decrease maximum lift. Together with these considerations, practicality of construction must be considered, as a long thin wing will be more difficult to structurally support without adding excessive weight which would decrease flight efficiency.

Taking these factors into consideration, an AR of 6 was chosen as this keeps Cdi to a minimum whilst maintaining a moderate lift curve slope. Reynolds number at this AR is also safely 15% above the threshold stated in teaching material of 1×10^5 which ensures low Re effects such as flow separation do not occur at or close to the specified cursing speed. Larger wing aspect ratios also reduce the versatility of the aircraft, requiring a large area for take-off and landing as well as reducing the durability of the aircraft. This is an important consideration due to MAV use case being for safety critical surveillance.

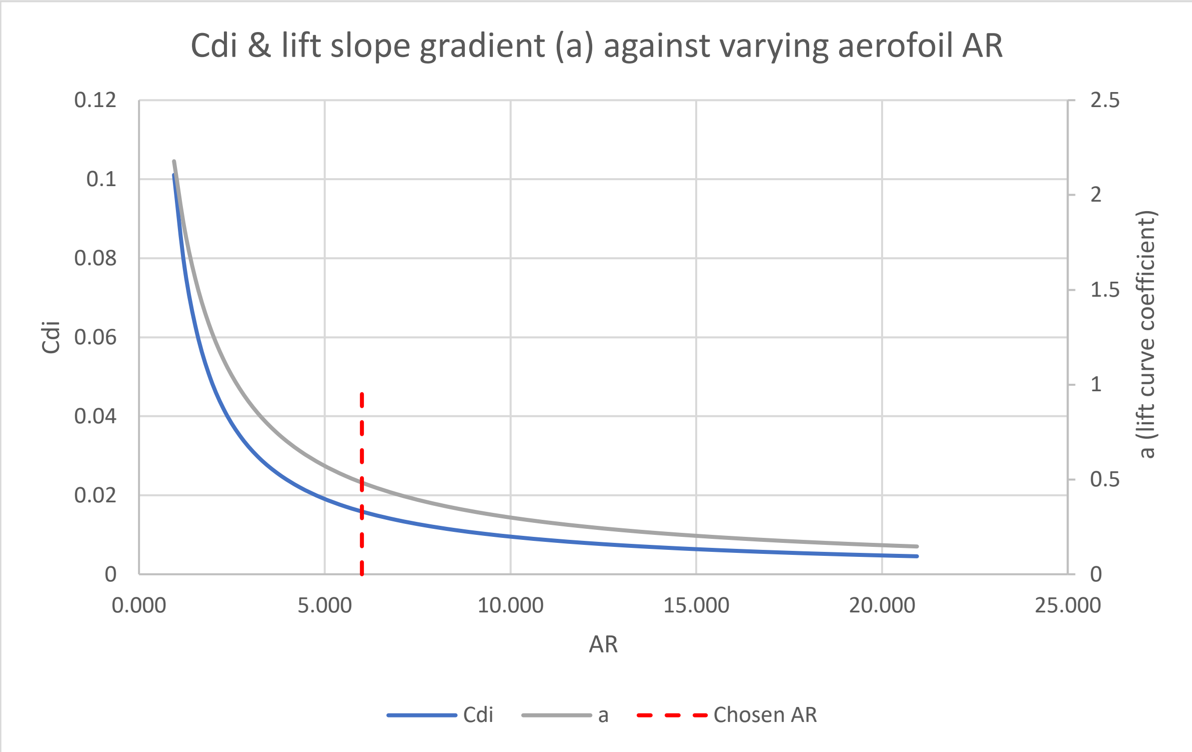

FIGURE 1 – GRAPH SHOWING CHANGE OF INDUCED DRAG COEFFICIENT AND LIFT SLOPE GRADIENT WITH INCREASING WING ASPECT RATIO

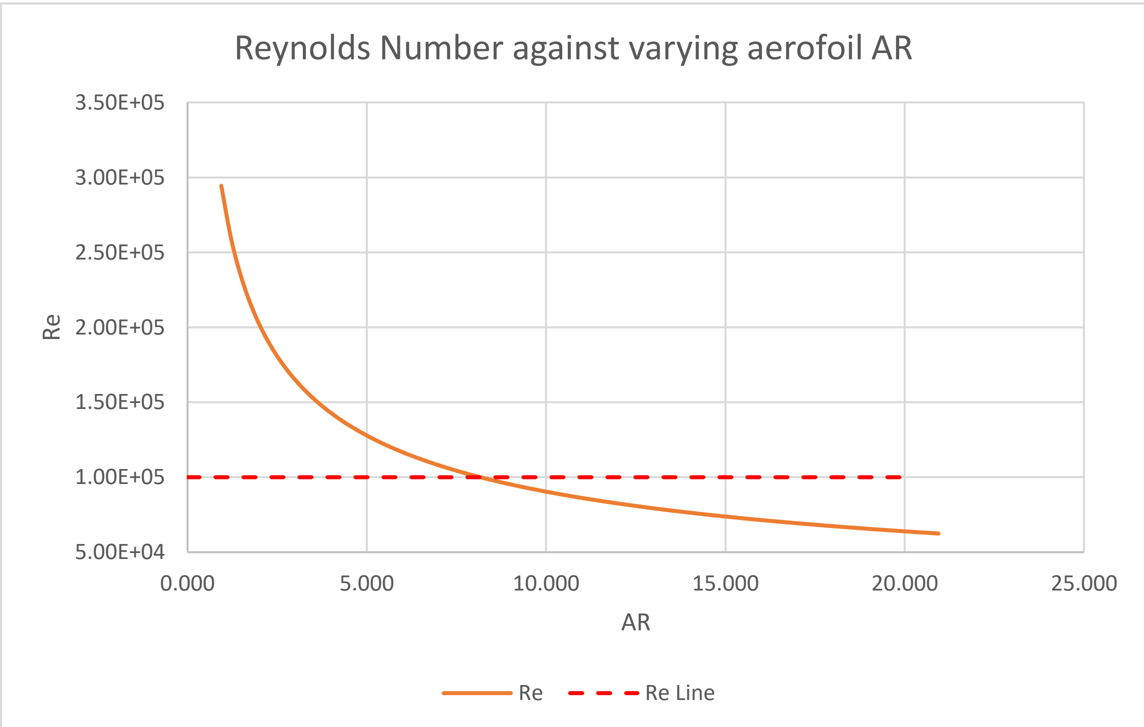

FIGURE 2 – GRAPH SHOWING VARIATION OF REYNOLDS NUMBER WITH INCREASING WING ASPECT RATIO

Aerofoil selection

Parameter	Value
C_l	0.5708
Re	1.17×10^5
C_{d_i}	0.038101

Initial Investigation

To determine the aerofoil factors most acutely affecting drag at the specified operating conditions, XFoil analysis was undertaken at varied maximum camber and thicknesses; the point of maximum camber was fixed by the design constraints. These initial profiles being: 2412, 2406, 1412, 1406; chosen to observe the results of altering the thickness and camber of the aerofoil independently. The results from these simulations were plotted to gain insight into lift slope profiles and therefore stall points for these aerofoils, as well as drag characteristics at different angles of attack. Preceding plotting of this data, AOAs where a solution did not converge were iterated further or removed where a solution couldn't converge given 3000 iterations, as this implied unstable flow.

Results from these simulations revealed that larger amounts of camber required smaller angles of attack for equivalent lift, however also had larger drag coefficients at these points. It was also found that there is a limit to this effect, as reducing the camber to zero (symmetrical aerofoil) resulted in a large increase in drag. This was due to flow separation from the wing, occurring at 0.0815*chord. Smaller aerofoil thicknesses reduced profile drag but decreased Cl_{max} and therefore the stall-point of the aerofoil. This would reduce the operating range, reducing manoeuvrability and ability of the aircraft to resist stall. This was shown during XFoil analysis, as solutions for thin aerofoils at larger AOA did not converge despite a large number of iterations and favourable setting of previous solutions due to unstable and detached flow. Furthermore, a thin aerofoil is more difficult to manufacture accurately and retain structural integrity. With a relatively low AR of 6 though, this shouldn't be a problem due to the smaller bending moments associated with the smaller wingspan.

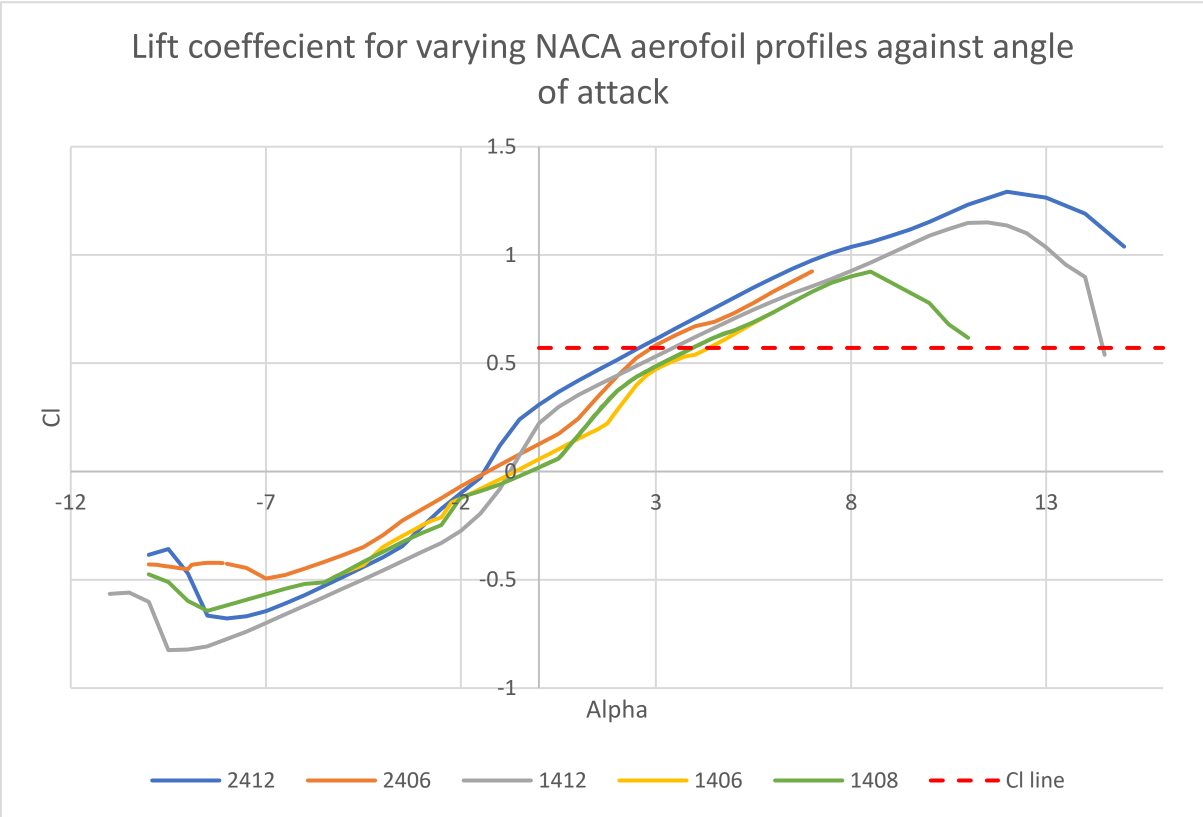

FIGURE 3 – GRAPH SHOWING LIFT COEFFICIENT AGAINST ANGLE OF ATTACK FOR VARIOUS NACA 4 DIGIT AEROFOIL PROFILES

Aerofoil Comparison

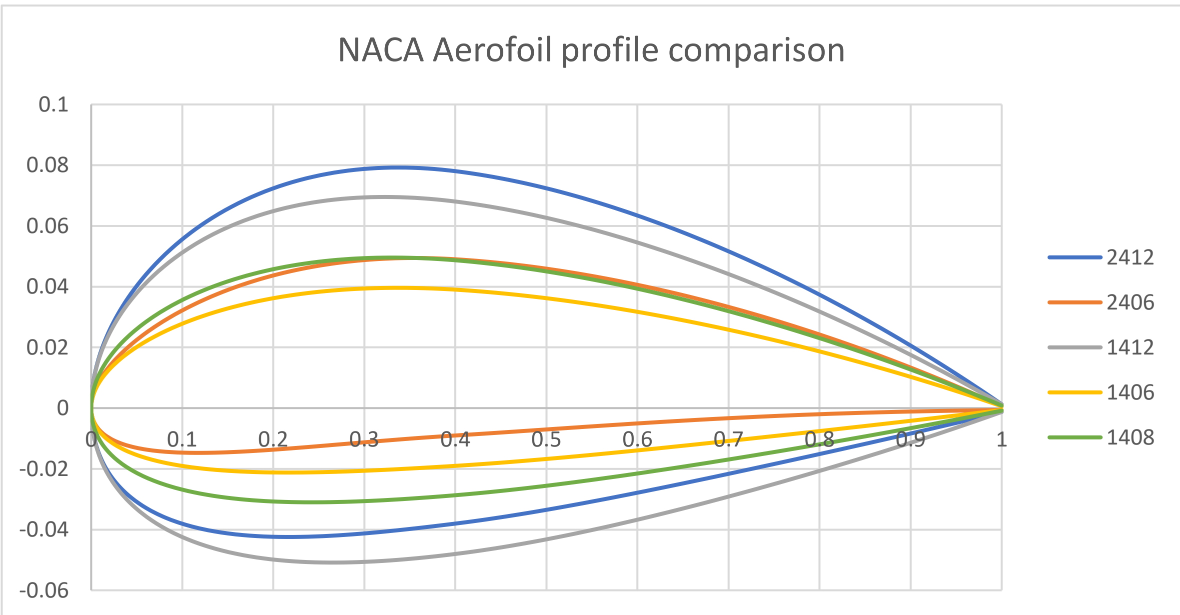

FIGURE 4 – GRAPH COMPARING AEROFOIL PROFILES RELATIVE TO CHORD LENGTH

Drag reduction

To determine the aerofoil with the lowest drag at the lift coefficient required at cruise, polars were plotted with data from XFoil. Figure 5 shows an enlarged view about the required 2D lift coefficient of 0.5708 and that the aerofoils with the lowest drag at this Cl are NACA 1408 and NACA 2406. The graph also reveals that both aerofoils aren't operating at their highest L/D ratio. However, iterating through XFoil simulations with an increased thickness (NACA 1409, NACA 1410) to move this curve the operating condition closer to Max L/D, made no further improvements to drag. A similar experiment was undertaken to shift Max L/D of NACA 2406 to the operating condition by reducing thickness further, however a drag increase was observed, owing to early flow separation (0.0590 of chord). This low of a thickness was also determined to be in-practical to build and flow too un-stable to use as an aerofoil in this application. Given wider choice of NACA aerofoils, e.g., NACA 5-digit, a more optimal aerofoil could be designed to operate at its Max L/D.

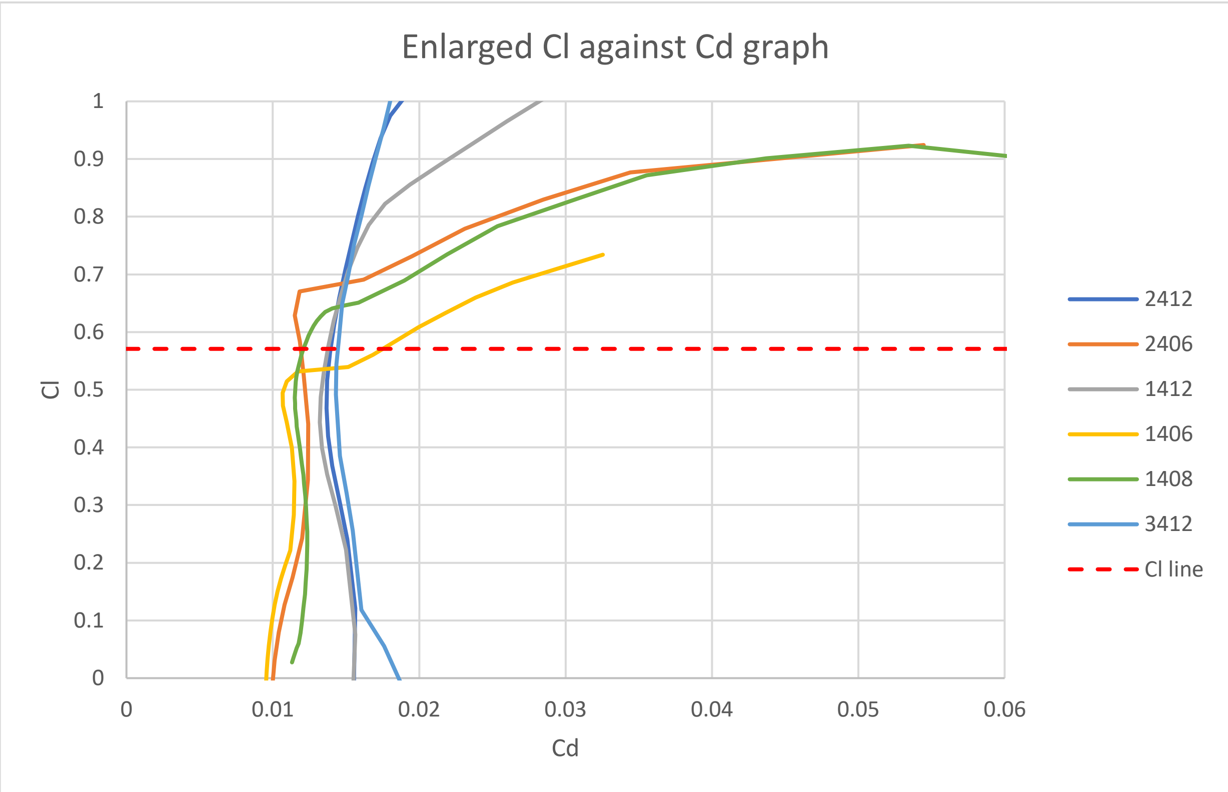

Figure 5 – Graph showing lift coefficient against drag coefficient for various NACA 4-digit aerofoil profiles close to specified cruise conditions

Other Aerodynamic considerations

As well as drag, other characteristics of the aerofoil at the design conditions must be evaluated to ensure its suitability. One such key characteristic, is the stall angle of the aerofoil and the shape of the lift curve before and after this point. XFoil analysis (Figure 3) showed that thicker aerofoils had a larger Cl_{max} and hence a larger operating window. Increased Camber affected stall due to the shifted curve as discussed in the 'Initial Investigation' section, however also levelled the stall curve, giving a more gradual transition into stall which increases controllability of the aircraft and time window to correct stall.

Aerofoil thickness practicality

Although thinner aerofoils offer less drag, physics will constrain the thickness due to practicality of manufacture and forces on the wing during operation. To investigate the smallest practical thickness, the aerofoil profiles were scaled in accordance with the chord dimensions defined during specification of the wing aspect ratio. In addition to this, similarly scaled MAVs were researched[1] and were found to have larger spans with similar aerofoil thicknesses (approximately NACA XX10) therefore the thinnest practical aerofoil thickness was deemed to be NACA XX08.

Effect of aerofoil profile on thrust

Total drag on the wings of the MAV is a combination of the lift induced drag Cd_i and the profile drag Cd_p. Lift induced drag Cd_i is proportional to the lift coefficient C_L^2 and is set by the design specification from weight W, wing area, A and cruise velocity, v. Profile drag is dependent upon the aerofoil profile and Reynolds number Re and is found using XFoil analysis.

$$C_{D_i} = \frac{C_L^2}{\pi AR} \qquad (1)$$

$$C_L = \frac{W}{\frac{1}{2}\rho v^2 A} \qquad (2)$$

$$C_d = \frac{2F_d}{\rho u^2 A} \qquad (3)$$

To determine thrust required for the aircraft at cruise (neglecting body drag) the profile and lift induced drag coefficients are summed and the drag equation C_d re-arranged for the drag force F_d which will be equal to the thrust required to maintain velocity at the cruise condition specified. This being established, it can be said that a minimum profile drag will translate to a minimum thrust required, therefore the findings for minimising drag also apply to thrust reduction. Figure 6 demonstrates this, using drag data for varying thickness aerofoils with 2 different camber profiles. Although smaller thrust requirements can be obtained through reducing thickness beyond NACA XX08, the resulting flow is unstable and lift characteristics around the operating point aren't favourable as discussed in the 'Aerofoil selection' section. This figure also shows a critical thickness, at which the thrust requirement vastly increases. For larger camber aerofoils this critical value is lower, owing to the shallower angle of attack required for equivalent lift of a more cambered aerofoil which delays separation.

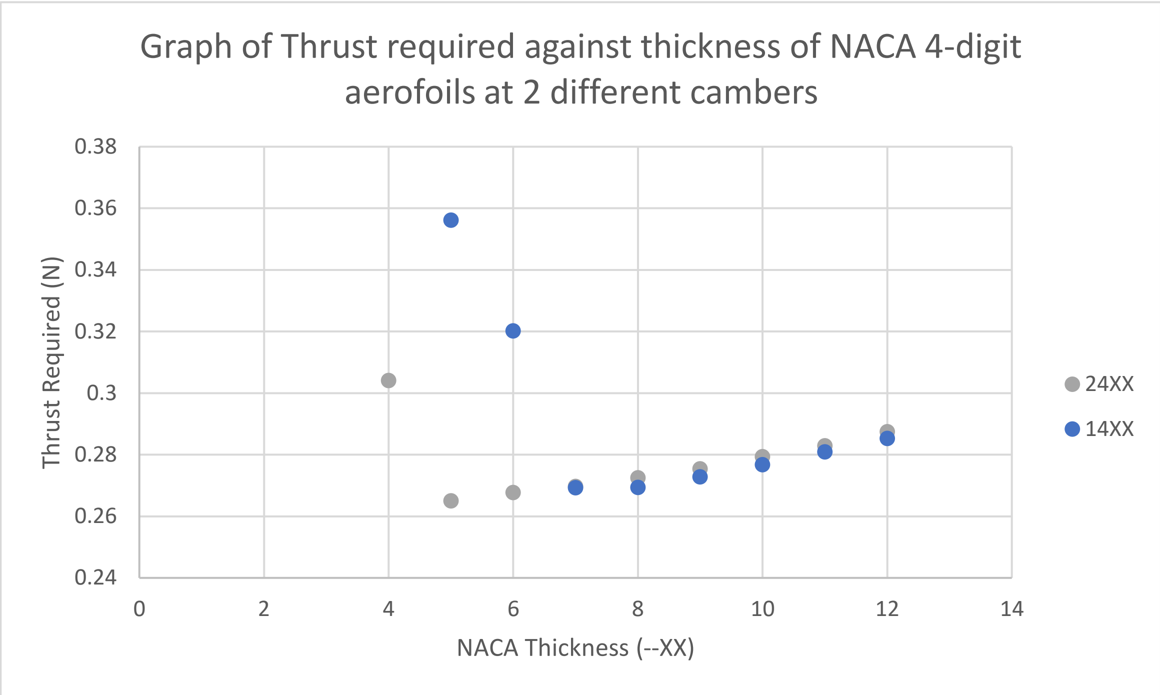

FIGURE 6 – GRAPH SHOWING RELATIONSHIP BETWEEN NACA THICKNESS AND THRUST REQUIRED AT 2 DIFFERENT CAMBERS

Conclusions

- AR should be set as high as possible, allowing for $\approx 10\%$ higher Re than the critical value of 1×10^5. This minimises lift induced drag and maximises aerodynamic efficiency. An AR of 6 was deemed optimal given the operating conditions and design constraints.
- Aerofoil should be made with a thickness as close to NACA XX08 as feasible, as this minimises drag while avoiding flow separation and keeping the aerofoil practical to build.
- Maximum camber should be kept to NACA 1XXX. Larger and smaller values increase drag due to flow separation.

References

[1] 'Whirlwind Scratchy - Composite RC Gliders'. https://composite-rc-gliders.com/en/p/whirlwind-scratchy (accessed Nov. 16, 2022).