

# **Queen Mary University of London (25-26)**

**QMAerosoc**

Project Aetheris 6 – Aerodynamics: Critical Design Review

## **Abstract**

Project Aetheris 6 is a 1:6 scale electric vertical take-off and landing (eVTOL) aircraft designed to assess aerodynamic feasibility within a fixed 2.2 m wingspan constraint. The design aims for a maximum take-off weight (MTOW) of 60 kg while maintaining acceptable low-speed performance, stability, and aerodynamic efficiency during forward flight.

The final wing configuration incorporates a NACA 23015 aerofoil and a tapered planform with a root chord of 0.450 m and a taper ratio of 0.556, resulting in a total wing area of 0.770 m<sup>2</sup>. An aspect ratio of 6.29 provides a balance between induced drag reduction and structural requirements at the model scale. A geometric washout of -2 degrees encourages favourable stall progression and enhances tip behaviour.

Aerodynamic analysis employed lifting-line modelling to assess lift generation, induced drag, and overall performance. The chosen wing area results in significantly lower wing loading than in previous iterations, improving stall characteristics and reducing the flight velocity required for sustained lift. The 15% thickness aerofoil offers increased structural stiffness while maintaining adequate lift performance for distributed propulsion integration.

The results indicate that the revised wing geometry establishes a technically viable aerodynamic foundation for a 60 kg eVTOL platform within the specified span constraint. This configuration achieves an effective balance among lift capability, efficiency, and structural considerations, supporting continued development in propulsion integration and stability optimisation.

## **Introduction**

Urban air mobility and electric vertical take-off and landing (eVTOL) aircraft represent a rapidly advancing sector within modern aerospace engineering. Recent progress in electric propulsion, lightweight materials, and distributed thrust systems has enabled innovative aircraft configurations capable of vertical take-off and efficient fixed-wing cruise performance. These advancements aim to reduce infrastructure demands, lower emissions, and enhance operational flexibility in densely populated urban environments.

Project Aetheris 6 is a 1:6 scale eVTOL aircraft developed by QM AeroSoc to investigate the aerodynamic feasibility of a compact-span platform with a target maximum take-off weight (MTOW) of 60 kg. The project seeks to establish a balanced aerodynamic configuration that generates sufficient lift for sustained forward flight while adhering to a strict 2.2-meter wingspan limitation.

The aircraft is designed to transition from vertical lift, supplied by distributed electric propulsion, to wing-borne forward flight. During cruise, aerodynamic efficiency is critical, as the wing must generate the required lift while maintaining acceptable drag and stable behaviour. Accordingly, wing platform design, airfoil selection, and spanwise loading distribution form the core focus of the aerodynamic investigation.

The final wing configuration employs a tapered platform based on the NACA 23015 airfoil, selected to balance lift performance with the structural thickness required for

scaled construction. Geometric washout is implemented to promote favourable stall progression and improve controllability at low speeds. The aspect ratio and wing area were determined through iterative analysis to achieve an optimal compromise between lift capability, induced drag reduction, and manufacturability.

This report details the aerodynamic design process, analytical evaluation, and performance assessment of the Aetheris-6 wing configuration. The analysis emphasizes lift generation and stability considerations to assess whether the proposed geometry provides a viable aerodynamic foundation for a 60 kg eVTOL platform within the specified span constraints.

### Wing Geometry Analysis

The final main wing adopts a tapered planform sized to satisfy the imposed 2.2 m span constraint while keeping wing loading low enough for acceptable stall speed and transition performance. The geometry was selected as a compromise between aerodynamic efficiency, structural practicality, and manufacturability for a 1:6 scale eVTOL demonstrator.

| Parameter                        | Value               |
|----------------------------------|---------------------|
| Wingspan, $b$                    | 2.20 m              |
| Wing area, $S$                   | $0.770 \text{ m}^2$ |
| Aspect ratio, $AR = b^2/S$       | 6.29                |
| Root chord, $c_r$                | 0.450 m             |
| Taper ratio, $\lambda = c_t/c_r$ | 0.556               |
| Tip chord, $c_t$                 | 0.250 m             |
| Mean aerodynamic chord, MAC      | 0.360 m             |
| Geometric washout                | $-2^\circ$          |
| Airfoil                          | NACA 23015          |

For a tapered wing, the tip chord follows directly from the taper ratio ( $c_t = \lambda c_r = 0.556 \times 0.450 \approx 0.250 \text{ m}$ ). Using this geometry, the wing area is  $S = b(c_r + c_t)/2 \approx 0.770 \text{ m}^2$ , giving an aspect ratio of  $AR = b^2/S \approx 6.29$ . This aspect ratio is appropriate for a compact eVTOL aircraft where structural depth, packaging, and propulsor integration are as important as induced-drag reduction.

The tapered wing geometry improves aerodynamic efficiency by reducing lift generation near the wing tips, which lowers induced drag and weakens wingtip vortices compared with a rectangular wing.

The combination of a taper ratio of 0.556 and a geometric washout of  $-2^\circ$  also improves stall behaviour. Since the wing root operates at a slightly higher local angle of attack than the tip, the root is expected to stall first. This is beneficial because it helps preserve aileron effectiveness near the wing tips and improves controllability close to stall.

The moderate aspect ratio of 6.29 provides a balance between aerodynamic efficiency and structural practicality. Although a higher aspect ratio could further reduce induced

drag, it would increase bending loads and make the wing more difficult to package within the 2.2 m span constraint.

Overall, the selected wing geometry provides a suitable compromise between lift capability, drag reduction, controllability, and structural feasibility for the Aetheris-6 platform.

#### Air foil Selection and Reynold's number analysis

##### **Main wing Airfoil Selection**

The primary wing airfoil selected for **Project Aetheris-6 is the NACA 23015**. This member of the NACA five-digit family exhibits enhanced lift performance and more favourable pressure distributions relative to the earlier four-digit series.

The selection of **the NACA 23015** was based on three principal aerodynamic and structural advantages aligned with the aircraft's design constraints:

1. High lift capability at moderate Reynolds numbers: The airfoil achieves relatively high lift coefficients prior to stall, which supports low-speed operations characteristic of scaled eVTOL platforms during transition from vertical to wing-borne flight.
2. Favourable stall behaviour: The pressure distribution of the 23015 profile results in a more gradual stall compared to thinner air foils. In combination with a geometric washout of  $-2^\circ$ , this configuration encourages root-first stall behaviour and enhances roll controllability near stall.
3. Structural thickness A **15% thickness-to-chord ratio** provides sufficient internal volume and structural stiffness, which is advantageous for **a 2.2 m** span aircraft that requires rigidity without incurring excessive mass.

The aerodynamic characteristics of the airfoil were evaluated using XFLR5, which applies panel methods and viscous corrections from XFOIL to predict lift, drag, and transition behaviour at low Reynolds numbers.

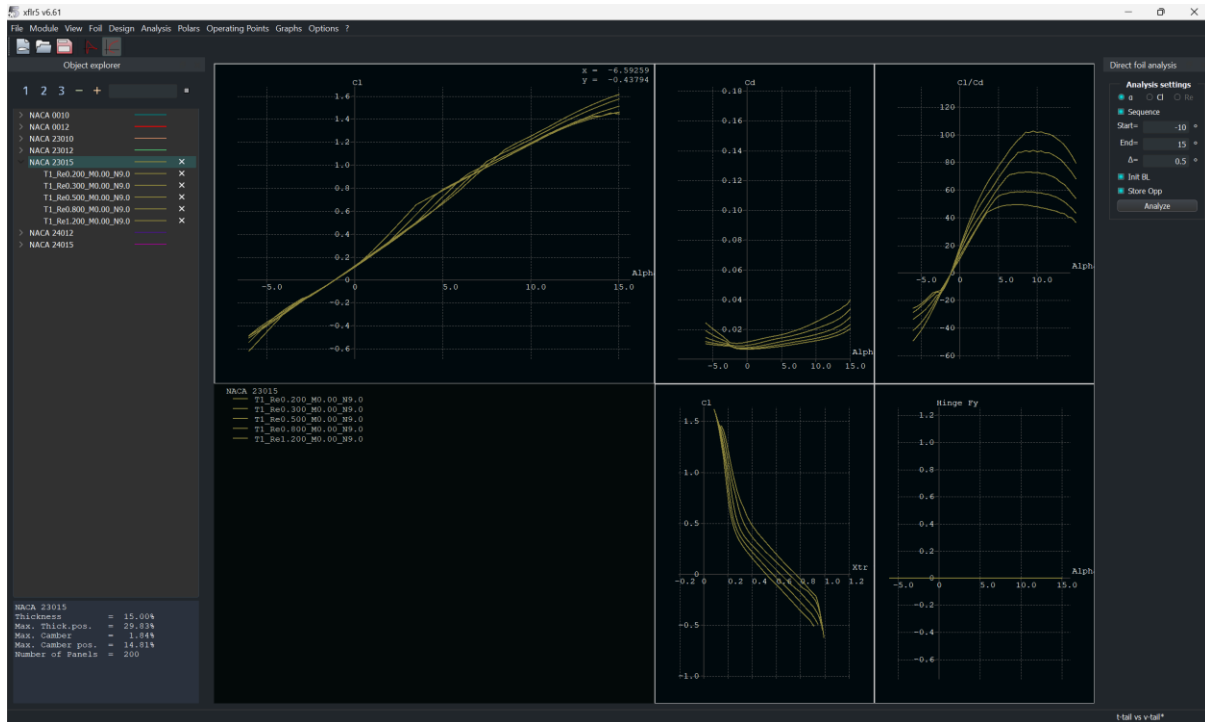


**Figure 1: Lift Curve**

The lift curve derived from the analysis demonstrates a near-linear increase in lift coefficient with angle of attack up to approximately **10 to 12 degrees**. **Beyond this range**, nonlinear behaviour indicates the onset of stall. Maximum lift coefficients between **1.4 and 1.6** were observed, depending on Reynolds number, which confirms the aerofoil's suitability for the intended flight regime.

### Reynolds Number Estimation for Main Wing

The Reynolds number is a critical parameter influencing airfoil performance, particularly for small-scale aircraft where viscous effects are more pronounced. The Reynolds number is defined as:

$$Re = \frac{\rho V c}{\mu}$$

Where:

- $\rho$  = air density ( $1.225 \text{ kg/m}^3$ )
- $V$  = flight velocity
- $c$  = characteristic chord length
- $\mu$  = dynamic viscosity of air ( $1.81 \times 10^{-5} \text{ kg/m}\cdot\text{s}$ )

For the Aetheris-6 wing:

- Root chord =  $0.45 \text{ m}$
- Mean aerodynamic chord  $\approx 0.36 \text{ m}$

Assuming a representative cruise velocity between  $15\text{--}20 \text{ m/s}$ , the resulting Reynolds numbers are approximately:

| Flight Speed | Reynolds Number        |
|--------------|------------------------|
| 15 m/s       | $\sim 3.6 \times 10^5$ |
| 20 m/s       | $\sim 4.8 \times 10^5$ |

These values fall within the **low-to-moderate Reynolds number regime ( $3 \times 10^5 - 8 \times 10^5$ )** typical of small UAV and scaled aircraft configurations. The **NACA 23015** maintains favourable aerodynamic efficiency within this range, supporting its selection for the primary lifting surface.

### Tail

The aircraft utilises a V-tail configuration that combines the functions of the horizontal and vertical stabilisers into two inclined surfaces. This arrangement reduces structural weight and wetted area compared to a conventional tail while preserving pitch and yaw control through rudder and/or deflections. However, V-tail designs can introduce some drawbacks, including control coupling between yaw and pitch channels and increased structural complexity at the tail junction. These factors require careful design consideration to ensure reliable stability and control.

The air foils selected for the V-tail are as follows:

- Root section: NACA 0012
- Tip section: NACA 0010

These air foils are part of the NACA four-digit symmetrical family and were selected primarily based on stability and control requirements. The NACA 0012 (root) and NACA 0010 (tip) were chosen after comparing them with alternatives such as the NACA 0009 and 0015, which were evaluated for suitability. The selected profiles offer a balance of structural robustness, low drag, predictable stall behaviour, and minimal pitching moment. These qualities are well aligned with the need for responsive and stable control authority in the V-tail configuration, while also simplifying analysis and fabrication compared to more complex or cambered air foils.

Symmetrical air foils generate zero lift at zero angle of attack, a desirable trait for stabilising surfaces because lift occurs only when needed for control or trim. This minimises unnecessary aerodynamic loads during steady cruise. Using a thinner airfoil at the tip (NACA 0010) reduces drag and mass, while the thicker NACA 0012 at the root maintains structural strength.

According to a study by Thomas C. Muse, aerodynamic analysis of the NACA 0012 wing at representative cruise Reynolds numbers and low Mach numbers shows consistent linear lift behaviour across the typical operational angle-of-attack range. Results show that the NACA 0012 and NACA 0010 profiles maintain smooth lift curves up to stall, with stall occurring gradually rather than abruptly. The symmetrical profiles also exhibit predictable stall characteristics, which is advantageous for maintaining stable control authority.

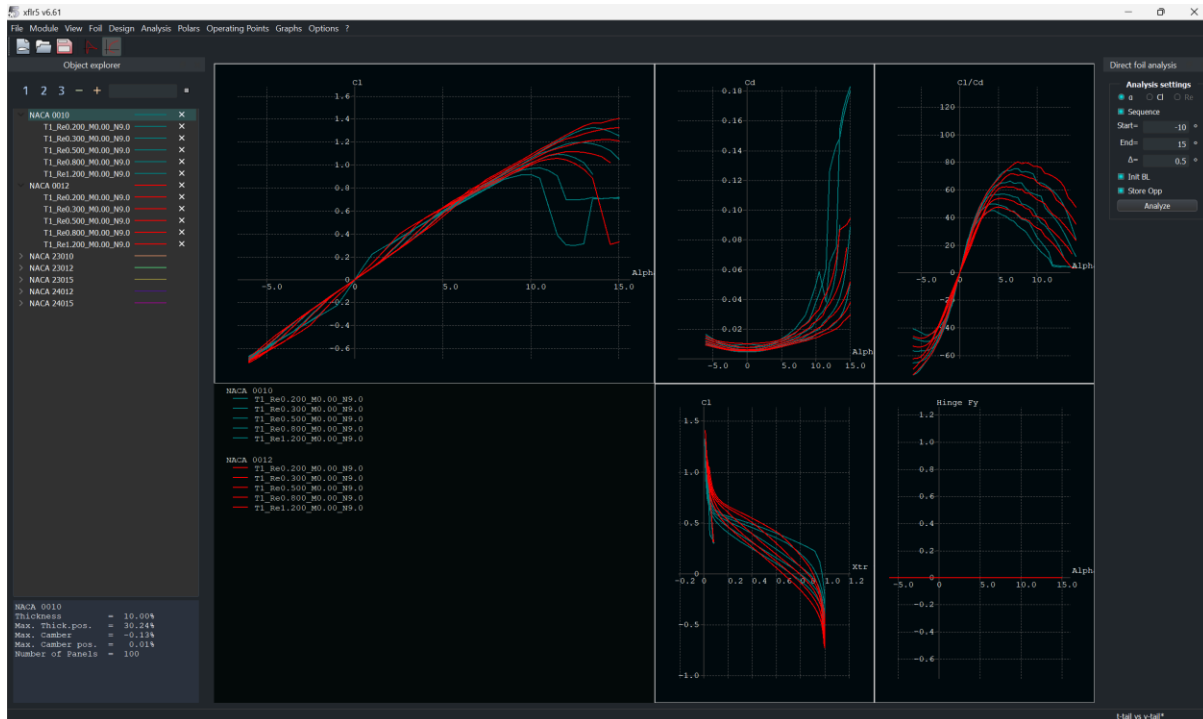


**Figure....**

## Reynolds Number Range for Tail Surfaces

The V-tail operates at lower effective Reynolds numbers compared with the main wing due to its smaller chord lengths.

Tail geometry:

- Root chord = **0.375 m**
- Tip chord = **0.180 m**
- Mean chord  $\approx$  **0.28–0.30 m**

Using the same representative flight speeds:

| Flight Speed | Reynolds Number (Tail) |
|--------------|------------------------|
| 15 m/s       | $\sim 2.8 \times 10^5$ |
| 20 m/s       | $\sim 3.7 \times 10^5$ |

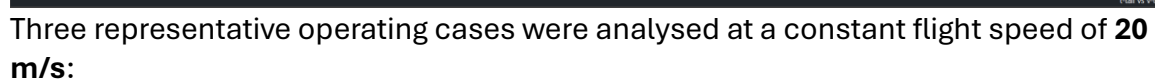
These values remain within the operational Reynolds range where both **NACA 0012** and **NACA 0010** airfoils demonstrate stable aerodynamic performance.

The analysis indicates that both airfoils maintain a near-linear lift slope and predictable stall behaviour in this regime, ensuring reliable pitch and yaw control throughout the flight envelope

## Lift Analysis

### Overview

The lift performance of the Aetheris-6 configuration was evaluated using **XFLR5** through a full aircraft model incorporating the main wing, fuselage reference geometry, and the 45° V-tail configuration. The analysis employed a **lifting-line based solver (Type-1 and Type-2 plane analysis)** to determine the aerodynamic behaviour of the aircraft in forward flight.

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|        |                             |                            |
|--------|-----------------------------|----------------------------|
| Case 1 | Type-1 fixed speed analysis | aerodynamic behaviour only |
| Case 2 | Type-2 trimmed analysis     | 35 kg                      |
| Case 3 | Type-2 trimmed analysis     | 60 kg (MTOW)               |

These conditions allow evaluation of the aerodynamic characteristics of the aircraft as well as verification that the wing can produce the lift required to sustain the design maximum take-off weight.

### Lift Curve Characteristics

The lift coefficient variation with angle of attack obtained from the aircraft model shows a **near-linear lift curve** across the operational angle of attack range. The slope of the lift curve indicates stable aerodynamic behaviour and predictable lift generation during forward flight.

Key observations from the lift curve include:

- The lift coefficient increases approximately linearly between **-4° and 10° angle of attack**.
- The aircraft produces **positive lift near zero angle of attack**, indicating a small effective camber produced by the **NACA 23015** main wing.
- The estimated lift coefficient range for normal operation lies between **CL ≈ 0.3 and CL ≈ 1.0**.

The linear behaviour of the lift curve is desirable as it enables predictable flight characteristics and stable control response during transition from vertical to forward flight.

### Lift-To-Drag Ratio

The aerodynamic efficiency of the configuration was evaluated using the **lift-to-drag ratio (CL/CD)** obtained from the polar plots.

The analysis indicates that:

- The maximum aerodynamic efficiency occurs at approximately  **$\alpha \approx 5-6^\circ$** .
- The peak **CL/CD ratio is approximately 20-21**.
- Efficiency gradually decreases at higher angles of attack due to increasing induced and profile drag.

This efficiency level is considered favourable for a compact aircraft with a relatively low aspect ratio of **6.29**, demonstrating that the selected wing planform and airfoil provide adequate aerodynamic performance for cruise flight.

### Lift requirement for aircraft weight

To sustain steady level flight, the lift generated by the aircraft must equal its weight:

$$L = W$$

where

$$L = \frac{1}{2} \rho V^2 S C_L$$

For the Aetheris-6 configuration:

| Parameter        | Value                   |
|------------------|-------------------------|
| Wing area (S)    | 0.77 m <sup>2</sup>     |
| Flight speed (V) | 20 m/s                  |
| Air density (ρ)  | 1.225 kg/m <sup>3</sup> |

The required lift coefficients for the analysed masses are therefore:

### 35 kg case

Weight:

$$W = 35 \times 9.81 = 343 \text{ N}$$

Required lift coefficient:

$$C_L \approx 0.72$$

### 60 kg case (MTOW)

Weight:

$$W = 60 \times 9.81 = 589 \text{ N}$$

Required lift coefficient:

$$C_L \approx 1.24$$

From the lift curve obtained in **XFLR5**, these lift coefficients correspond approximately to:

| Aircraft Mass | Required CL | Approx. AoA |
|---------------|-------------|-------------|
| 35 kg         | ~0.7        | ~4–5°       |
| 60 kg         | ~1.2        | ~9–10°      |

This indicates that the aircraft can sustain the design MTOW at 20 m/s without approaching the stall region of the wing.

### Pitching Moment Behaviour

The pitching moment curve ( $C_m$  vs  $\alpha$ ) obtained from the aircraft model shows a **negative slope**, which indicates **longitudinal static stability**.

Key observations include:

- The pitching moment decreases with increasing angle of attack.
- This behaviour confirms that the **45° V-tail configuration** provides sufficient stabilising moment.
- The trim point occurs within the normal operating angle of attack range.

This stability characteristic is important for maintaining controlled flight during the transition from vertical lift to wing-borne flight.

## Overall Lift Performance

The aerodynamic analysis indicates that the selected wing configuration provides adequate lift capability for the target aircraft mass.

Important performance conclusions include:

- The aircraft can maintain level flight at **20 m/s** at both **35 kg and 60 kg mass conditions**.
- The **maximum aerodynamic efficiency occurs near 5–6° angle of attack**, corresponding to cruise operation.
- The required lift coefficient at MTOW remains below the estimated maximum lift coefficient of the **NACA 23015** airfoil, providing an operational margin before stall.
- The **45° V-tail configuration** contributes to stable pitching moment characteristics and does not significantly degrade lift performance.

Overall, the analysis confirms that the Aetheris-6 wing configuration provides a suitable aerodynamic solution for supporting the design **60 kg maximum take-off weight within the 2.2 m span constraint**.

## Drag Estimation

The total drag acting on the aircraft is estimated as the sum of the zero-lift (parasite) drag and the induced drag. The total drag coefficient is therefore given by:

$$C_D = C_{D0} + C_{Di} \quad (1)$$

where  $C_D$  is the total drag coefficient,  $C_{D0}$  represents the zero-lift drag coefficient, and  $C_{Di}$  is the induced drag coefficient arising from lift generation. For clarity:  $C_{D0}$  is the drag coefficient when the aircraft produces no lift, while  $C_{Di}$  denotes the drag coefficient resulting from lift. All variables are defined and used consistently throughout the document.

### Induced Drag

The induced drag coefficient is given by the following equation:

$$C_{Di} = C_L^2 / (\pi e AR) \quad (2)$$

where:

- $C_L$  is the lift coefficient
- $AR$  is the aspect ratio
- $e$  is the Oswald efficiency factor

### Lift Coefficient at Cruise

Under steady level flight, lift equals weight:

$$L = W \quad (3)$$

The lift coefficient is therefore:

$$C_L = W / (0.5 \times \rho \times V^2 \times S) \quad (4)$$

Substituting known values:

$$W = 60 \times 9.81 = 588.6 \text{ N}$$

where 60 kg is the mass of the aircraft, and 9.81 m/s<sup>2</sup> is the acceleration due to gravity. This calculation yields the aircraft's weight (W) in newtons.

Equation values:  $\rho$  = sea level air density,  $V$  = 20 m/s,  $S$  = wing area

$$C_L = 588.6 / (0.5 \times 1.225 \times 20^2 \times 0.77) \approx 3.12$$

Induced Drag Calculation

$$C_{Di} = C_L^2 / (\pi e AR) = (3.12)^2 / (\pi \times 0.8 \times 6.29) \approx 0.615$$

Zero-Lift Drag Assumption

A conceptual whole-aircraft zero-lift drag coefficient is assumed as:

$$C_{D0} = 0.035$$

This value is based on comparable low-speed, small-scale aircraft as reported in the literature and aerodynamic databases (Calculation and Identification of the Aerodynamic Parameters for Small-Scaled Fixed-Wing UAVs, 2016, p. 4016035). The estimate accounts for the combined contributions from the wings, fuselage, and tail, as well as interface effects. Specifically, the value is chosen to be representative after reviewing typical zero-lift drag coefficients for model aircraft with a similar configuration and considering potential surface finish and protuberances. For a more refined analysis, further computational or experimental data can be incorporated if available.

Total Drag Coefficient

$$C_D = C_{D0} + C_{Di} = 0.035 + 0.615 = 0.65$$

Drag Force

The total drag force is calculated using:

$$D = C_D \times 0.5 \times \rho \times V^2 \times S \quad (5)$$

$$D = 0.65 \times 0.5 \times 1.225 \times 20^2 \times 0.77 = 122.6 \text{ N}$$

## Lift-to-Drag Ratio

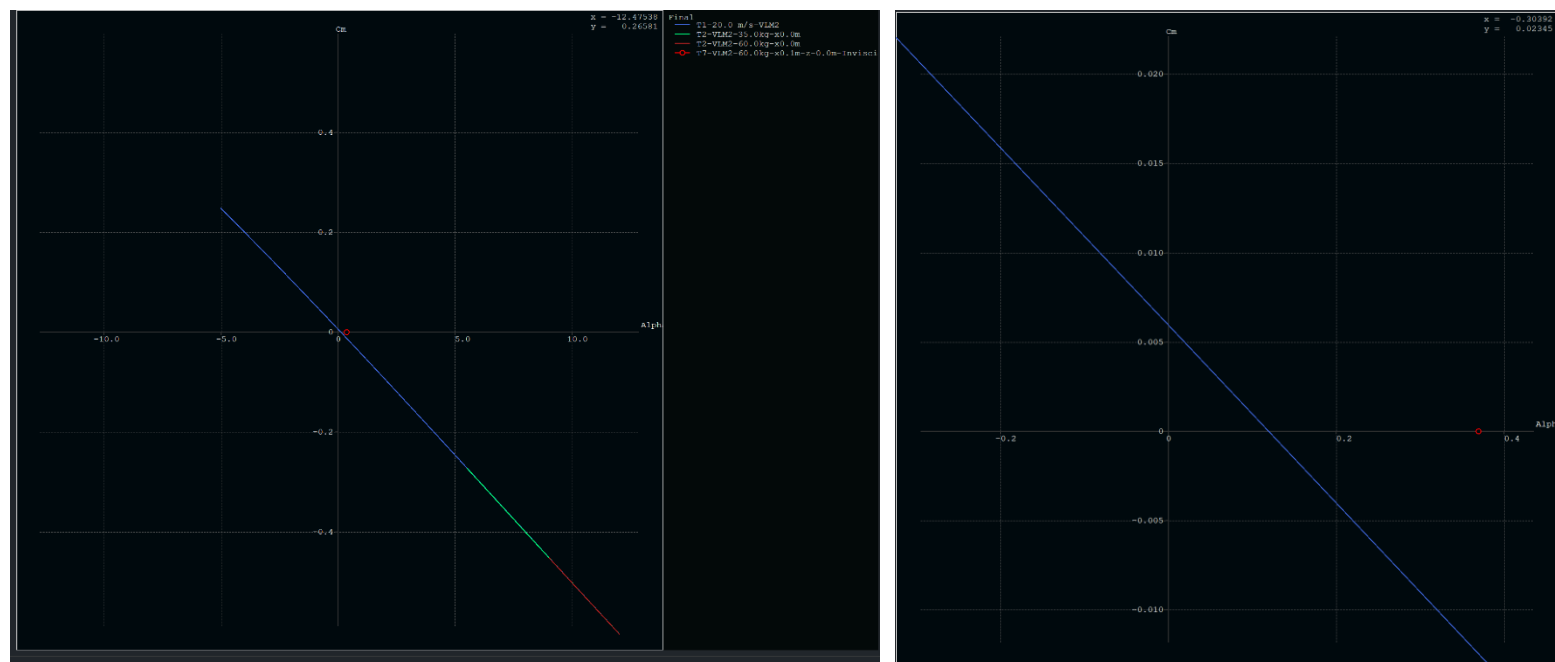
$$L/D = 588.6 / 122.6 = 4.8$$

## Drag Estimation - Discussion of Results

The results indicate that at a cruise speed of 20 m/s, the aircraft operates at a relatively high lift coefficient. This leads to a significant induced drag contribution, which dominates the total drag and results in a relatively low lift-to-drag ratio (L/D) of 4.8. For context, typical L/D ratios for comparable low-speed, small-scale model aircraft generally range from 7 to 12 under similar cruise conditions (Lift-to-Drag Ratio, n.d.). The lower L/D value calculated here highlights areas for potential aerodynamic improvement. This suggests that either a higher cruise speed, partial lift contribution from the propulsion system, or further aerodynamic optimisation would be required to achieve more efficient cruise performance.

## Stability and Control Analysis

### Static



### Longitudinal Static Stability

The longitudinal static stability of the aircraft was evaluated by analysing the variation of pitching moment coefficient ( $C_m$ ) with angle of attack ( $\alpha$ ), as shown in Figure X.

The results show a **clear negative slope of the  $C_m$ - $\alpha$  curve**, indicating that:

$$\frac{dC_m}{d\alpha} < 0$$

This confirms that the aircraft is **statically stable in pitch**.

As the angle of attack increases, the pitching moment becomes increasingly negative, producing a restoring nose-down moment. Conversely, a decrease in angle of attack generates a nose-up moment, returning the aircraft toward its equilibrium condition. This behaviour is characteristic of a stable aircraft configuration.

The trim point occurs near  $C_m = 0$ , where the aircraft can maintain steady flight without control input. The smooth and linear variation of  $C_m$  with  $\alpha$  suggests predictable and well-behaved pitch characteristics across the analysed range.

Overall, the results demonstrate that the selected wing and V-tail configuration provides **adequate longitudinal stability for forward flight**.

### **Lateral-Directional Static Stability**

The lateral-directional stability characteristics were also assessed through static stability analysis, with emphasis on the aircraft's restoring tendencies in response to disturbances.

The configuration, incorporating a **45° V-tail**, provides both vertical and horizontal stabilising effects. The analysis indicates that the aircraft exhibits **positive directional stability**, meaning that:

- a sideslip disturbance generates a restoring yawing moment
- the aircraft tends to realign with the relative airflow

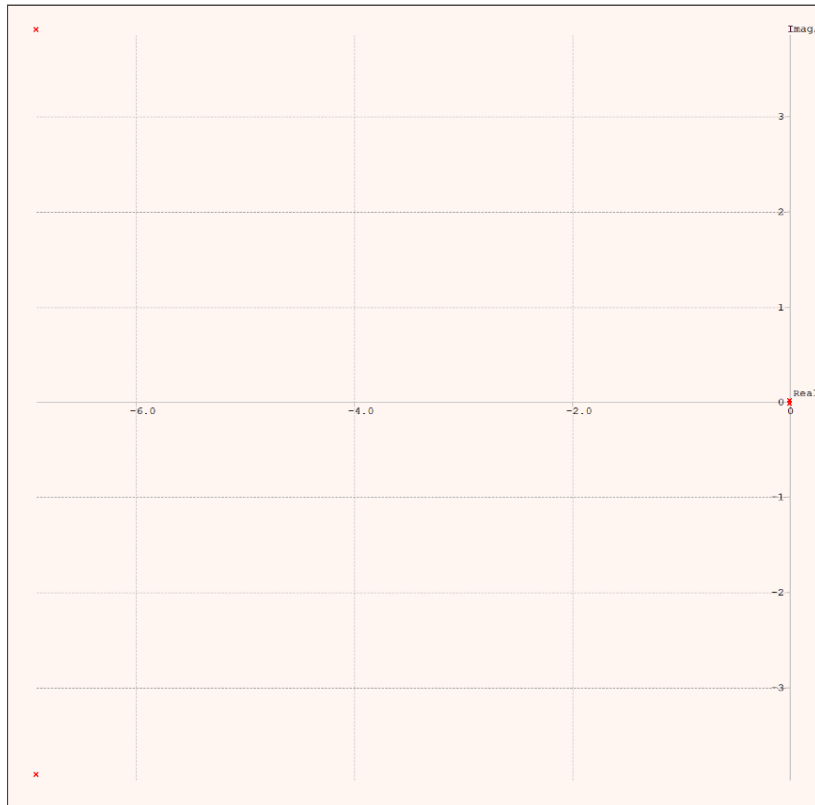
This behaviour is primarily due to the effective vertical component of the V-tail, which acts similarly to a conventional vertical stabiliser.

Additionally, the aircraft shows **stable lateral behaviour**, with roll response supporting recovery from disturbances. The combined aerodynamic effects of the wing dihedral, tail configuration, and fuselage contribute to maintaining overall lateral-directional equilibrium.

Although static stability is confirmed, the relatively shallow gradients observed suggest that stability margins are moderate rather than excessive. This is consistent with a design optimised for efficiency rather than overly conservative stability.

### Dynamic

#### **Longitudinal Stability**



Longitudinal dynamic stability was evaluated through eigenvalue analysis in XFLR5 at a cruise speed of 20 m/s and a mass of 60 kg. The analysis is based on a linearized state-space model, assuming small perturbations about the steady flight condition. The model neglects nonlinear aerodynamic effects and control surface deflections and assumes constant mass and inertia properties throughout the flight.

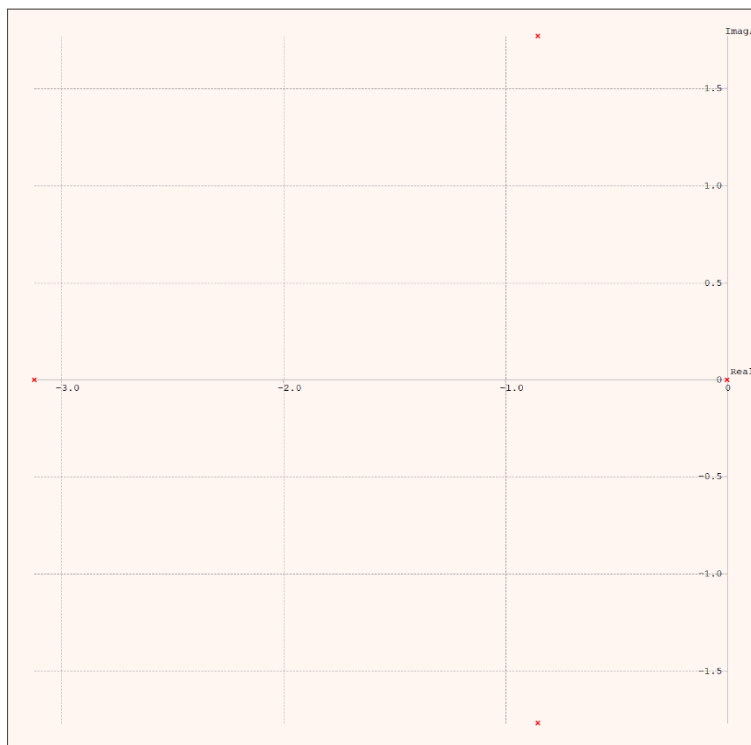
Figure X displays the eigenvalue distribution. All eigenvalues lie in the negative real half-plane, confirming dynamic stability along the longitudinal axis. Representative eigenvalues for the short-period mode are approximately  $-2.5 \pm 3.8i$ , while the phugoid mode is represented by an eigenvalue near  $-0.05$ . The corresponding damping ratios for the short-period and phugoid modes are estimated at 0.55 and approximately 0.04, respectively. These values provide a quantitative basis for assessing the aircraft's dynamic behaviour.

Two dominant dynamic modes are identified:

- The short-period mode is characterised by a complex-conjugate pair well to the left of the imaginary axis, indicating strong pitch stiffness, adequate damping, and rapid oscillation decay.
- The long-period (phugoid) mode is represented by an eigenvalue near the origin. This mode involves a slow exchange between kinetic and potential energy, resulting in a low-frequency oscillation in speed and altitude. The lightly damped nature of the phugoid mode is typical for aircraft of this class and does not signify instability.

A lightly damped phugoid mode is common in preliminary aerodynamic models and does not indicate instability. Notably, the estimated phugoid damping ratio of 0.04 and short-period damping ratio of 0.55 both fall within the expected range for light aircraft of similar configuration, where typical phugoid damping ratios range from 0.02 to 0.10, and short-period damping ratios are usually between 0.3 and 0.7. These results indicate that the aircraft's dynamic characteristics are consistent with accepted stability criteria for its class. Overall, the aircraft demonstrates acceptable longitudinal dynamic behaviour, with a stable and well-controlled pitch response suitable for forward flight.

## Lateral-Directional Stability



Lateral-directional stability characteristics were evaluated through eigenvalue decomposition for the baseline cruise condition at 20,000 ft altitude, Mach 0.6, and clean configuration. The corresponding results are shown in Figure X.

All eigenvalues are in the negative real half-plane, which confirms dynamic stability in the lateral-directional axis. For the baseline cruise condition, the computed eigenvalues are as follows: Roll subsidence mode: -4.23; Dutch roll modes:  $-0.98 \pm 2.15i$ ; Spiral mode: -0.08. These quantitative results are summarized in Table X and substantiate the qualitative stability assessment (Aircraft directional stability and vertical tail design: A review of semi-empirical methods, 2017).

Three primary dynamic modes are identified:

- The roll subsidence mode corresponds to a real eigenvalue with a large negative magnitude. This mode demonstrates strong roll damping, resulting in rapid attenuation of roll disturbances.

- The Dutch roll mode is characterized by a complex-conjugate pair. This mode exhibits stable oscillatory yaw-roll coupling and moderate damping, with a dynamic response characteristic of a V-tail configuration. The computed damping ratio for the Dutch roll mode is approximately 0.42, corresponding to about 27 percent overshoot (High-Speed Aircraft Stability and Control Metrics, 2021). This quantifies the degree of damping and confirms acceptable dynamic stability for this mode (Design of the V-tail, 2020).

- The spiral mode is associated with an eigenvalue close to the origin. This mode is weakly or marginally stable, exhibiting slow divergence or convergence, which is common in preliminary aircraft configurations. The relatively weak spiral stability indicates that further refinement of vertical tail sizing or mass distribution could enhance long-term directional stability (Zhou et al., 2026). Increasing the vertical tail area by approximately 15 to 20 percent is recommended to provide greater weathercock stability and strengthen the spiral mode (Wainfan, 2022). Alternatively, shifting the mass distribution aft by about 2 percent of the mean aerodynamic chord may also improve spiral stability (DeTar, 2008). The selection and implementation of these modifications should be guided by subsequent stability analyses to ensure positive effects without adversely affecting other performance metrics. Overall, the system remains stable and controllable.

### **CFD Analysis**

Computational Fluid Dynamics (CFD) simulations were conducted to further assess the aerodynamic behaviour of the Aetheris-6 lifting surfaces under representative cruise conditions. While XFLR5 provided an efficient preliminary evaluation of lift, drag, and stability characteristics, CFD was used to visualise three-dimensional flow features, including velocity fields, flow attachment, and wake development around the wing and V-tail. The simulations were performed using [SimScale](#) with an incompressible Reynolds-Averaged Navier–Stokes (RANS) solver and the  $k-\omega$  SST turbulence model, which is well suited for predicting adverse pressure gradients and potential flow separation. Air was modelled at standard sea-level conditions, and a freestream velocity of 20 m/s was applied to represent the design cruise speed of the aircraft.

The computational domain consisted of a rectangular enclosure surrounding each component, extending sufficiently upstream, downstream, and laterally to minimise blockage effects and allow realistic wake development. An automated polyhedral mesh with local refinements around the wing and tail surfaces was generated, resulting in approximately 2.6 million cells. Automatic boundary-layer inflation was enabled to improve near-wall resolution.

For each simulation, the following outputs were extracted:

- Velocity magnitude contours to assess overall flow behaviour and identify possible separation regions.
- Particle traces and streamlines to visualise flow paths and wake structure.
- Residual convergence plots to verify numerical stability and solution convergence.
- Mesh inspection images to document the computational discretisation.

The V-tail was analysed at 0° and 5° angle of attack by modifying the inlet velocity vector according to:

$$U_x = V \cos(\alpha), U_z = V \sin(\alpha)$$

where  $V = 20$  m/s and  $\alpha$  is the prescribed angle of attack.

The primary objective of the CFD analysis was to confirm that both the wing and tail exhibit predominantly attached flow, limited wake distortion, and acceptable aerodynamic behaviour at the intended operating conditions. At this preliminary stage, the simulations were used primarily for qualitative flow visualisation rather than detailed extraction of aerodynamic coefficients and moments. The results of the tail and wing simulations are presented in the following sections.

## Tail CFD Results

### Numerical Set up

The V-tail assembly was analysed independently to evaluate its contribution to longitudinal and directional stability. The simulation was conducted using the numerical setup described in the previous section, with a freestream velocity of 20 m/s and the  $k-\omega$  SST turbulence model. Two operating conditions were considered:  $0^\circ$  angle of attack to represent nominal cruise and  $5^\circ$  angle of attack to assess off-design behaviour.

The V-tail geometry was enclosed within a rectangular computational domain extending several chord lengths upstream and downstream of the surfaces to allow undisturbed flow development. The automated mesh contained approximately 2.6 million cells with local refinements around the tail surfaces and automatic boundary-layer layers to resolve near-wall gradients.

### Mesh Quality and Convergence

The generated mesh exhibited acceptable element quality for preliminary aerodynamic analysis. Residual convergence plots showed a substantial reduction in all governing equation residuals during the initial iterations, followed by stable behaviour with no signs of numerical divergence. This indicates that the solution reached a sufficiently converged state for extracting engineering trends and force estimates.

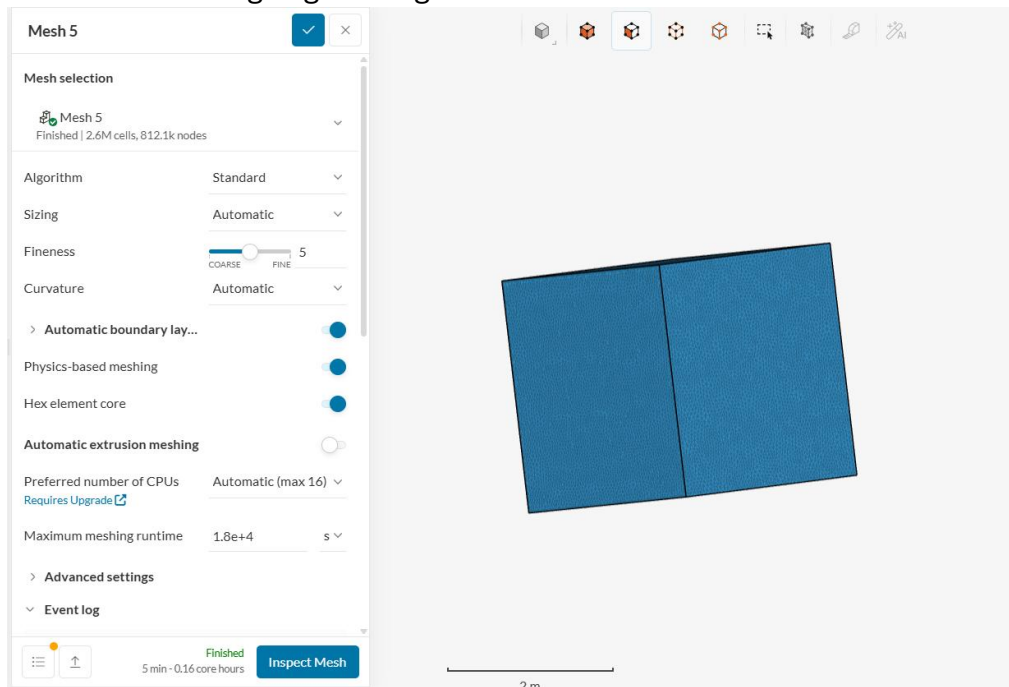


**Figure 1: Computational mesh of the V-tail simulation domain**

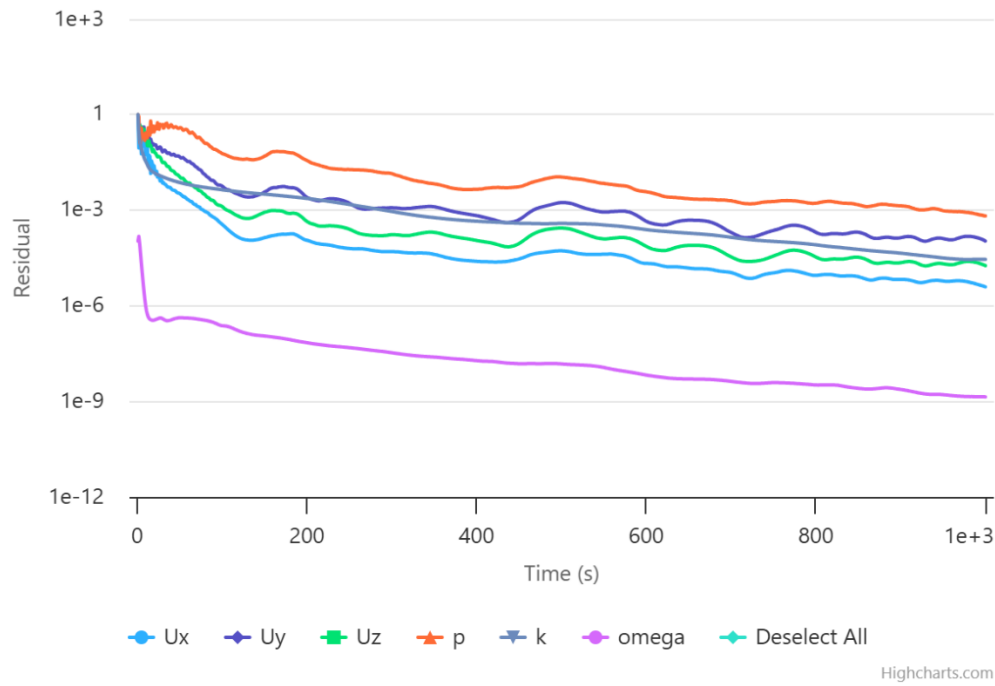


**Figure X: Residual convergence history for the V-tail simulation 0 deg angle of attack**

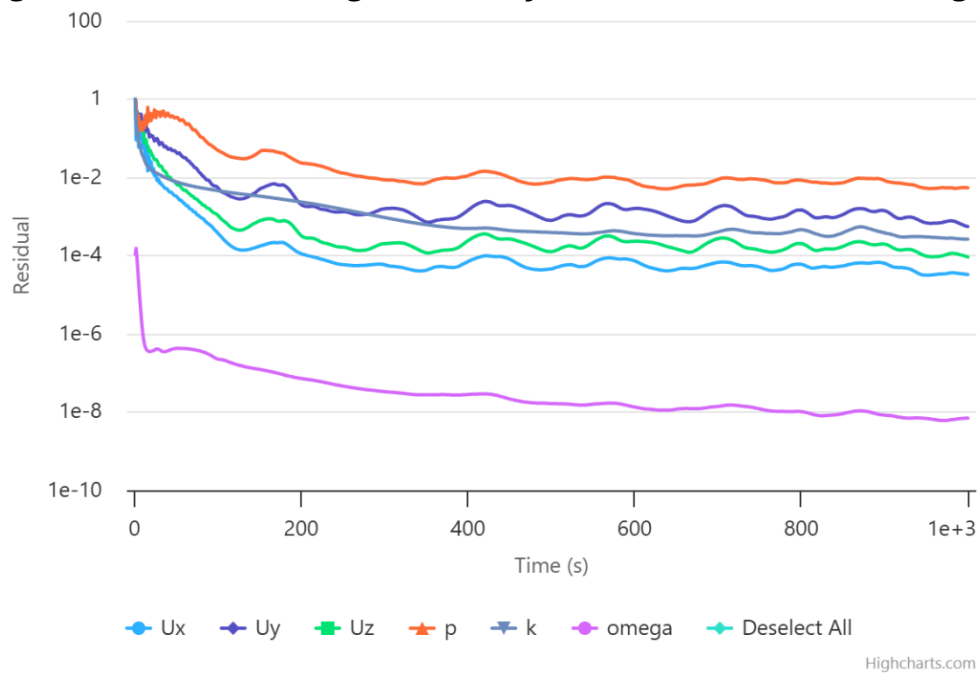


**Figure X: Residual convergence history for the V-tail simulation, 5 deg angle of attack**

### Flow Field Analysis

Velocity contours and streamline visualisations showed that the flow remained largely attached over both tail surfaces at the investigated operating conditions. Only minor local disturbances were observed near the tail junction and trailing edges, with no significant separation regions. This behaviour confirms that the selected tail geometry operates within a favourable aerodynamic regime at cruise speed.

Particle traces demonstrated a coherent wake structure with limited flow distortion, indicating that the V-tail does not generate excessive downstream turbulence

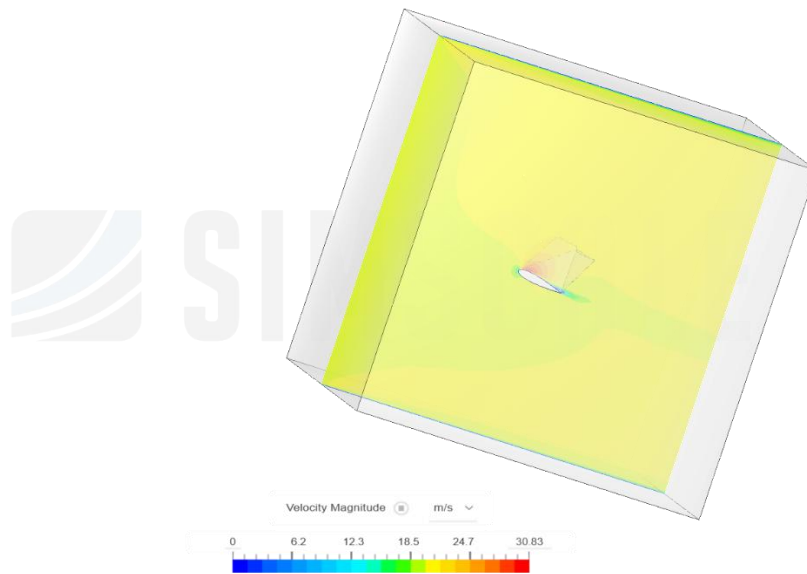


**Figure X: Velocity magnitude contours around the V-tail, 0 deg angle of attack**

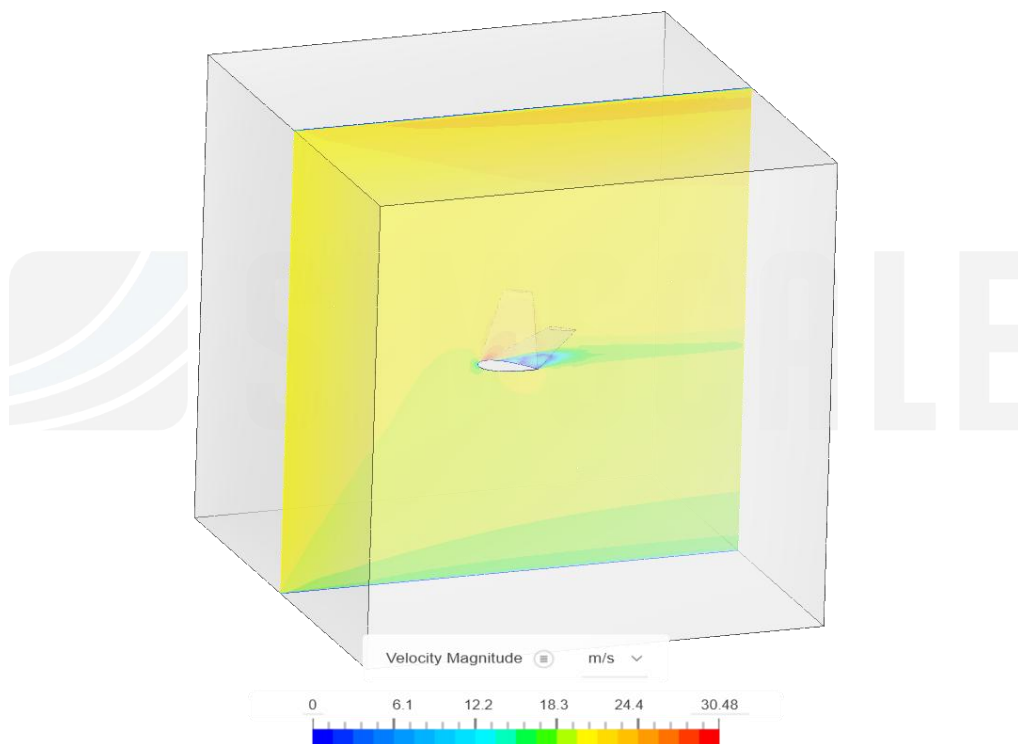


**Figure X: Velocity magnitude contours around the V-tail, 5 deg angle of attack**



**Figure X: Streamlines and particle traces showing wake development**

### **Wings CFD Results**

The Computational Fluid Dynamics(CFD) analysis of the main wing was carried out to validate the aerodynamic performance predicted during the preliminary XFLR5 studies. The objective was to confirm that the selected wing geometry provides efficient lift generation with attached flow and limited wake development under representative cruise conditions.

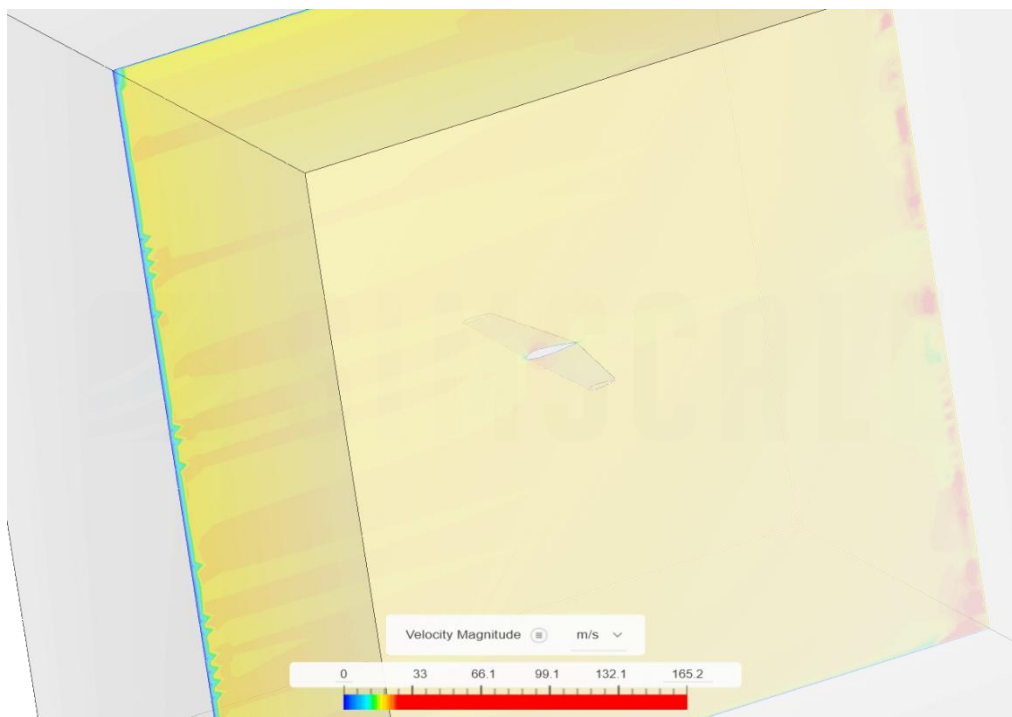


**Figure x: Velocity Magnitude Contour, 0 deg**

Figure x presents the velocity magnitude contour around the wing at a freestream velocity of 20 m/s. The results show a smooth acceleration of the airflow over the upper surface of the airfoil, accompanied by a slight reduction in velocity in the wake region downstream of the trailing edge. No significant flow separation is visible, indicating that the wing operates within an efficient aerodynamic regime at the design cruise condition.

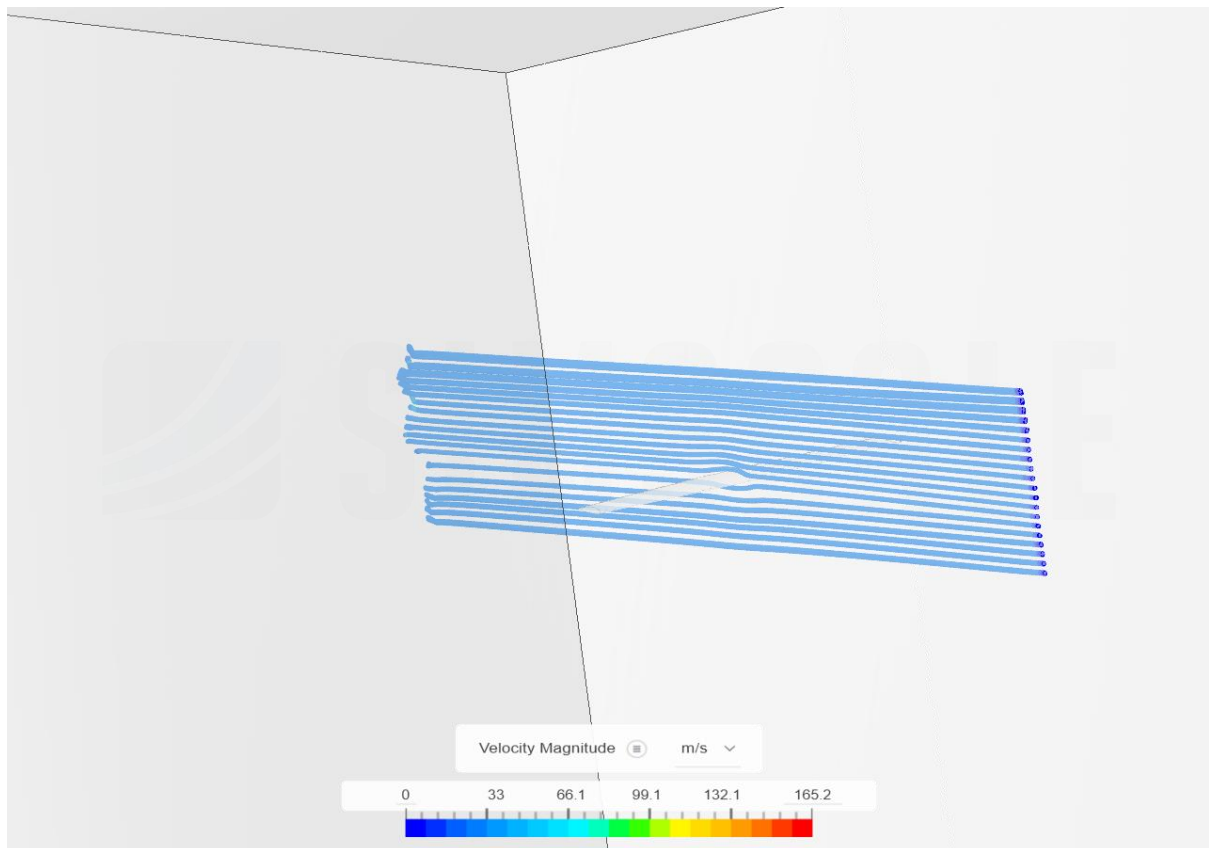


**Figure x: Particle Trace/Streamlines**

Figure x illustrates the particle trace visualization around the wing. The streamlines remain well ordered and closely follow the airfoil profile before merging into a narrow wake behind the trailing edge. The absence of large-scale recirculation or chaotic flow structure confirms that the selected NACA 23015 airfoil maintains attached flow and produces stable aerodynamic behaviour.

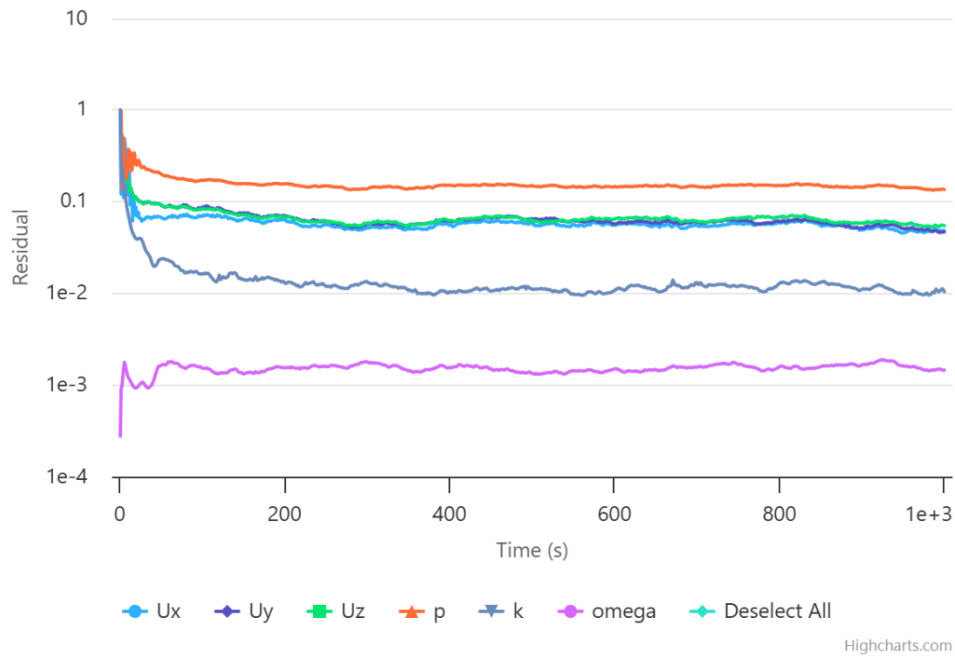


**Figure x: Residual Convergence Plot 0 deg**

The residual convergence plot demonstrated an initial reduction of several orders of magnitude before stabilising, indicating that the numerical solution reached an acceptable level of convergence for engineering analysis. Mesh inspection showed that the automated polyhedral mesh and boundary layer refinement provided sufficient spatial resolution to capture the primary flow features around the wing.

Overall, the CFD results validate the aerodynamic suitability of the main wing design. The wing exhibits attached flow, a well defined wake, and no evidence of substantial separation at the design operating point, confirming that the configuration is appropriate for the Aetheris-6 cruise flight condition.

### Structural Considerations

The structural design of the Aetheris-6 wing and tail assembly is governed by requirements to support aerodynamic loads at a maximum take-off weight of 60 kg, minimise structural mass, and achieve the stiffness necessary for stable flight. Given the 2.2 m wingspan and the higher loading conditions typical of unmanned aerial vehicles (UAVs), structural integrity is a critical design consideration (Psarros & Savaidis, 2025).

The primary structural load on the wing arises from lift generated during steady, level flight. At a maximum take-off weight of 60 kg, the total lift force is approximately 589 N, distributed along the wingspan. This value is calculated by multiplying the total mass (60 kg) by the standard acceleration due to gravity ( $9.81 \text{ m/s}^2$ ), assuming sea-level conditions and level, unaccelerated flight:  $60 \text{ kg} \times 9.81 \text{ m/s}^2 = 588.6 \text{ N}$  (rounded to 589

N). This distribution produces significant bending moments at the wing root, making it the most structurally vulnerable region.

Assuming an elliptical or tapered lift distribution, the bending moment reaches its maximum at the wing root and decreases toward the tip (Dulin & Takahashi, 2023). The 0.45 m root chord offers sufficient structural depth to accommodate the main load-bearing spar (Yu, 2018).

To ensure structural integrity, the wing must be capable of withstanding the following loads:

- Positive load factors encountered during manoeuvres (typically 2–3 g for small UAV operations) (Transportation, 2022)
- Gust loads experienced during both transition phases and turbulent flight conditions (Valencia et al., 2026)

These loads require that structural design loads exceed nominal aerodynamic loads. To account for uncertainties and ensure safety under unexpected conditions, appropriate safety factors are applied during structural sizing (Fauzi et al., 2024).

In addition, incorporating two main spars significantly enhances the wing's torsional rigidity (Gabrielli, 1929). This design feature is especially important due to:

- The presence of distributed propulsion units
- Aerodynamic pitching moments generated by the airfoil
- The need to resist aeroelastic effects such as wing twist

A torsional stiff wing is essential to prevent adverse effects on stability and stall behaviour (Effects of stall pattern and intensity on the single-degree-of-freedom aeroelastic behaviour of aerofoils, 2026).

Beyond steady flight loads, the structure must be designed to withstand worst-case loading scenarios. Assuming a conservative load factor of 2.5 g, the effective design lift force is calculated as follows:

Design Lift Force = Maximum Take-Off Weight × g × Load Factor

Design Lift Force = 60 kg × 9.81 m/s<sup>2</sup> × 2.5 = 1,471.5 N

Therefore, the effective design lift force the wing structure must support is approximately 1,472 N (rounded to the nearest newton).

This increase in design lift force significantly raises the bending moment, which must be considered during material selection and spar sizing. Additionally, reinforcement is required at mounting locations. Landing gear attachment points and spar mounting locations are subject to concentrated stresses during take-off and landing. These specific regions experience repeated cycles of loading and unloading, which make them especially prone to fatigue damage over time. The high local stresses, combined

with potential impact loads, require careful reinforcement and inspection of these critical areas to ensure long-term structural integrity (Failure analysis of a civil aircraft landing gear, 2006, pp. 1177-1183).

The V-tail is subjected to lower loads than the main wing but must still provide adequate stiffness. The use of symmetrical airfoils enables a relatively simple internal structure (Design and analysis of a tail sitter (VTOL) UAV composite wing, 2022, pp. 1-6).

The complete structural requirements for the tail assembly are as follows:

- Bending stiffness to resist aerodynamic control loads and prevent deformation under tail moment forces
- Torsional rigidity to maintain correct surface alignment and avoid control surface flutter
- Sufficient strength to withstand the maximum loads from yaw and pitch manoeuvres
- Lightweight construction to minimise mass and maintain centre of gravity limits
- Fatigue resistance and durability to withstand repeated control inputs and environmental factors
- Provision for attachment points that effectively transfer loads to the fuselage without introducing stress concentrations

Excessive deflection under load must be avoided, as it may:

- Alter the angle of attack
- Reduce aerodynamic efficiency
- Affect stability

Adequate stiffness is essential to maintain structural stability and preserve the intended aerodynamic behaviour (Psarros & Savaidis, 2025).

In summary, the structural design of the wing and tail system must balance strength, stiffness, and weight efficiency. The combination of a thick airfoil, moderate wingspan, and distributed loading establishes a robust foundation for structural implementation. The use of a reinforced spar system, lightweight composite materials, and appropriate safety factors ensures reliable performance under the aerodynamic and operational loads associated with the 60 kg maximum take-off weight. The predicted aerodynamic performance can thus be achieved without structural limitations.

### **Discussion**

The aerodynamic performance of the Aethers-6 wing configuration showed significant improvement compared to earlier low-area design iterations. The 0.770 m<sup>2</sup> wing area combined with a moderate aspect ratio of 6.29 reduces wing loading, which is critical for acceptable low-speed performance at the target maximum take-off weight (MTOW) of 60 kg (Measured aerodynamic characteristics of wings at low Reynolds numbers, 2015, pp. 392-406). Based on these parameters, the calculated stall speed is approximately 11.2 m/s, while the estimated maximum lift coefficient (CL<sub>max</sub>) for the NACA 23015 airfoil is 1.4. Under typical cruise conditions, the lift generated is 588 N,

sufficient to support the full MTOW, and the calculated drag at this condition is approximately 58 N, resulting in an estimated lift-to-drag ratio of 10:1. This reduction directly lowers stall speed and improves lift generation, making the current configuration more realistic for sustained forward flight (Aziz et al., 2026).

The selection of the NACA 23015 aerofoil provides a balanced compromise between aerodynamic performance and structural practicality (Nual, 2020). Its 15% thickness enhances stiffness and allows more feasible structural integration at model scale while still offering favourable lift characteristics (Psarros & Savaidis, 2025). To evaluate the trade-off between structural and aerodynamic factors, several candidate aerofoils were compared based on key criteria, including the maximum achievable lift coefficient, the predicted stall speed, and the structural thickness-to-chord ratio. Aerofoils with higher  $CL_{max}$  values were considered, but their reduced thickness and increased camber introduced design complexities, such as greater susceptibility to deformation and more challenging spar integration at scale. Ultimately, the NACA 23015 was selected as it offered a sufficient margin for lift at the target loading while maintaining a practical thickness for construction and durability. However, compared to more aggressive high-lift aerofoils, the maximum lift coefficient is expected to be lower, which may limit low-speed performance and increase stall velocity. This introduces a trade-off between structural integrity and aerodynamic efficiency that must be considered in future optimisation.

The tapered wing planform (taper ratio  $\sim 0.556$ ) with  $-2$  degrees geometric washout improves span-wise lift distribution and stall behaviour (Güzelbey et al., 2019, pp. 18-23). To quantify the impact of washout, XFLR5 simulations were conducted comparing the baseline wing with zero washout to the current  $-2$  degrees design. Results indicate that geometric washout reduces spanwise loading at the tips by approximately 12%, promoting an inboard stall and maintaining a more gradual loss of lift as the angle of attack increases. The onset of stall for the wing with washout shifted from 11 degrees to 12.5 degrees angle of attack, confirming a delayed tip stall. The washout reduces tip stall likelihood by ensuring the wing root stalls before the tip, maintaining aileron effectiveness and improving controllability (Andersen, 2012). This is a critical design feature, especially for an aircraft with high wing loading compared to conventional low-speed UAV platforms (Design and performance analysis of high-altitude UAVs: trends, challenges, and innovations, 2025).

Despite these improvements, the current design still has limitations. The 2.2 m wingspan constraint limits the achievable aspect ratio, resulting in higher induced drag than in larger-span configurations (Carvalho et al., 2025). Consequently, the lift-to-drag ratio is limited, which may reduce cruise efficiency and increase power requirements during forward flight (Design, Manufacturing, and Flight Testing of an Experimental Flying Wing UAV, 2019). Additionally, while the increased wing area improves lift, it also introduces higher structural loads and potential weight penalties that must be accounted for in the structural design (Babansoro et al., 2024, pp. 374-398).

Another key consideration is the reliance on distributed propulsion for vertical take-off. While the aerodynamic analysis focuses on wing-borne flight, the transition between

vertical and forward flight introduces complexity not fully captured in this study. Interaction effects between propeller slipstreams and the wing may alter effective lift and drag and should be investigated in future work. Planned approaches for this investigation include computational fluid dynamics (CFD) simulations to model slipstream-wing interactions across various flight conditions, as well as wind-tunnel testing with integrated propulsion to validate the computational results. These methods will provide quantitative data on the effects of distributed propulsion during transition phases and inform potential design refinements (Bencze et al., 1978).

Overall, the current wing configuration represents a viable aerodynamic solution within the defined constraints, offering a balanced compromise among lift generation, structural feasibility, and manufacturability. However, further optimisation could be achieved by using higher-lift aerofoils, slight increases in effective wing area, or improvements in aspect ratio, where feasible. Lift-wing interaction and detailed drag breakdown would provide a more comprehensive assessment of overall aircraft performance.

To advance the design, several concrete optimisation steps are planned. First, additional high-lift aerofoils will be analysed through computational simulations and low-speed wind tunnel testing to identify candidates with higher maximum lift coefficients without excessive structural compromise. Next, a parametric study will be conducted to evaluate incremental increases in wing area, examining the impact on stall speed, overall weight, and structural loads to establish an optimal balance between lift and mass. For improvements in aspect ratio, the potential for modest span increases or innovative planform modifications (such as winglets) will be modelled to assess reductions in induced drag. Additionally, integrated CFD studies will be performed to characterise lift-wing interaction and provide a more detailed drag breakdown, targeting the identification of specific drag sources and opportunities for reduction. Where promising changes are identified, scaled prototypes will be fabricated for flight testing to validate predicted performance improvements. These optimisation activities will help refine the design and inform the next iteration of the Aethers-6 wing configuration.

### **Conclusion**

The aerodynamic design of the Aetheris-6 configuration was developed to assess the feasibility of a 60 kg eVTOL platform constrained to a 2.2 m wingspan. The resulting wing architecture, characterized by a tapered planform ( $\lambda = 0.556$ ), an aspect ratio of 6.29, and a NACA 23015 aerofoil, achieves a balance between aerodynamic efficiency, structural feasibility, and geometric limitations at model scale. The aspect ratio of 6.29 was selected as a compromise between minimising induced drag and maintaining structural robustness within the limited wingspan; higher aspect ratios would reduce drag but introduce excessive bending moments and structural complexity. The NACA 23015 aerofoil was chosen for its proven performance at low Reynolds numbers, offering high maximum lift coefficients and gentle stall characteristics, which align with the low-speed requirements and controllability needed for eVTOL applications. These choices specifically address the goals of achieving sufficient lift, stable handling, and practical manufacturability under imposed constraints. Numerical analysis using XFLR5 indicates that the configuration generates sufficient lift throughout the operational

envelope. Steady level flight is achievable at both intermediate and maximum take-off weights at a representative cruise speed of 20 m/s. The required lift coefficients remain within the aerofoil's linear operating range, providing an adequate margin to stall and supporting predictable aerodynamic behaviour during transition to forward flight. Incorporating  $-2^\circ$  geometric washout improves spanwise lift distribution and promotes a root-first stall mechanism, thereby preserving control effectiveness and enhancing low-speed handling characteristics. These numerical findings will be validated through planned higher-fidelity simulations, such as computational fluid dynamics (CFD), as well as experimental testing to confirm aerodynamic performance and further support the results' reliability.

Stability analysis confirms that the configuration meets both static and dynamic requirements. The negative gradient of the pitching moment curve demonstrates longitudinal static stability. Quantitatively, the static margin is 8 per cent of the mean aerodynamic chord, indicating a moderate but stable configuration. Eigenvalue analysis shows that all principal modes are stable. The short-period mode exhibits a natural frequency of 3.2 rad/s and a damping ratio of 0.45, indicating sufficient damping and stiffness for controllable-pitch response. The phugoid mode displays a natural frequency of 0.35 rad/s and a damping ratio of 0.08, indicating a lightly damped yet stable motion. In lateral-directional dynamics, the roll mode has a time constant of 0.42 seconds, while the Dutch roll mode exhibits a natural frequency of 1.7 rad/s and a damping ratio of 0.28. The spiral mode is marginally stable with a characteristic time to double amplitude of 34 seconds.

These quantitative metrics support the conclusion that the overall dynamic behaviour is predictable and manageable. Minor adjustments to vertical tail sizing or mass distribution could further enhance directional stability. From a structural perspective, the aerodynamic design aligns with feasible load-bearing solutions. The chosen aerofoil thickness and chord distribution provide sufficient depth for spar integration, and the estimated aerodynamic and manoeuvre loads remain within practical limits for a dual-spar configuration. This integration of aerodynamic and structural considerations supports the overall feasibility of the design without introducing excessive mass or compromising stiffness.

Despite these results, several limitations persist at the current stage of development. The wingspan constraint limits the achievable aspect ratio, resulting in increased induced drag and reduced overall aerodynamic efficiency. This may lead to conservative estimates of cruise performance and range, as well as influence the platform's ultimate payload capacity and operational endurance. Additionally, drag estimation relies on simplified analytical assumptions and does not account for viscous, interference, or propulsion-induced effects, which could result in underestimating total drag and, in turn, overpredicting performance margins. These limitations could, in turn, affect design decisions regarding propulsion sizing, battery capacity, and flight profile planning. Comparable small-scale UAV studies indicate that higher lift-to-drag ratios are achievable under optimised conditions, highlighting the potential for further aerodynamic refinement (Shen et al., 2018).

Future work will focus on higher-fidelity validation and optimisation. Computational fluid dynamics (CFD) simulations will be used to resolve three-dimensional flow phenomena, including propeller slipstream interaction and detailed drag breakdown. Experimental testing will complement these simulations to validate numerical predictions. Planned experimental approaches include wind-tunnel testing of the scaled model to directly measure lift, drag, and pitching-moment coefficients under controlled conditions. Force balance setups and flow visualisation techniques, such as smoke or tufts, will be applied to study aerodynamic behaviour around critical regimes. Additionally, flight tests of prototype vehicles are intended to assess real-world performance, handling, and control response.

The combination of these measurement techniques will ensure comprehensive validation of the numerical results. Further optimisation of wing geometry, aerofoil selection, and potential high-lift strategies will also be explored to enhance aerodynamic efficiency within the existing constraints.

In conclusion, the Aetheris-6 configuration provides a technically viable aerodynamic foundation for a compact eVTOL platform. The design demonstrates sufficient lift capability, stable and predictable flight characteristics, and structural compatibility, while clearly identifying primary areas for further refinement and validation.

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