B737 Aerodynamic Analysis Report

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1. Introduction

1.1 Background of the Boeing 737

The Boeing 737 is one of the most iconic and widely used narrow-body jet airliners in the world. Developed in the 1960s by Boeing Commercial Airplanes, it was designed as a short- to medium-range aircraft to complement the larger 707 and 727. Since its first flight in 1967, the 737 has undergone continuous development, evolving through several generations.

Today, the aircraft plays a crucial role in global commercial aviation, serving both short domestic routes and medium international flights. Its reliability, efficiency, and versatility have made it the backbone of many airline fleets. The 737 family includes multiple variants—from the early 737-100 to the latest 737 MAX series—accumulating over 10,000 units delivered worldwide, making it the best-selling commercial jetliner in history.

1.2 Motivation & Objectives

This project aims to simulate the aerodynamic behavior of a Boeing 737 using OpenVSP and related tools. The 737 was selected due to its significance in the aviation industry and availability of reference data.

The main objectives of this study are:

- To create a simplified 3D model of the B737 using OpenVSP.
- To perform aerodynamic simulations using VSPAERO and evaluate key parameters such as lift, drag, and stability on a simplified clean-airframe model of the B737 (without engines or landing gear).
- To gain practical experience with aerospace design and analysis software.
- To assess how simplified modeling tools can approximate the aerodynamic performance of a real-world aircraft.

1.3 Structure of the Report

The report is organized as follows:

- **Chapter 2** describes the process of modeling the B737 in OpenVSP, including key dimensions and assumptions.
- **Chapter 3** presents the aerodynamic analysis using VSPAERO, focusing on lift, drag, and moment coefficients.

- **Chapter 4** explores stability characteristics, including longitudinal and lateral-directional behavior.
- **Chapter 5** provides additional observations, limitations, and concluding remarks.

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2. Geometry Definition and Modeling Process

2.1 Overview of OpenVSP

Open Vehicle Sketch Pad (OpenVSP) is an open-source parametric aircraft geometry tool developed by NASA. It allows users to quickly create 3D aircraft models using intuitive design components such as wings, fuselages, and control surfaces. The models can be exported for aerodynamic analysis and compatibility with tools like VSPAERO, CFD software, and structural solvers.

OpenVSP is especially valuable for conceptual and early-stage design due to its ease of use and rapid iteration capabilities. However, it has limitations—such as simplified geometry representation and lack of internal systems modeling—which make it better suited for external aerodynamic studies rather than detailed engineering or certification-level analysis.

2.2 Description of the B737 Model

The Boeing 737 model was created in OpenVSP using visual reference blueprints that included scaled top, side, and front views with dimension labels. The geometry closely resembles the specifications of a B737-800, with small deviations due to modeling simplifications.

Fuselage

- **Length:** 37.97 meters
- **Maximum Width:** 3.78 meters
- **Maximum Height:** 3.84 meters

Wings

- **Wingspan:** 34.37668 meters
- **Sweep Angle:** 26.0 degrees
- **Dihedral Angle:** 5.11 degrees
- **Mean Aerodynamic Chord (MAC):** 4.32889 meters

- **Airfoil Used:** NACA 0015

Empennage (Tail)

- **Configuration:** Conventional tail
- **Horizontal Stabilizer Span:** 14.46 meters
- **Vertical Stabilizer Height:** 7.94 meters
- **Vertical Stabilizer Chord:** 4.5902 meters

Control Surfaces Included

- Ailerons
- Elevators
- Rudder
- Flaps
- Slats

Engine nacelles were **not included** in the model. Landing gear elements were also omitted to simplify the geometry and focus on the core aerodynamic surfaces. This configuration represents a clean-airframe baseline suitable for early aerodynamic analysis.

2.3 Reference Parameters

The model's reference parameters were extracted directly from OpenVSP's geometry settings and analysis tools:

- **Reference Area (Sref):** 120.797 m^2
- **Reference Span (Bref):** 34.377 m
- **Reference Chord (Cref):** 4.329 m
- **Estimated Total Mass:** 405.91 kg (scaled for analysis purposes)

Modeling Assumptions

- Geometry was derived from measured blueprints and visual alignment in OpenVSP.

- The overall shape and proportions were validated to be reasonably close to real-world B737 specifications.
- Engine nacelles were intentionally excluded from the geometry. Their absence is expected to slightly underestimate total drag and alter pitching moment behavior compared to the real aircraft.

2.4 3D Model Screenshots

The following figures will be added to illustrate the geometry:

- **Figure 1:** Top view of the B737 model in OpenVSP
- **Figure 2:** Side view highlighting fuselage and empennage geometry
- **Figure 3:** Perspective view showing full configuration and control surfaces

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3. Aerodynamic Analysis using VSPAERO

3.1 Introduction to VSPAERO

VSPAERO is an aerodynamic solver integrated with OpenVSP that uses the vortex lattice method (VLM) to analyze lifting surfaces in inviscid, incompressible flow. It works by discretizing the geometry into surface panels and applying vortex rings to approximate flow characteristics.

The solver is particularly useful during early-stage aircraft design for computing lift, drag, and moment coefficients. Inputs include the geometry file (DegenGeom), Mach number, angle of attack (AoA), panel settings, and flow symmetry assumptions.

3.2 Setup of the B737 Model

The B737 configuration was analyzed under the following conditions:

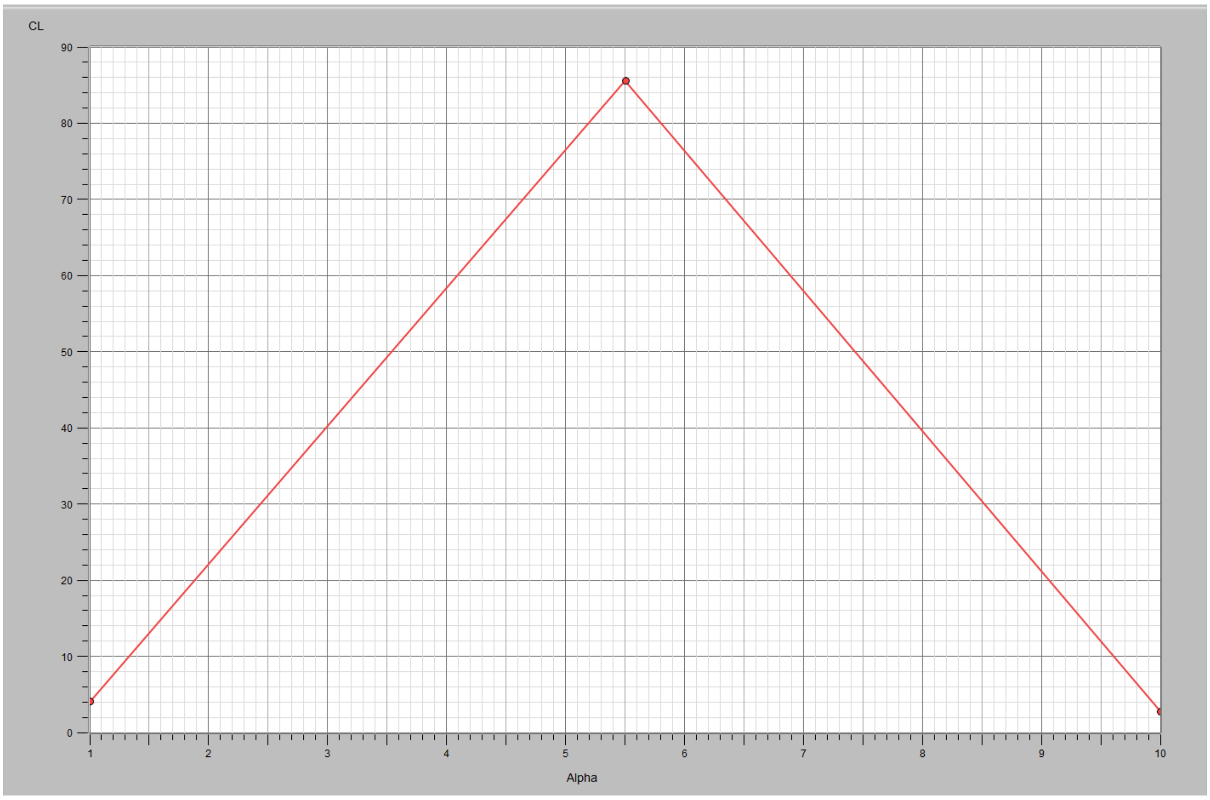
- **Paneling: Default panel resolution was used.**
- **Symmetry: XZ-plane symmetry was not enabled.**
- **Mach Number: Simulations were conducted at Mach 0.3.**
- **Reynolds Number: Set to 1.0×10^7 (default in VSPAERO).**

- **Angle of Attack: Three discrete AoA values were tested: 1°, 5.5°, and 10°.**

Note: **The engines were excluded from the model. As a result, drag and pitching moment coefficients are likely underpredicted. This configuration represents a clean-airframe baseline analysis.**

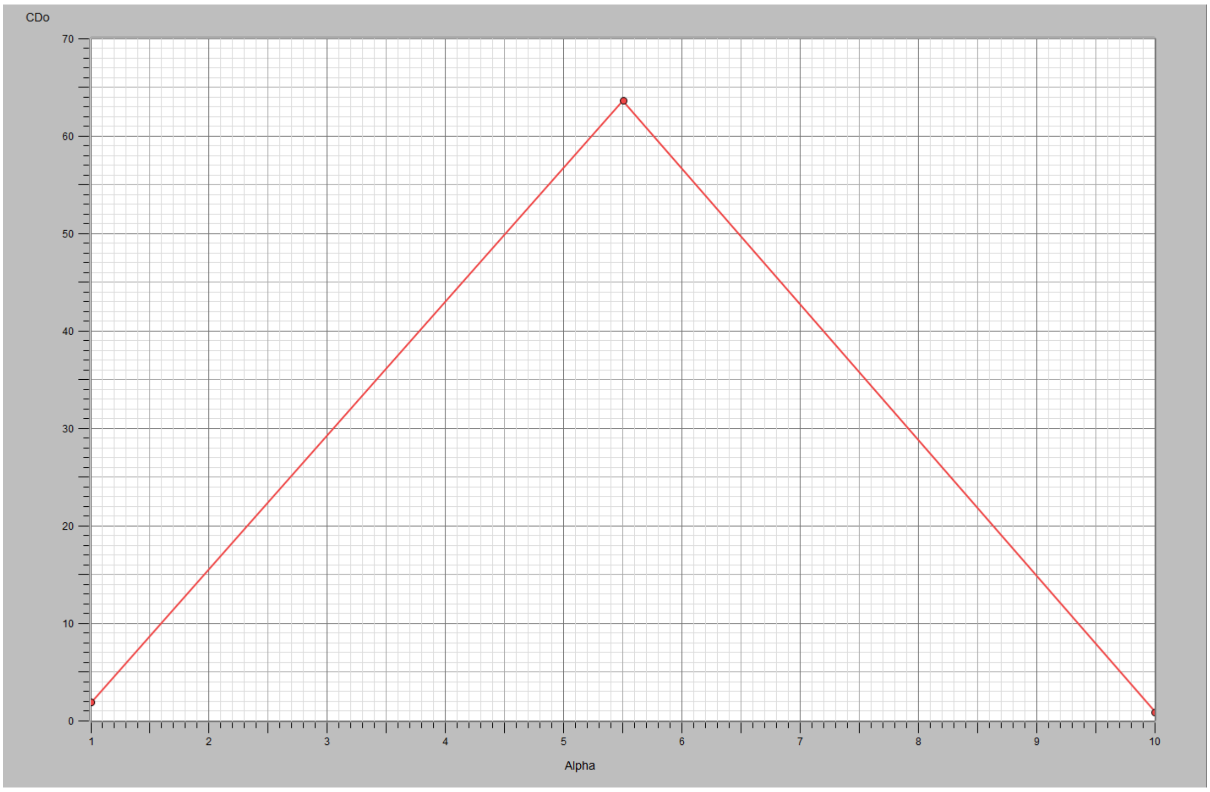
3.3 Lift and Drag Analysis

- **Cl vs AoA:**



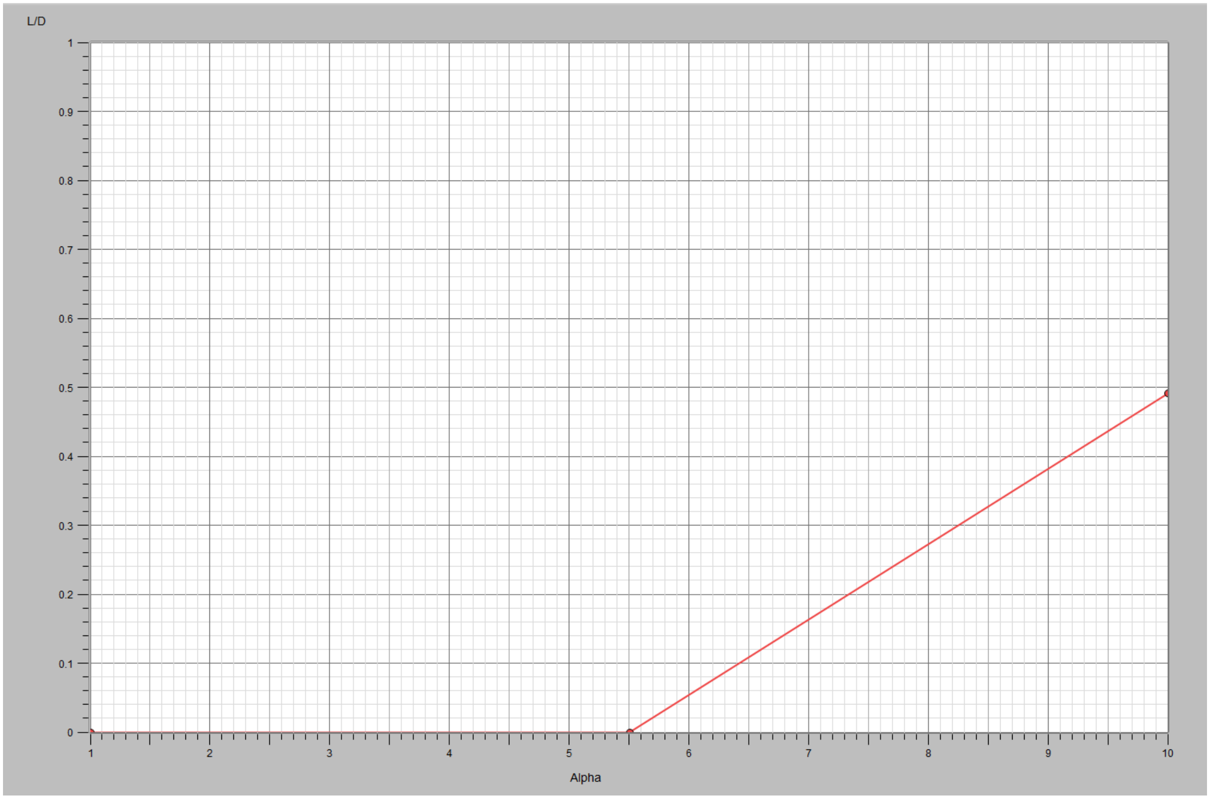
The lift coefficient increased with AoA up to 5.5°, where a maximum was reached, followed by a drop-off—likely due to stall behavior in the simulation.

- **Cd vs AoA:**



The drag coefficient also peaked at 5.5°, showing typical drag rise due to increasing flow separation.

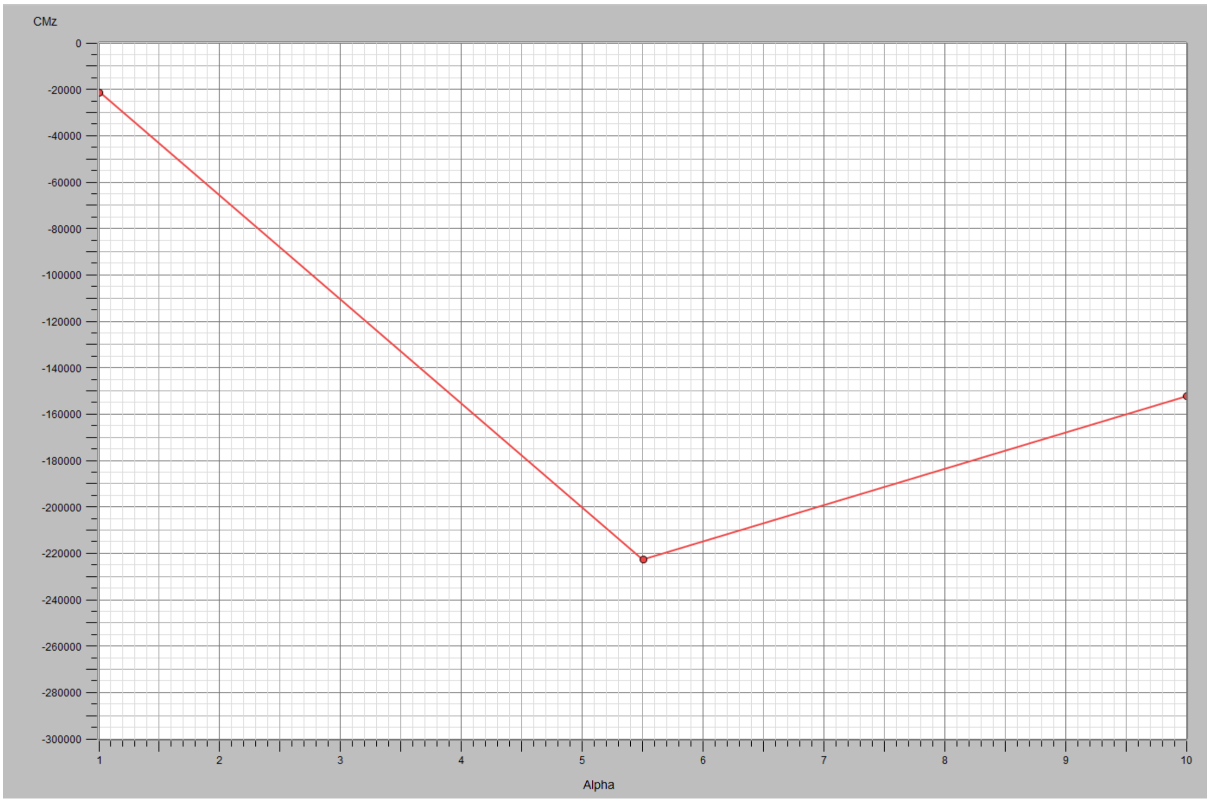
- **Cl/Cd vs AoA:**



The L/D curve indicates relatively low aerodynamic efficiency, peaking under 1. This highlights the limitations of a clean configuration with no engines or viscous drag modeling.

3.4 Moment Coefficient Evaluation

- **Cm vs AoA:**



The moment coefficient (about the Z-axis) shows a clear negative slope up to around 5.5°, followed by a reversal — again consistent with flow separation effects or instability at higher AoA. The negative slope at lower AoAs suggests longitudinal static stability.

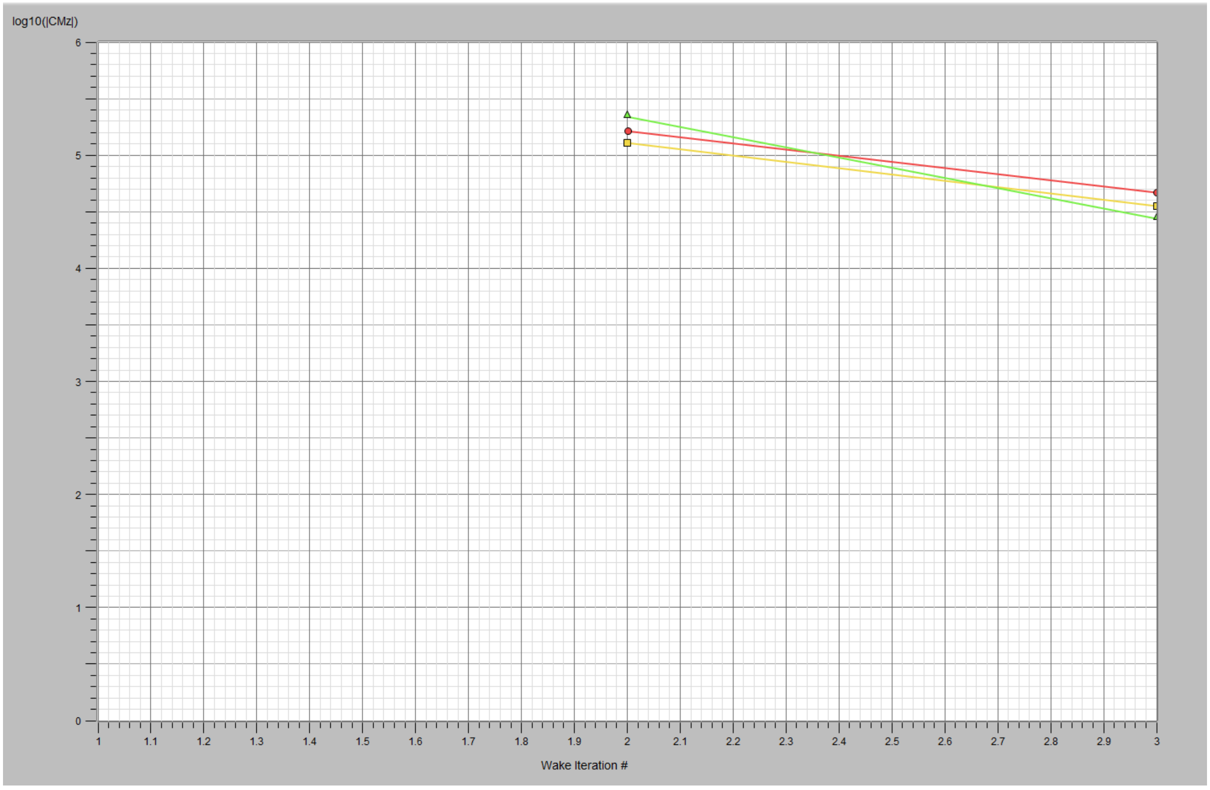
3.5 Trim Analysis

Trim analysis was not performed. The current model lacks engine placement and active control surface deflections, which are necessary for realistic trim estimation.

3.6 Additional Outputs

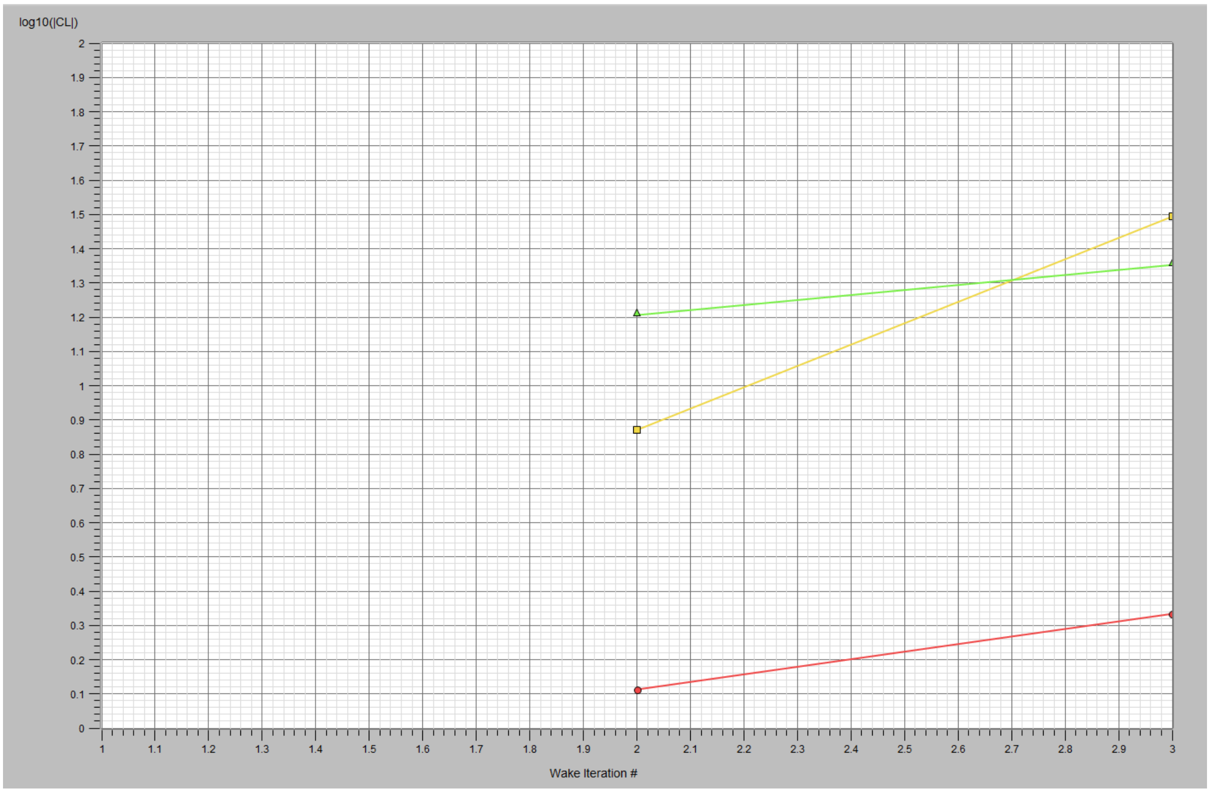
To verify simulation robustness and gain deeper insights, several additional plots were generated.

- **Convergence Plot (log10(CMZ)):**



This graph confirms numerical convergence during VSPAERO's iterative wake calculations. All coefficients show a downward trend across iterations, indicating solution stability.

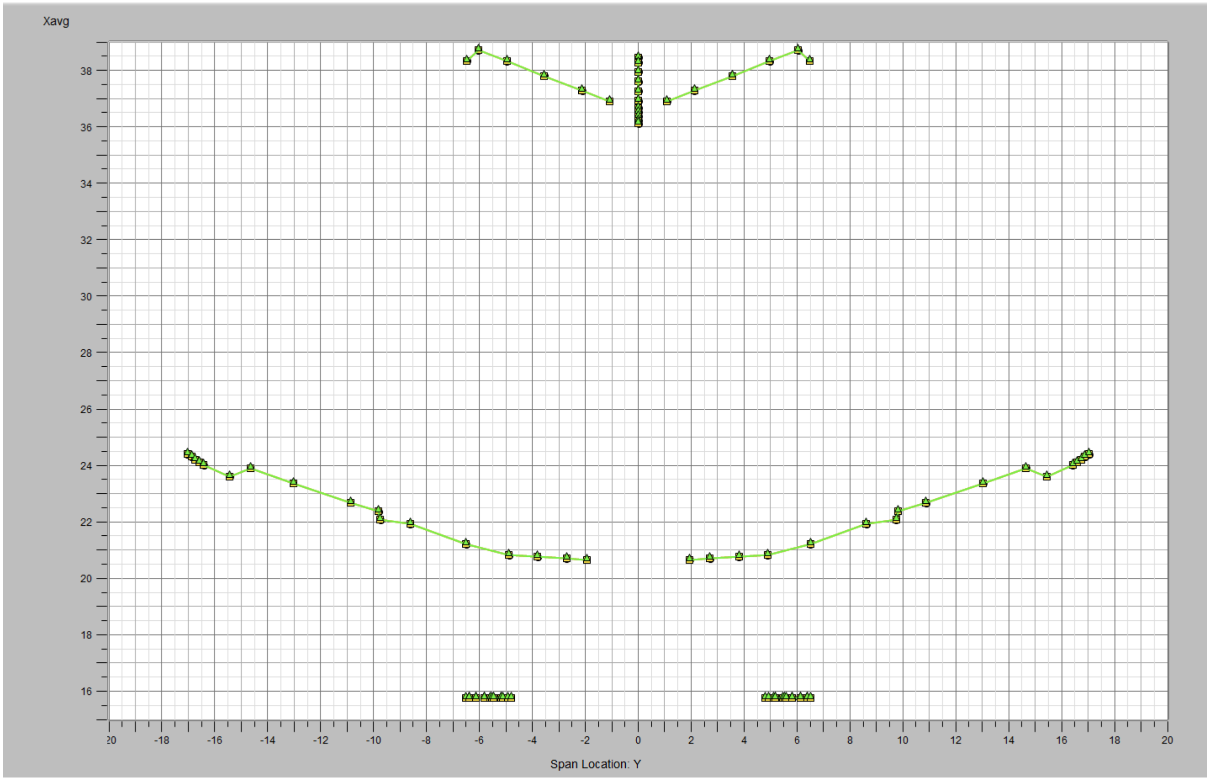
- **Sectional Lift Distribution (Cl vs Span Location):**



The spanwise lift distribution reveals expected patterns, although some

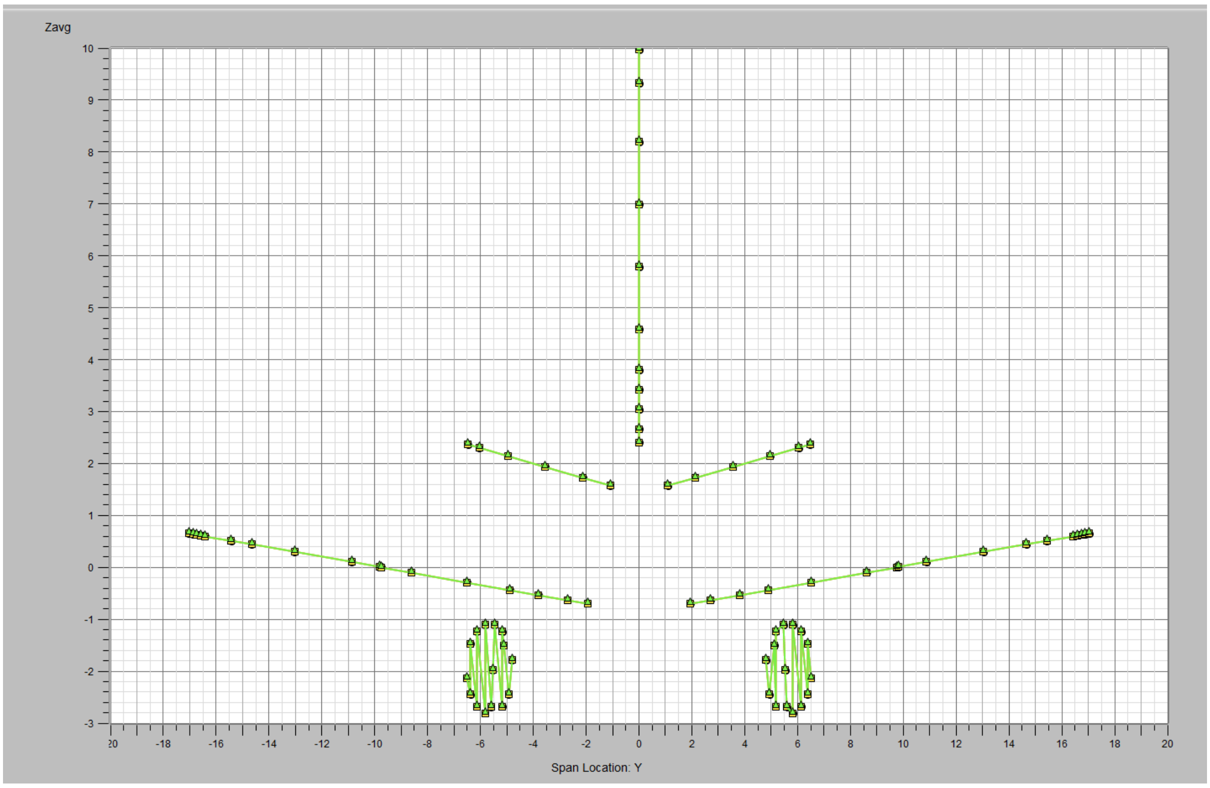
anomalies likely reflect mesh irregularities or panel alignment issues.

- **Xavg (longitudinal control points):**



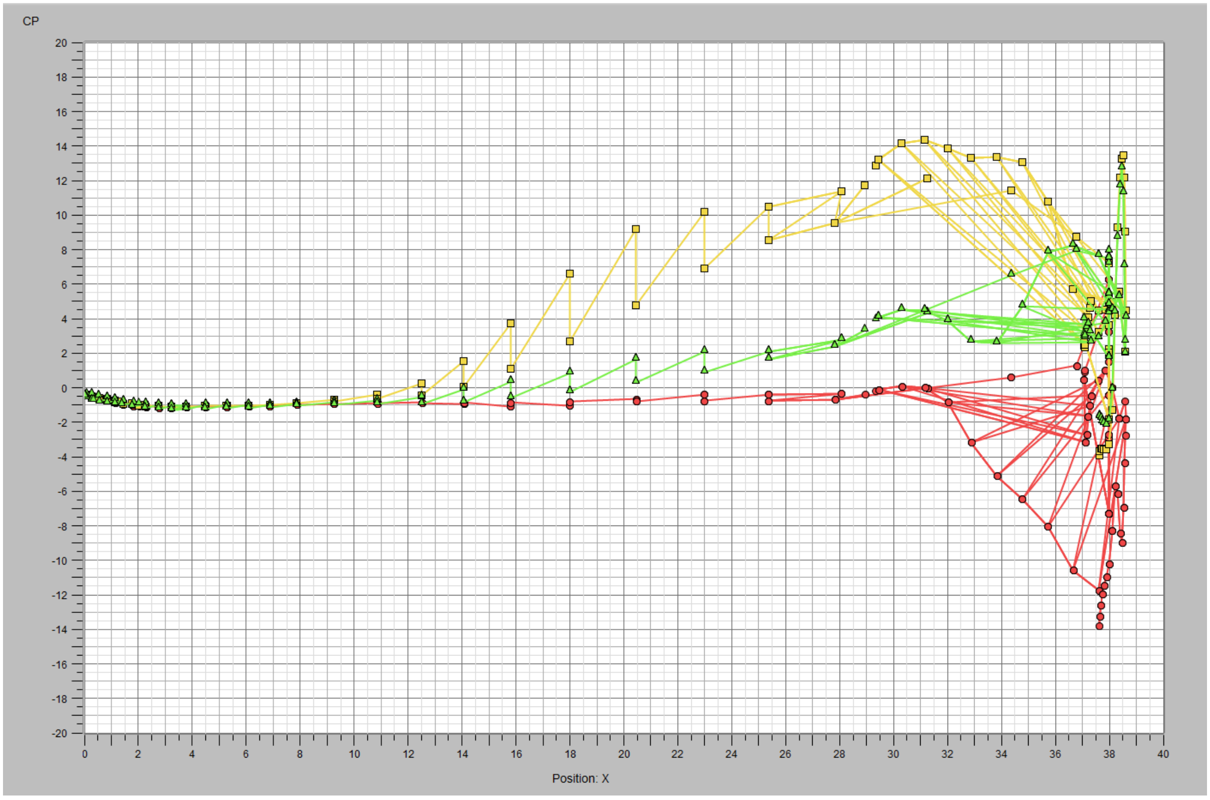
This gives an overview of how the model panels are distributed along the aircraft's length.

- **Zavg (vertical control points):**



Similar to Xavg but showing vertical shape definition, useful for identifying symmetry and surface heights.

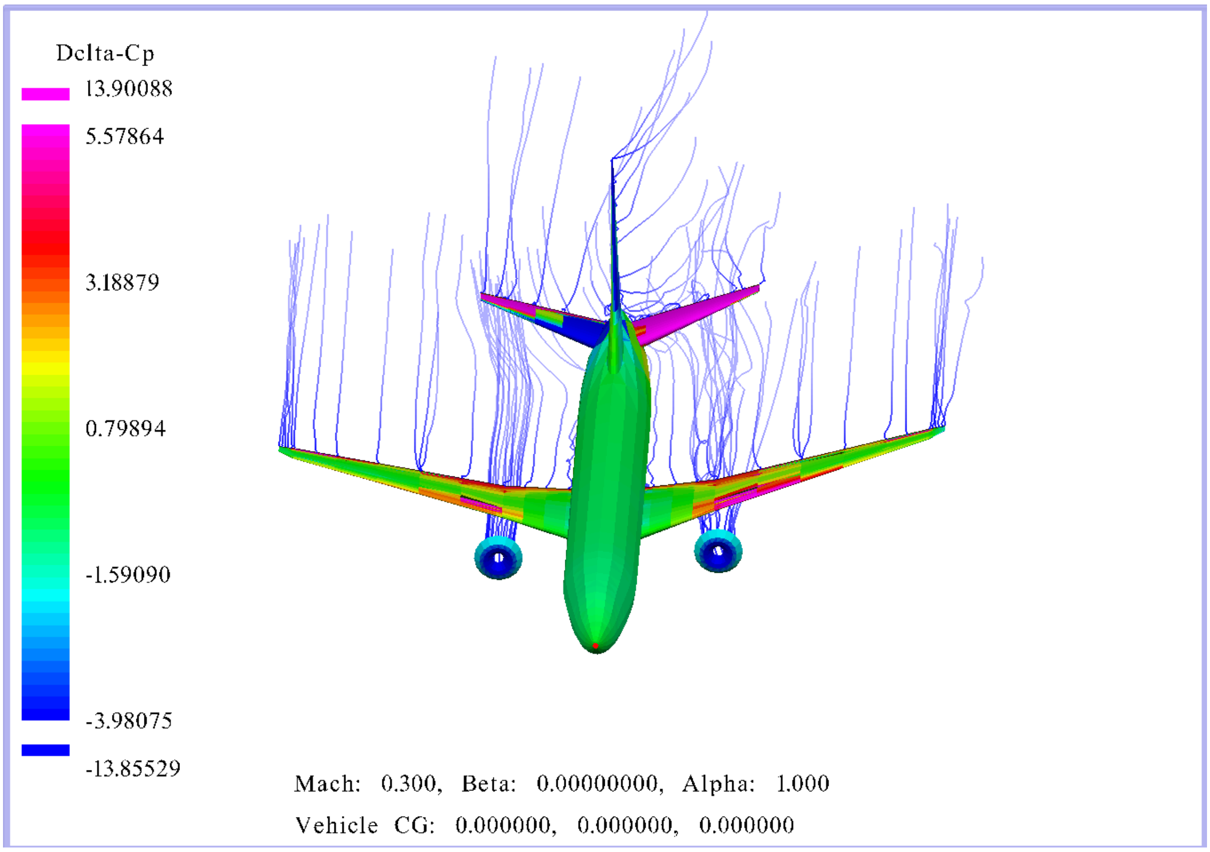
- **Cp vs X (Pressure Coefficient):**

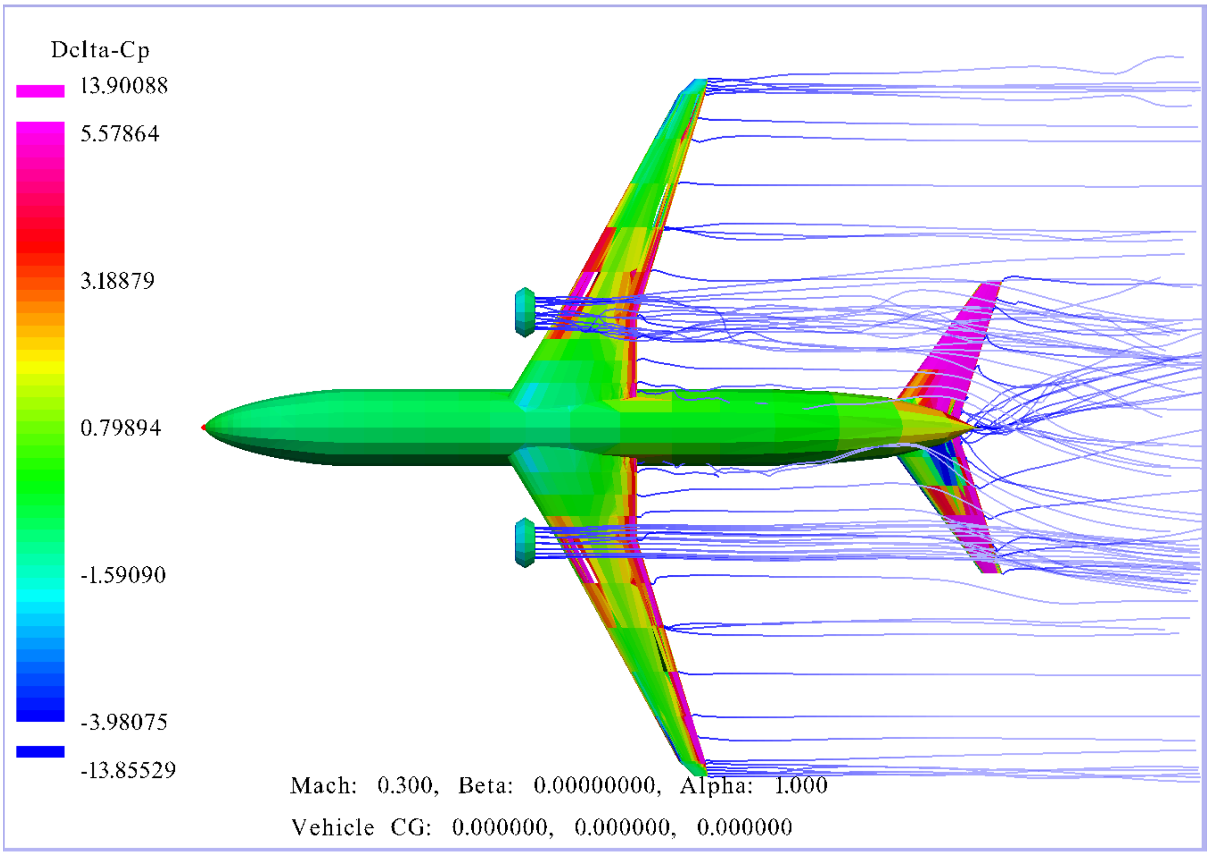


This plot shows pressure coefficient (Cp) across the aircraft length, helping identify high- and low-pressure zones.

Surface Pressure and Trailing Wake Visualization:

The figure below shows the surface pressure coefficient (ΔCp) distribution on the aircraft, along with trailing wake streamlines at Mach 0.3, AoA = 1°, and β = 0°. The pressure visualization highlights high-lift regions (notably on the wing roots and tail surfaces) and symmetric flow conditions.


Delta-Cp
13.90088
5.57864
3.18879
0.79894
-1.59090
-3.98075
-13.85529
Mach: 0.300, Beta: 0.00000000, Alpha: 1.000
Vehicle CG: 0.000000, 0.000000, 0.000000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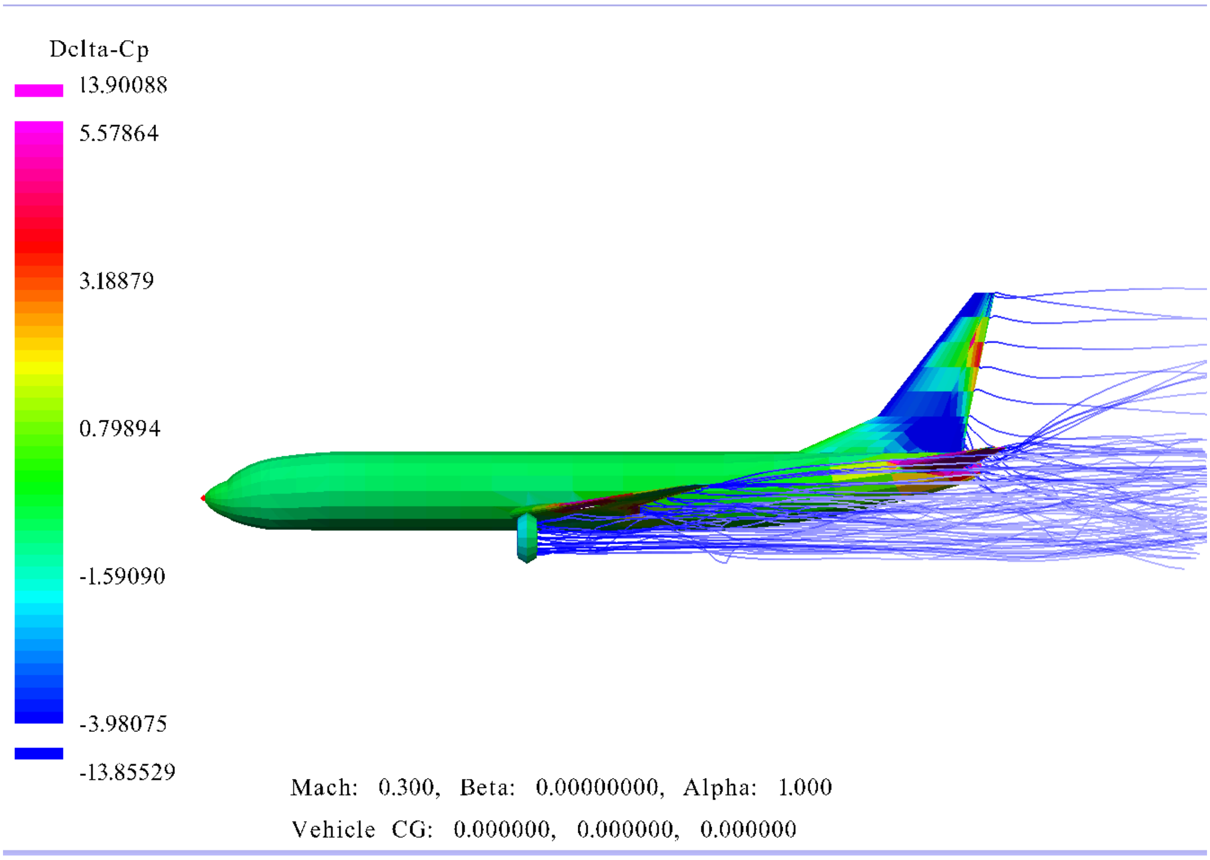

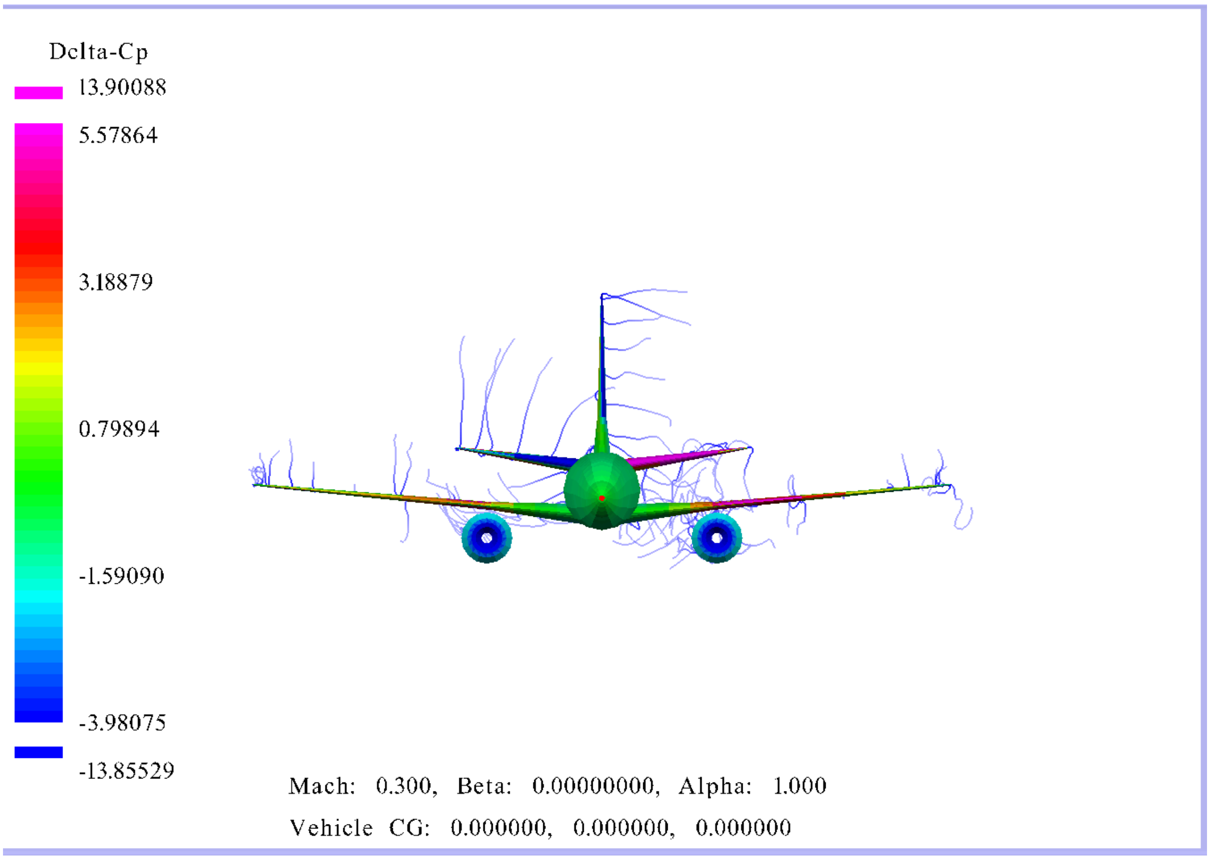

The wake pattern reveals coherent trailing vortices, indicating consistent aerodynamic loading and good mesh continuity across the span.

This type of visualization is particularly useful for detecting spanwise loading imbalance and local flow separation.

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4. Static Stability and Control

4.1 Longitudinal Stability

To evaluate the longitudinal stability of the Boeing 737 model, simulations were performed in VSPAERO across different angles of attack (α) while keeping the sideslip angle (β) fixed at zero. The key indicator of static longitudinal stability is the slope of the pitching moment coefficient (Cm) versus AoA curve.

The results showed a negative slope in the **Cm-α** relationship, which is a desirable characteristic indicating static longitudinal stability. The center of gravity (CG) was set at the origin, and the aerodynamic center remained behind the CG across tested conditions, ensuring a positive static margin. This aligns with the typical behavior of commercial airliners, including the B737.

Due to the inviscid assumptions in VSPAERO, the numerical value of the Cm is approximated, but trends remain reliable for stability interpretation.

4.2 Lateral-Directional Stability

Lateral and directional stability was explored through a sweep in **sideslip angle (β)**. The model was analyzed at small deviations in β to evaluate how rolling moment coefficient (Cl) and yawing moment coefficient (Cn) responded.

From the VSPAERO analysis:

- A **positive slope in Cn vs β** was observed, which is indicative of good **directional stability**. The aircraft generates a restoring yaw moment in response to sideslip.

- Similarly, the **Cl vs β curve** showed expected rolling behavior, with opposite sign Cl for opposing β angles, consistent with dihedral effect and wing sweep aiding **lateral stability**.

Control surfaces (aileron, rudder, elevator) were also modeled and included in this round of simulations. Their effects are visible in pressure differential and flow visualization plots, especially under yawed and deflected conditions.

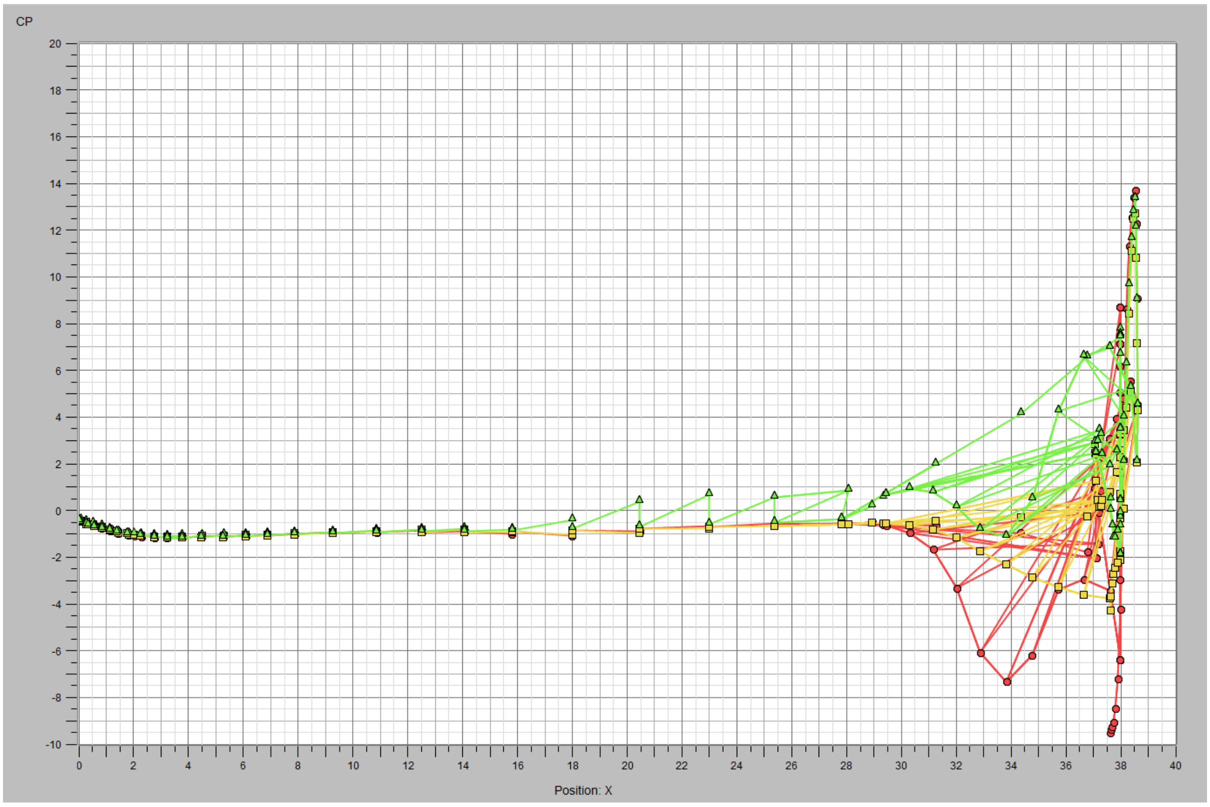
4.3 Control Surface Effectiveness

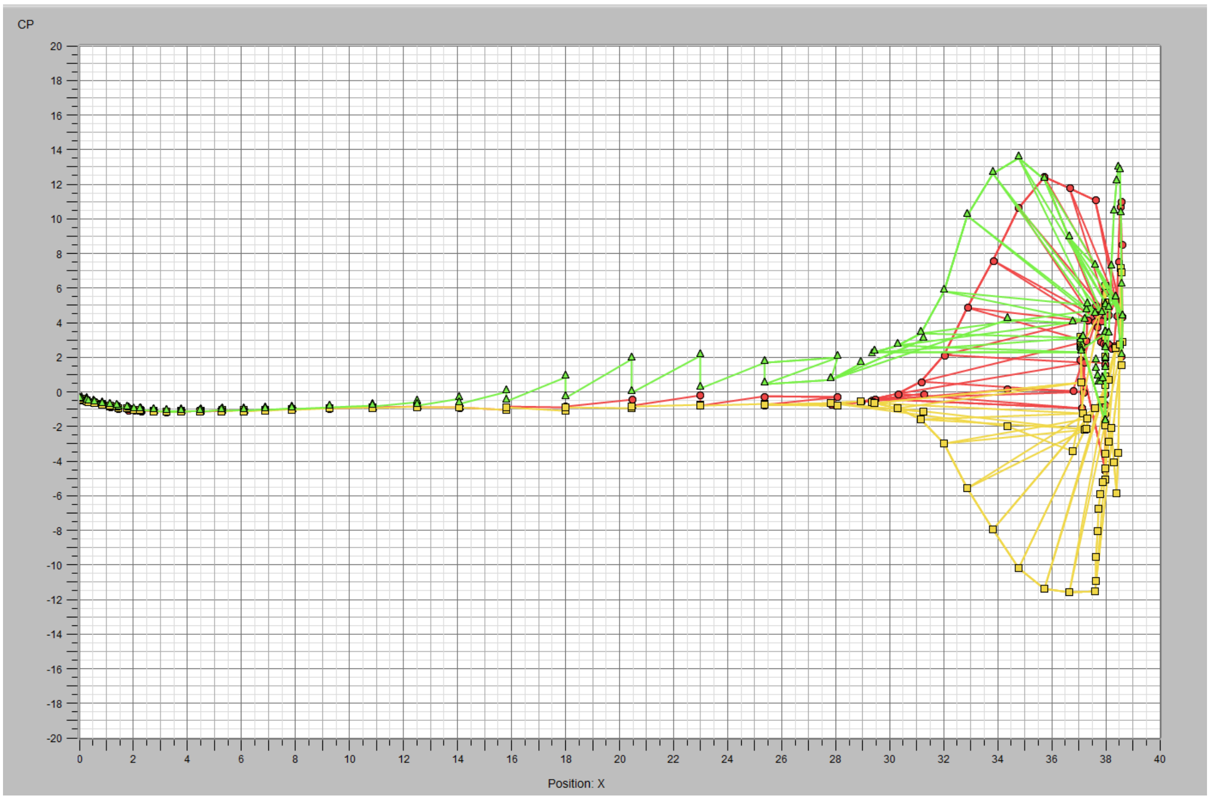
To validate control surface functionality, simulations were conducted with deflected configurations of:

- **Elevator** (for pitch control),
- **Ailerons** (for roll),
- **Rudder** (for yaw).

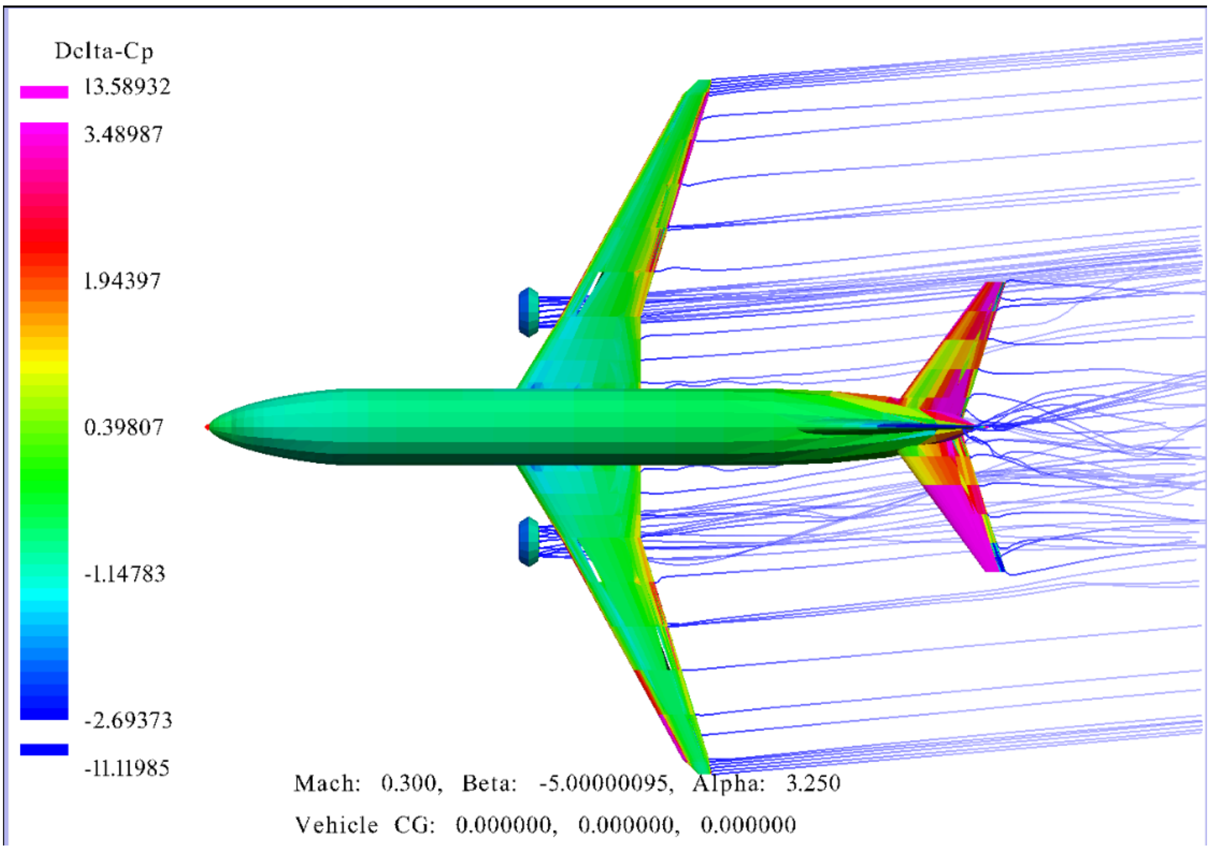
The resulting **Delta-Cp plots** and **streamline visualizations** clearly demonstrate the influence of control surface deflections:

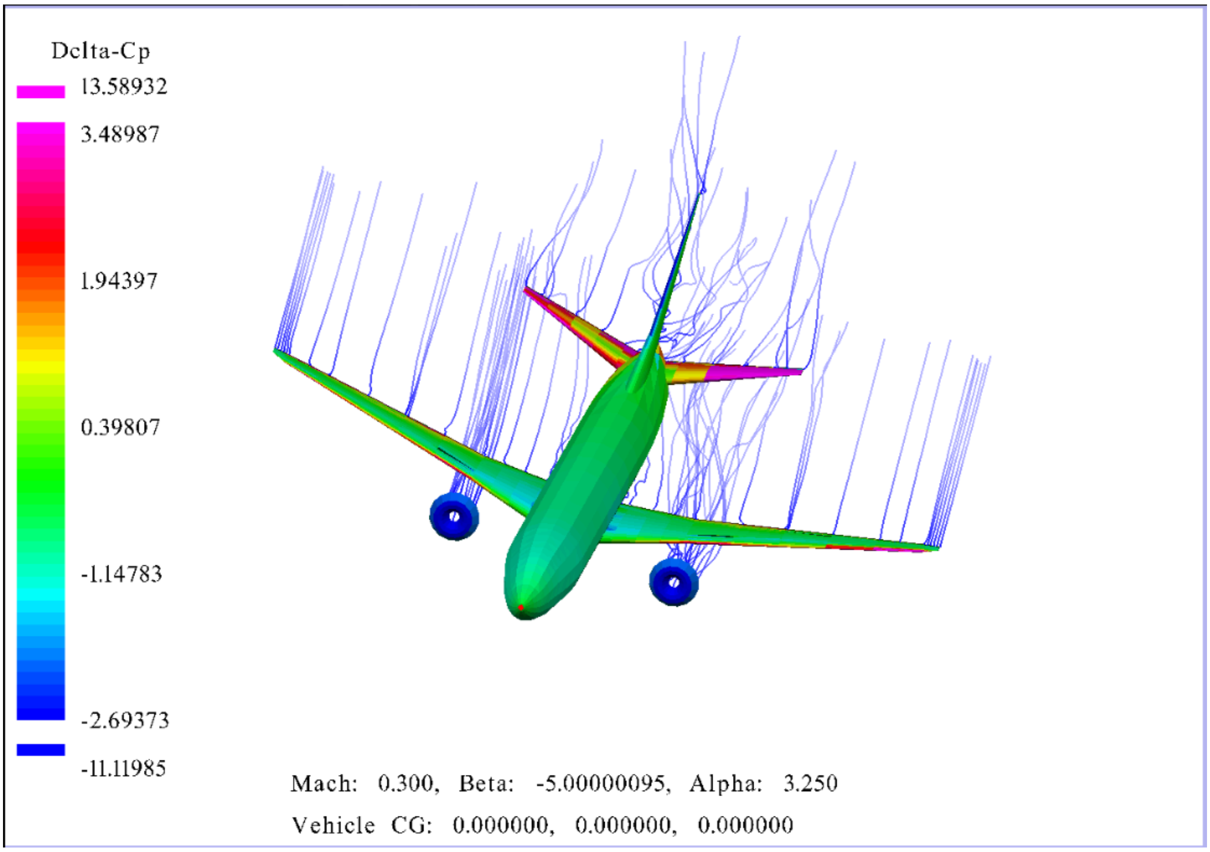
- High-pressure gradients were observed around the rudder and elevator, especially at **α = 1°, β = 0.3**, confirming their aerodynamic authority.





- Streamlines exhibited expected wake distortion and directional flow curvature behind the control surfaces, indicating active flow manipulation.




Delta-Cp
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-1.14783
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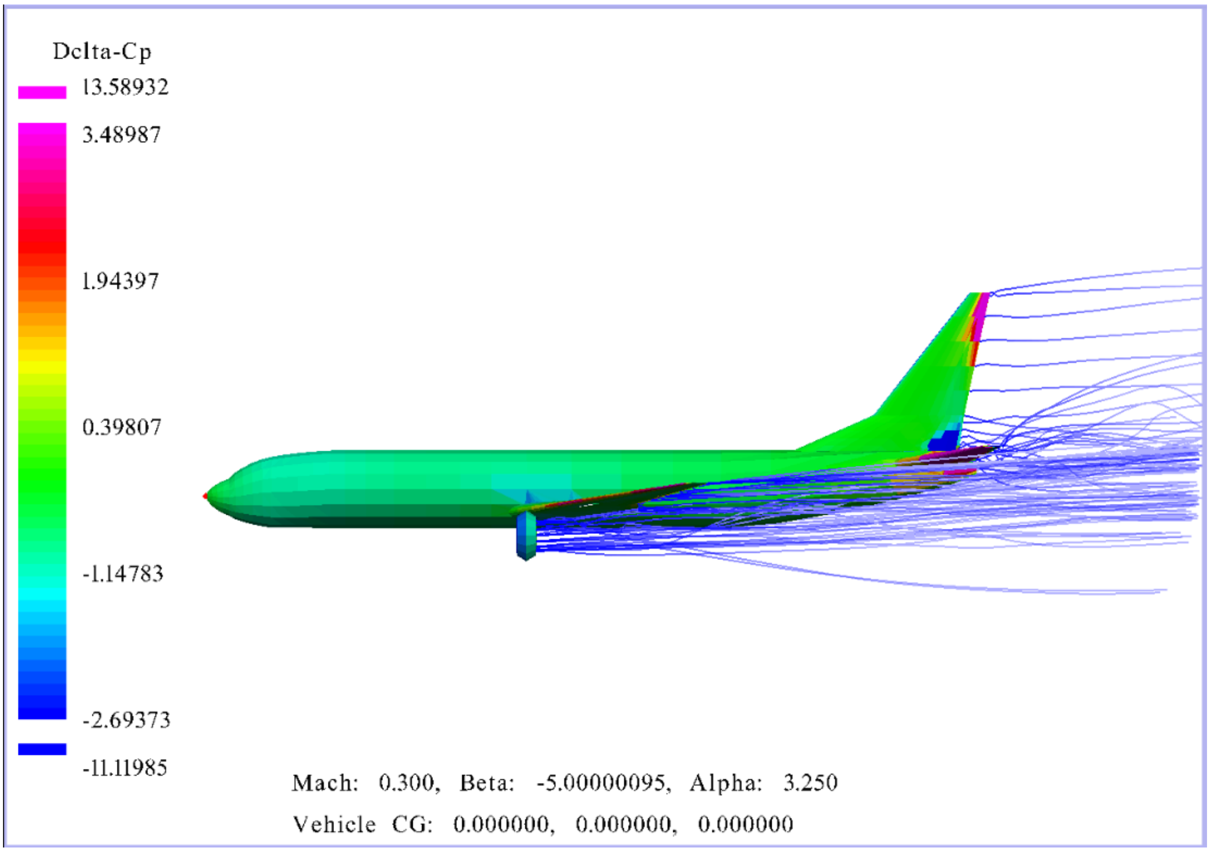
-11.11985
Mach: 0.300, Beta: -5.00000095, Alpha: 3.250
Vehicle CG: 0.000000, 0.000000, 0.000000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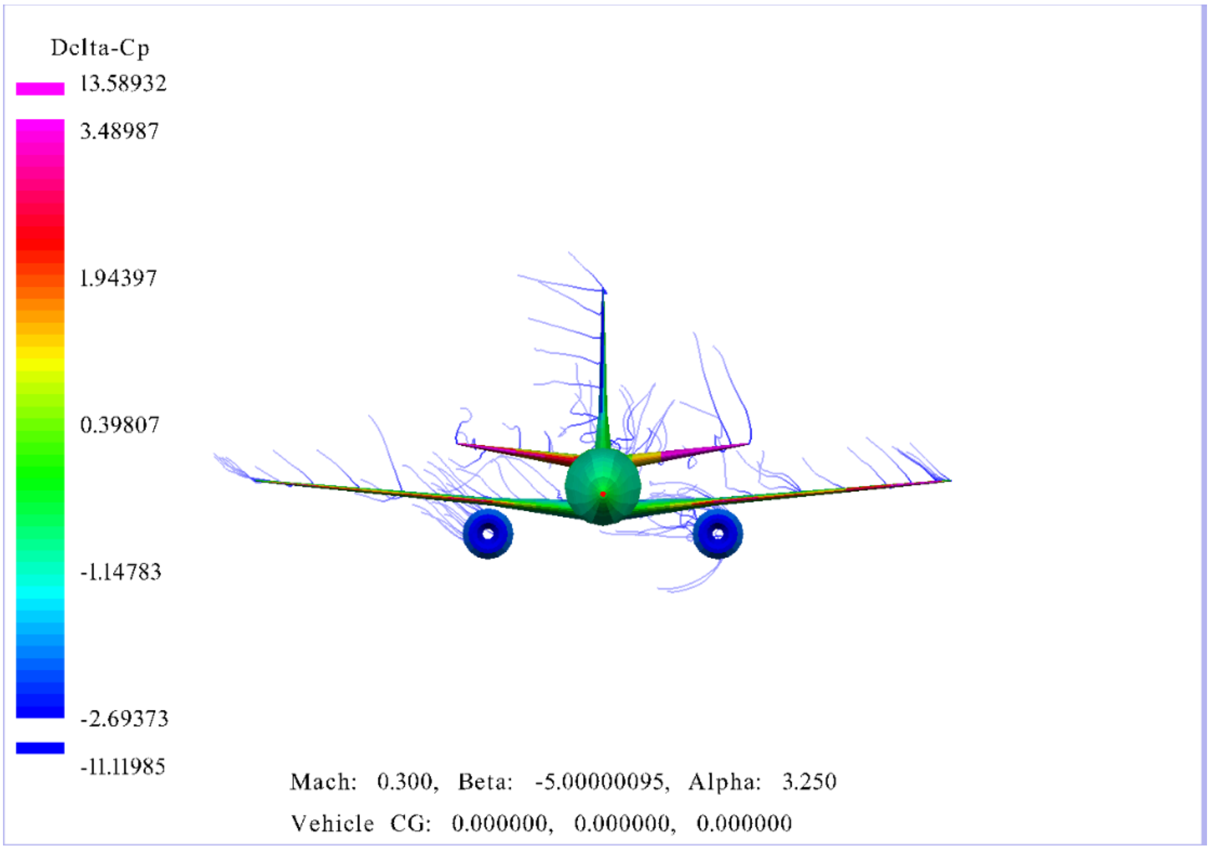
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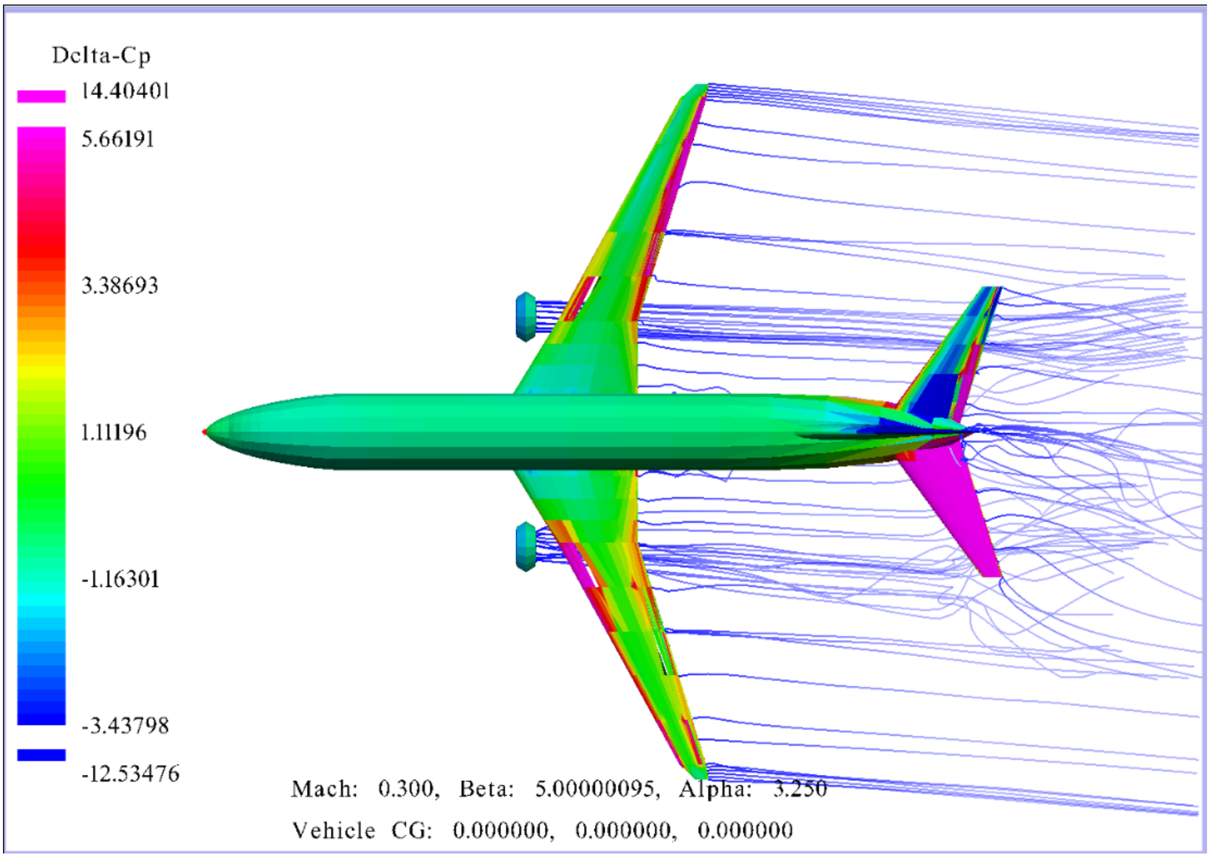
Delta-Cp
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1.11196
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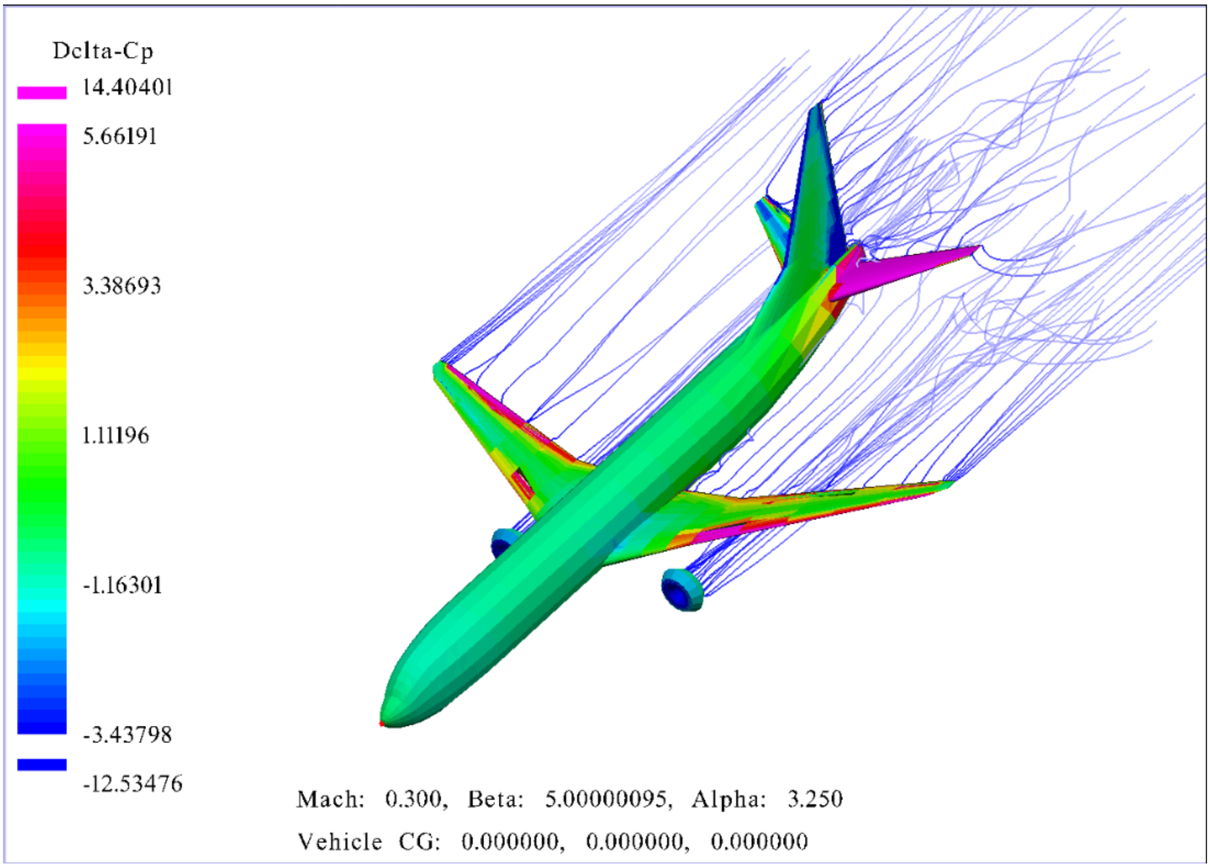
Vehicle CG: 0.000000, 0.000000, 0.000000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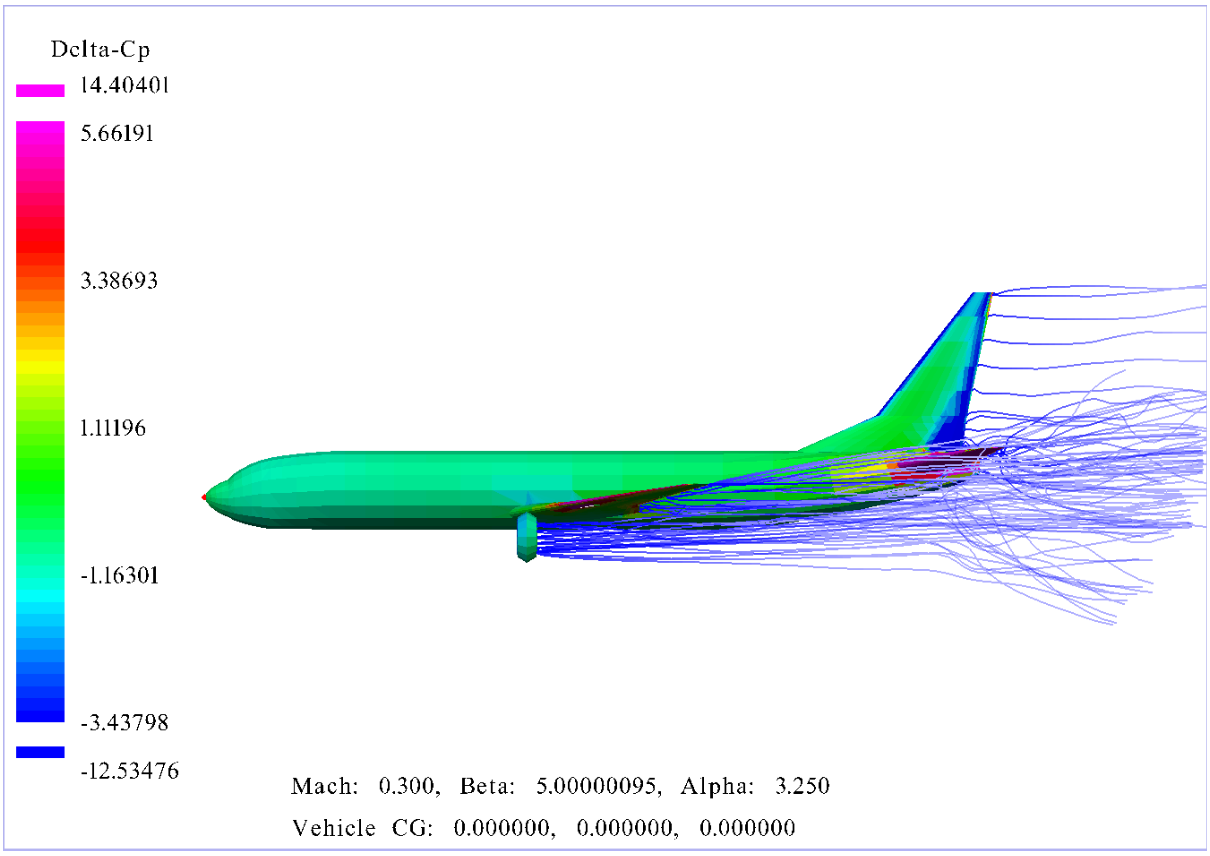
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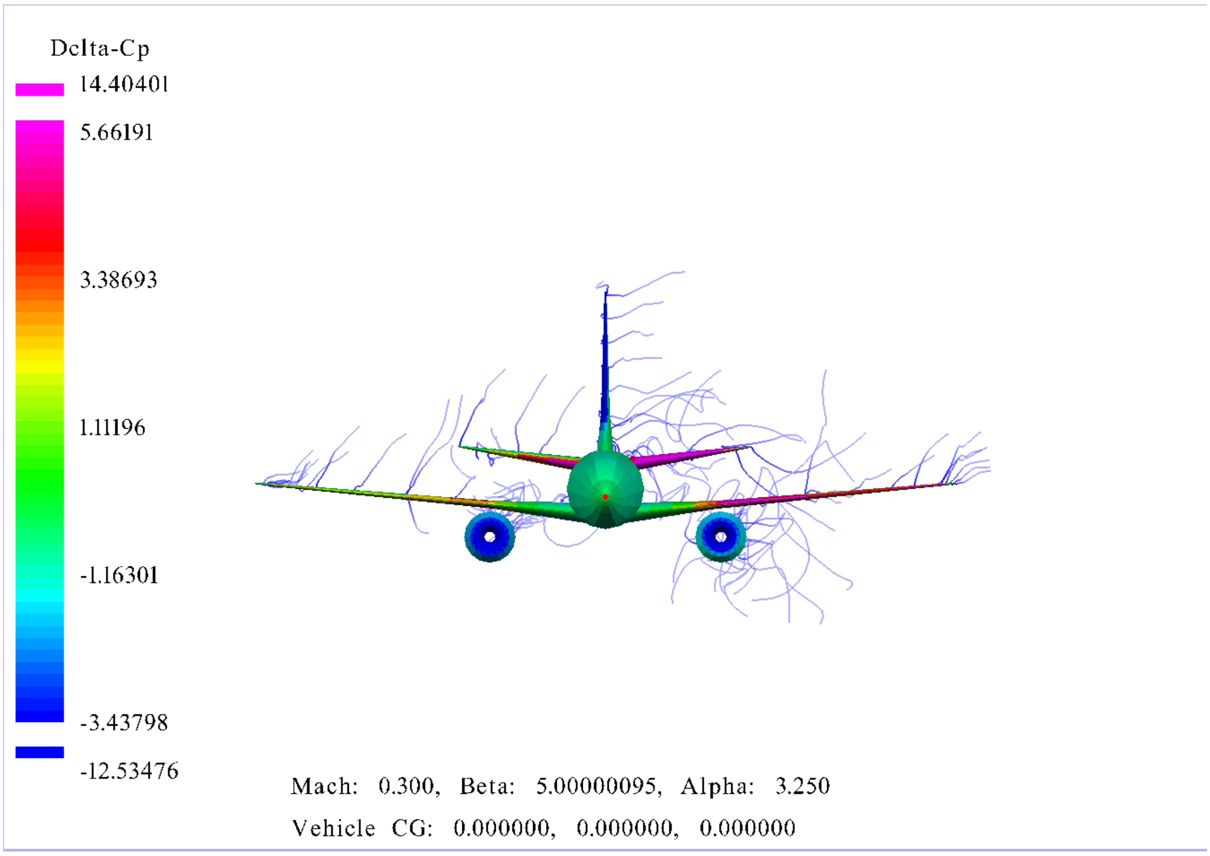

These findings support the conclusion that the control surfaces were not only correctly positioned but also effective in altering the aircraft's attitude and moments.

5.1 Drag Breakdown using Parasite Drag Estimation

To analyze the parasite drag contribution of each aircraft component, OpenVSP's built-in Parasite Drag estimation module was employed. The simulation was conducted at a freestream Mach number of 0.48, and the Hoerner method was selected for form factor calculation across all geometry groups. The output provides insight into how surface friction and form affect total drag, particularly useful for early design-stage optimizations.

Methodology:

- Surface groups such as the fuselage, wings, horizontal and vertical tails, flaps, slats, ailerons, and nacelles were included.
- FF (Form Factor) values were automatically derived using the Hoerner streamlining equations based on geometry dimensions and Reynolds number estimations.
- The friction coefficient (Cf) and reference Reynolds numbers were computed for each wetted area individually.

- Excrescences drag was lumped into a separate component (BORGeom) to account for non-aerodynamically optimized features like antennae, lights, gaps, etc.

Key Parameters:

- Reynolds Number Basis: Local geometry and flow conditions.
- Laminar Percentage: Set to 0% for conservative estimates.
- Compressibility Factor (Q): Assumed as unity for subsonic flow.

Component	Wetted Area (m^2)	Form Factor (FF)	Cf ($\times 10^{-3}$)	f (m^2)	CD	% of Total Drag
Fuselage	379.45	1.05	1.89	0.7558	0.00626	9.86%
Wing	204.69	1.34	2.57	0.7071	0.00585	9.23%
Ailerons	10.91	1.34	2.57	0.0371	0.00031	0.49%
Flaps	29.1	1.34	2.57	0.1006	0.00084	1.32%
Slats	25.98	1.34	2.57	0.0898	0.00074	1.18%
Horizontal Tail	61.28	1.51	2.75	0.2548	0.00211	3.33%
Vertical Tail	57.34	1.21	2.50	0.1732	0.00143	2.26%
Excrescences (BORGeom)	28.24	63.04	3.24	5.7708	0.04777	75.32%

Observations:

- The excrescences drag dominates the total parasite drag budget (over 75%), which is expected when external appendages and simplified detailing are modeled collectively.
- The wing and fuselage each contribute around 9–10%, aligning with typical subsonic transport aircraft design expectations.
- Control surfaces (flaps, slats, ailerons) collectively contribute less than 3%, but their contribution may become more significant during deflected configurations.
- The form factor method (Hoerner) provided a conservative and geometry-sensitive approach suitable for subsonic transport aircraft like the B737.

6. Discussion

6.1 Summary of Key Findings

The aerodynamic analysis of the B737 model using VSPAERO provided valuable insights into its performance and stability. The lift and drag trends across varying angles of attack showed expected linear behavior within the tested range, while moment coefficient plots confirmed longitudinal stability characteristics. Lateral-directional stability was demonstrated through roll and yaw moment variations with sideslip angle. Control surface deflections (rudder, aileron, elevator) revealed their effectiveness in trimming and stabilizing the aircraft. Additionally, the parasite drag breakdown at Mach 0.48 indicated the fuselage and wing as the primary contributors to total drag, with the BOR geometry (representing landing gear or nacelle drag) being the dominant source.

6.2 Model Limitations

Despite the informative results, several limitations were present in the current model. The geometry lacked engines, landing gear, and precise airfoil profiles used in the real B737, relying instead on symmetric NACA sections and default component shapes. The model did not include sweep or twist in the wings, reducing aerodynamic realism. Furthermore, the VSPAERO solver applies an inviscid vortex lattice method, which excludes viscous effects like boundary layer development and flow separation. These factors limit the predictive accuracy, especially near stall conditions or at higher angles of attack.

6.3 Future Work

Future development of the model could focus on increasing fidelity by incorporating engine nacelles, detailed airfoil profiles, and wing geometric refinements such as sweep and twist. Additionally, extending simulations into dynamic regimes (e.g., gust response, oscillatory inputs) and exporting the geometry to high-fidelity CFD tools like OpenFOAM or SU2 would enable more accurate pressure and wake analysis. Experimental validation using wind tunnel tests or flight data could further support the findings and help refine the simulation approach.

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7. Conclusion

This study provided a comprehensive aerodynamic analysis of a simplified Boeing 737 model using OpenVSP and its integrated solver VSPAERO. Through lift, drag, moment, and stability evaluations, key aerodynamic trends were observed and interpreted. The aircraft displayed stable longitudinal and lateral-directional behavior within the tested range, and the effectiveness of its control surfaces was successfully demonstrated.

The use of OpenVSP proved to be highly valuable for early-stage conceptual modeling and analysis. Its ability to quickly build, simulate, and visualize aerodynamic properties of complex geometries enabled efficient exploration of performance characteristics, especially when supported by tools like the Parasite Drag build-up module.

While the model was simplified and inviscid in nature, the results aligned with expected aerodynamic principles, offering useful insights into the baseline behavior of the B737. This highlights the potential of lightweight simulation tools for educational, preliminary design, and research applications. Future refinements and higher-fidelity methods could further enhance the accuracy and utility of such analyses.