Innovative Aerodynamic Design of a Business Jet: A BWB vs conventional design's Comparative Analysis Study

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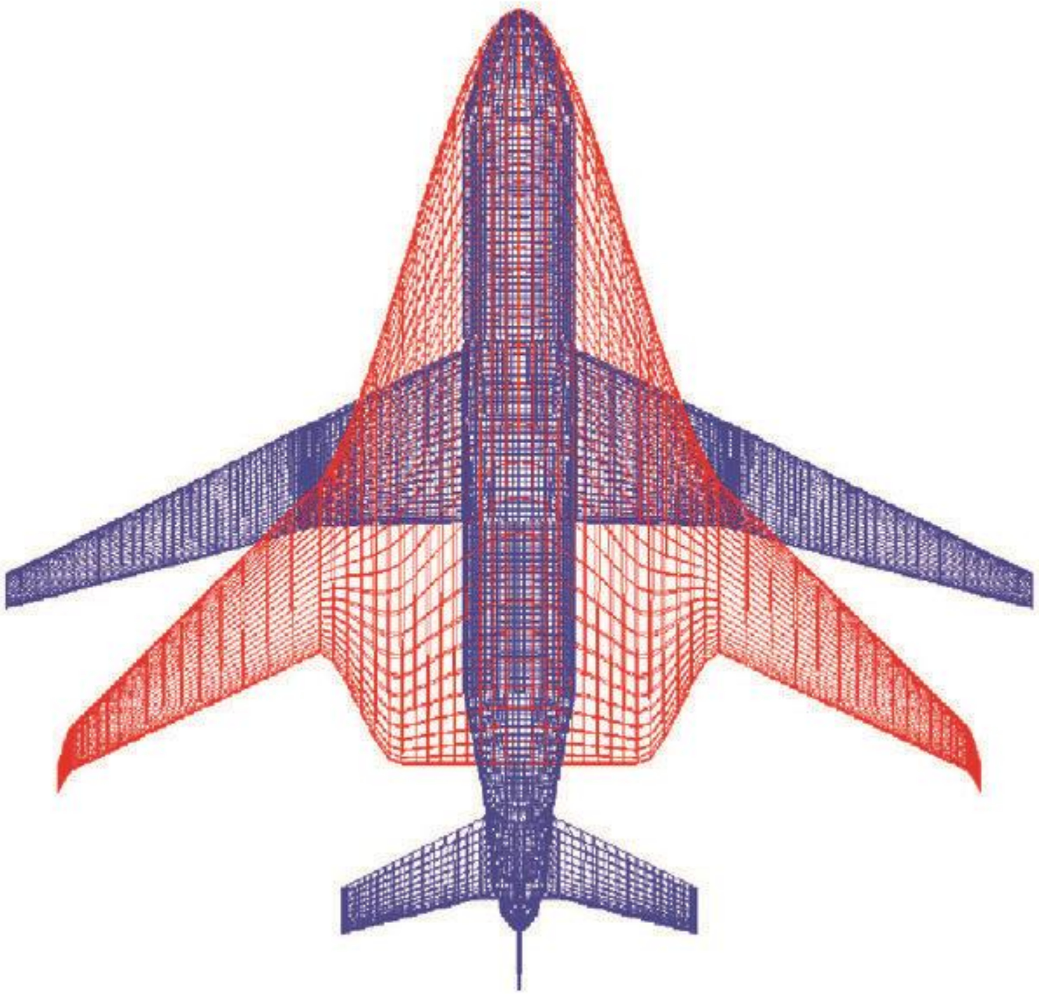
09/11/24

Contents

Introduction

- **Context: Business jets have traditionally followed a tube-and-wing (conventional) design due to its simplicity, efficiency, and well-established engineering principles.**
- **Challenges: However, modern demands for ultra-long-range capability, fuel efficiency, and sustainability have pushed the boundaries of conventional design.**
- **BWB Alternative: Blended Wing Body (BWB) designs are emerging as a viable alternative, offering potential improvements in aerodynamic efficiency and fuel savings through integrated fuselage-wing structures**

Introduction: Conventional vs. BWB Configurations



Conventional Design:

- Structure: Tube-and-wing with separate fuselage, wings, and tail.
- Advantages: Proven, simple design with efficient control surfaces and stability at high subsonic speeds.
- Limitations: Higher drag, limited lift distribution, and less fuel-efficient for ultra-long-range flights.

BWB Design:

- Structure: Integrated fuselage and wing, creating a seamless body that distributes lift over a larger surface area.
- Advantages: Potential for reduced drag, increased lift-to-drag ratio, and better fuel efficiency.
- Challenges: Complex stability and control issues, especially during takeoff and landing phases.

Literature Review

Literature Review: Conventional Tube-and-Wing Design

- Smith et al. (2020): Analyzed aerodynamic efficiency in conventional business jets and noted that optimized wing shapes and rear-mounted engines improved lift-to-drag (L/D) ratios and reduced drag(Chaitanya+CFD+Letter).

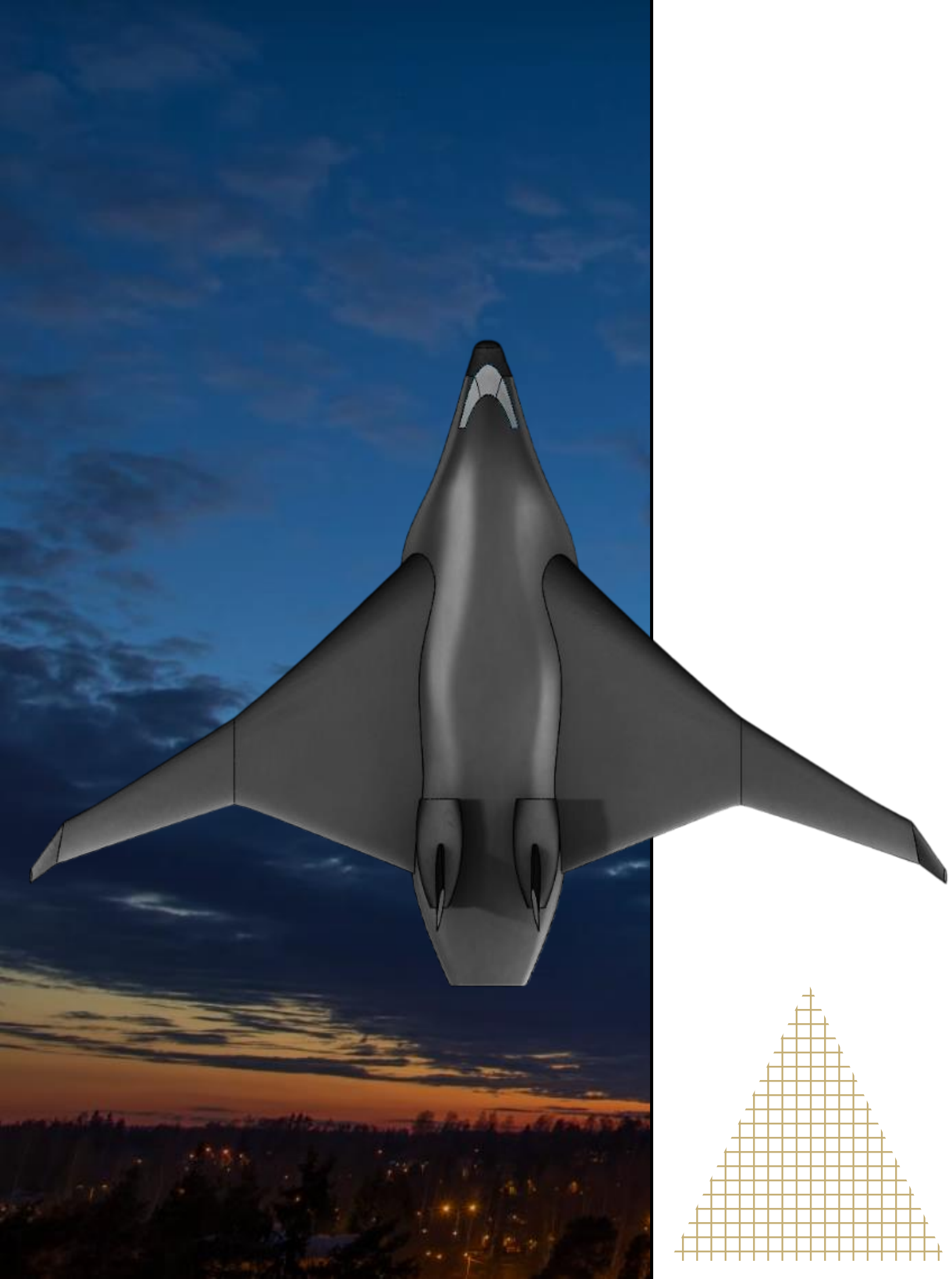
- Anderson and Martinez (2020): Discussed the effectiveness of winglets in reducing vortex drag, contributing to fuel efficiency and stability during cruise(Chaitanya+CFD+Letter).

- Shah and Paudel (2020): Investigated engine placement and found that rear-mounted engines decrease drag by minimizing wake interference with the fuselage(Chaitanya+CFD+Letter).

Key Findings:

- Conventional tube-and-wing configurations offer proven aerodynamic benefits but face limitations in further improving fuel efficiency due to structural constraints.

- Optimization of wing geometry, winglets, and engine placement have brought significant efficiency improvements but are reaching their performance limits in terms of ultra-long-range applications.



Literature Review: Blended Wing Body (BWB) Design

- Smith and Williams (2019): Conducted CFD simulations and wind tunnel tests showing that BWB designs could achieve fuel savings of 15-20% over conventional jets due to reduced parasite drag[1][2]
- Jones et al. (2020): Highlighted BWB's ability to provide up to 20% more cabin space, enhancing passenger comfort and operational flexibility[12]
- Ghimire et al. (2018): Found that embedding engines within the BWB structure improves thrust efficiency and further reduces drag[9]

Key Findings:

- BWB designs present significant aerodynamic and fuel efficiency advantages, especially at cruise conditions.
- Integration of engines and larger cabin volume make BWBs attractive for luxury business aviation, but control and stability challenges remain during critical flight phases like takeoff and landing.

Literature Review: CFD in Aircraft Design

- Turner and Black (2021): Used CFD to compare conventional and BWB designs, finding that BWB performs better at high angles of attack and is suited for long-haul, high-altitude flights[4]
- Deperrois and Walton (2019): Investigated drag reduction techniques (e.g., laminar flow control) for BWB configurations, demonstrating an additional 10-12% drag reduction potential.[11]
- Chu and Ho (2021): Analyzed aeroelastic effects in high-altitude turbulence, noting that BWB jets show better stability under such conditions due to distributed loads.[7]

Key Findings:

- CFD has proven essential for optimizing BWB and conventional designs, especially in predicting flow behavior and improving drag and lift characteristics.
- BWB benefits from advanced drag reduction techniques, making it a promising design for fuel-efficient long-haul business jets.

Literature Review - Optimization Techniques Using Orthogonal Arrays

- Shams et al. (2020): Applied Taguchi methods to optimize wing geometry for both conventional and BWB jets, achieving improved L/D ratios through controlled testing.[15]
- Shah et al. (2020): Used orthogonal arrays to enhance thrust vectoring in BWB jets, finding that engine placement significantly affects stability during takeoff and climb.[20]

Key Findings:

- Orthogonal array methodologies like Taguchi enable efficient testing of multiple design variables, which is particularly valuable for complex configurations like BWB.
- Optimizing thrust and wing geometry can enhance aerodynamic efficiency, especially for BWB designs where drag reduction is critical.

Research Gap and Problem Definition

Research Gaps:

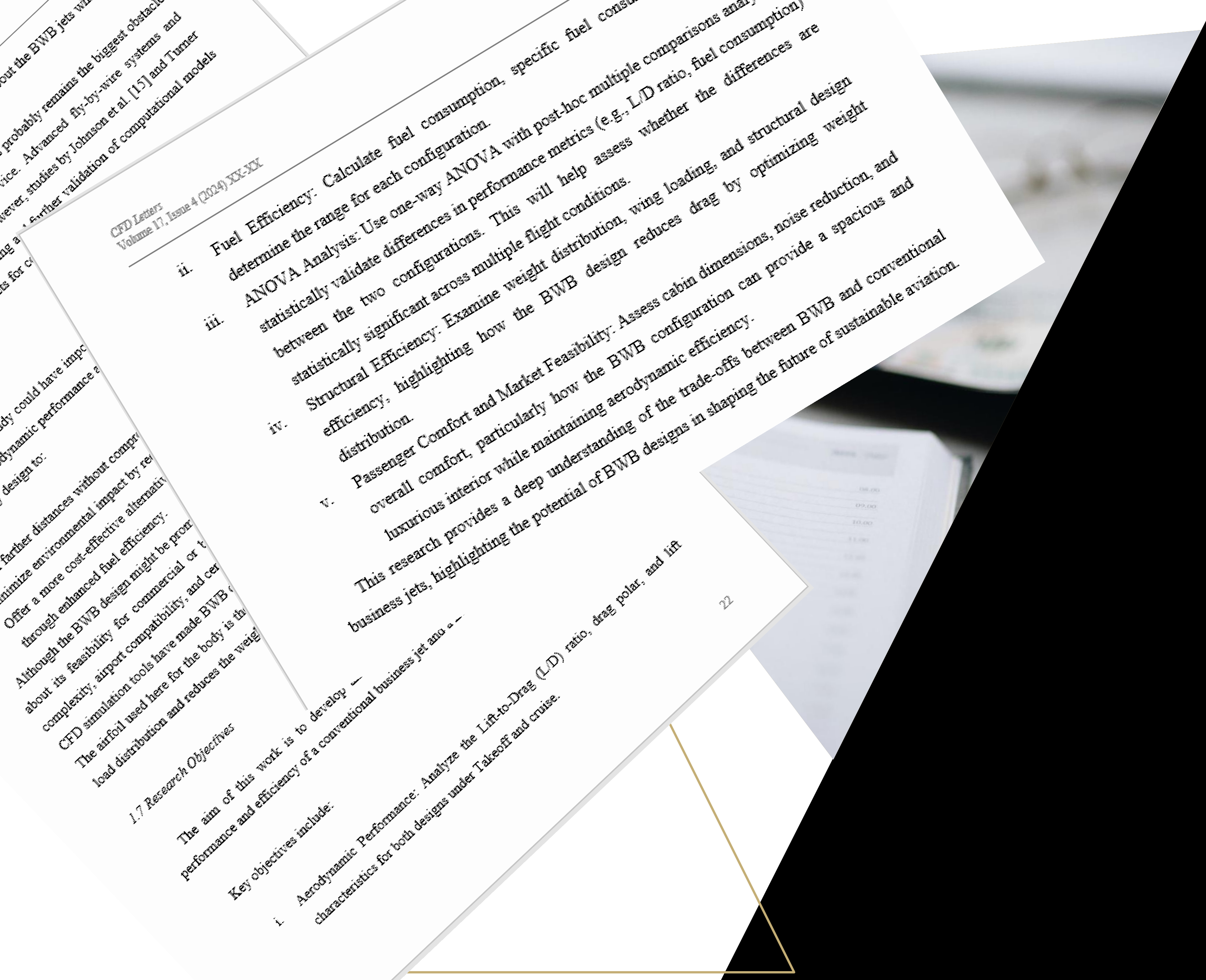
- Limited real-world flight data for BWB configurations, especially under varying flight phases like takeoff and landing.
- Control and stability issues with BWB designs, particularly due to the absence of traditional control surfaces.
- Lack of detailed analysis on the fuel efficiency impact of BWB vs. conventional configurations over ultra-long-range missions.

Problem Definition:

The study aims to address these gaps by conducting a comparative analysis of conventional and BWB business jet configurations, focusing on aerodynamic performance, fuel efficiency, and stability.

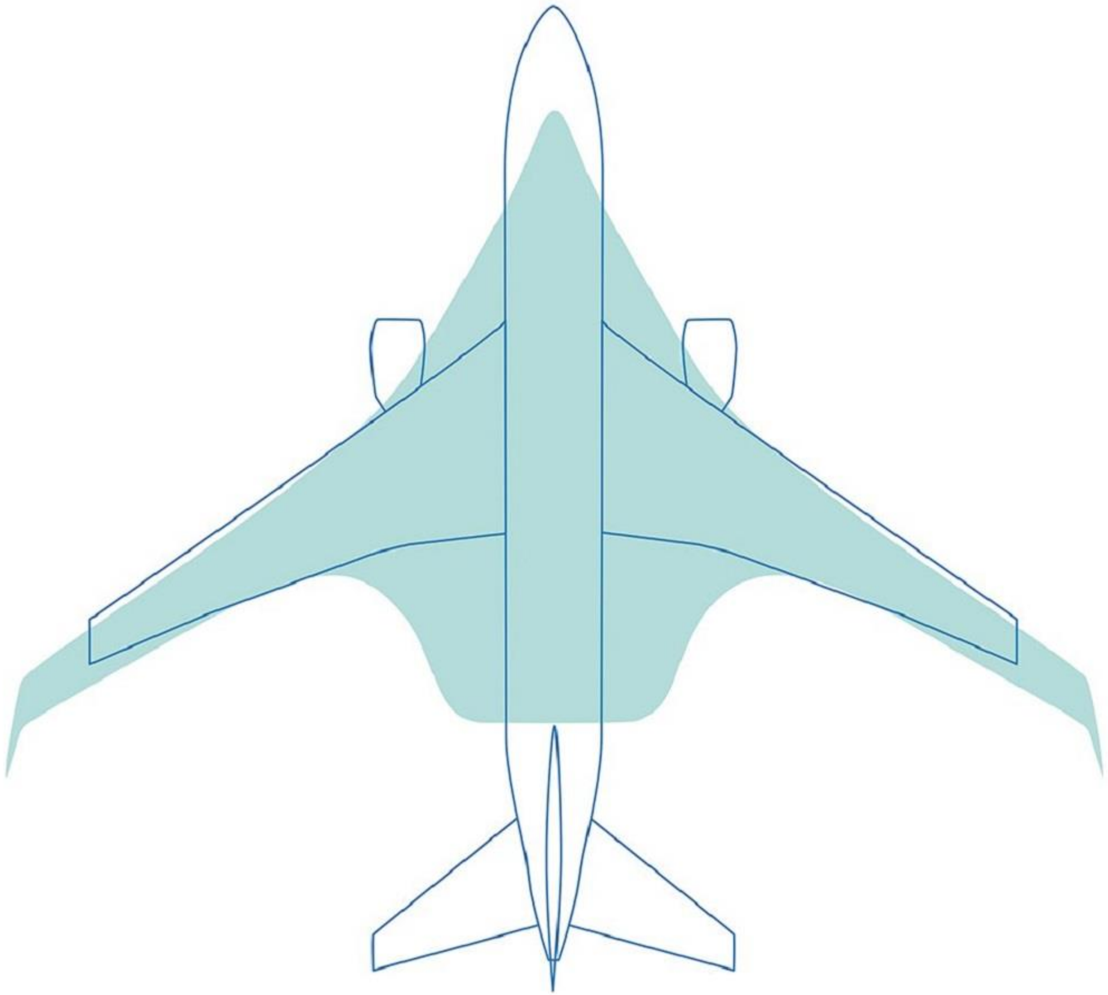
Goal:

To assess whether the BWB configuration offers viable improvements for high-performance business jets, especially in terms of sustainability and fuel efficiency.


CFD Letters
Volume 17, Issue 4 (2024) XX-XX
ii. Fuel Efficiency: Calculate fuel consumption, specific fuel consu
determine the range for each configuration.
iii. ANOVA Analysis: Use one-way ANOVA with post-hoc multiple comparisons analy
statistically validate differences in performance metrics (e.g., L/D ratio, fuel consumption)
between the two configurations. This will help assess whether the differences are
statistically significant across multiple flight conditions.
iv. Structural Efficiency: Examine weight distribution, wing loading, and structural design
efficiency, highlighting how the BWB design reduces drag by optimizing weight
distribution.
v. Passenger Comfort and Market Feasibility: Assess cabin dimensions, noise reduction, and
overall comfort, particularly how the BWB configuration can provide a spacious and
luxurious interior while maintaining aerodynamic efficiency.
This research provides a deep understanding of the trade-offs between BWB and conventional
business jets, highlighting the potential of BWB designs in shaping the future of sustainable aviation.
22
1.7 Research Objectives
The aim of this work is to develop
performance and efficiency of a conventional business jet and a
Key objectives include:
i. Aerodynamic Performance: Analyze the Lift-to-Drag (L/D) ratio, drag polar, and lift
characteristics for both designs under Takeoff and cruise.

Objectives

Specific Objectives



Aerodynamic Efficiency:

- Analyze and compare the lift-to-drag ratio (Cl/Cd) for both configurations.Assess aerodynamic stability in various flight phases (takeoff, cruise).

Fuel Economy:

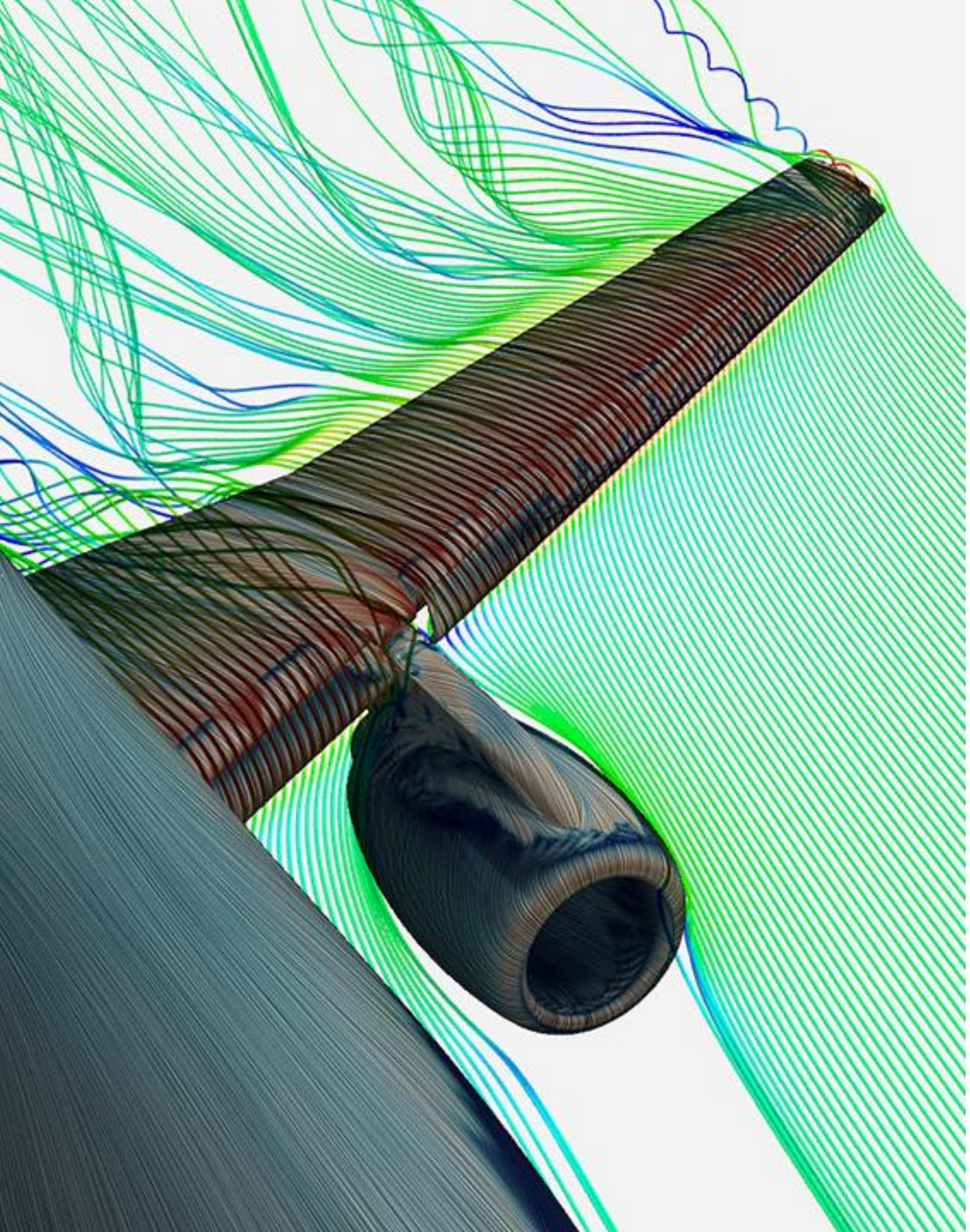
- Calculate specific fuel consumption (SFC) and fuel efficiency for each design.Determine if BWB provides significant fuel savings over conventional designs.

Statistical Analysis:

- Use ANOVA (Analysis of Variance) to validate the significance of differences in performance metrics like Cl/Cd and SFC across various flight conditions.

Structural and Passenger Comfort:

- Investigate structural efficiency, weight distribution, wing loading, and cabin comfort in each configuration.



Governing Equations: Navier-Stokes Equation

Navier-Stokes Equation: Governs fluid flow and forms the basis for CFD analysis.

Equation:

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}\right)=-\nabla p+\mu\nabla^2\mathbf{u}+\mathbf{f}$$

where:

ρ: Fluid density

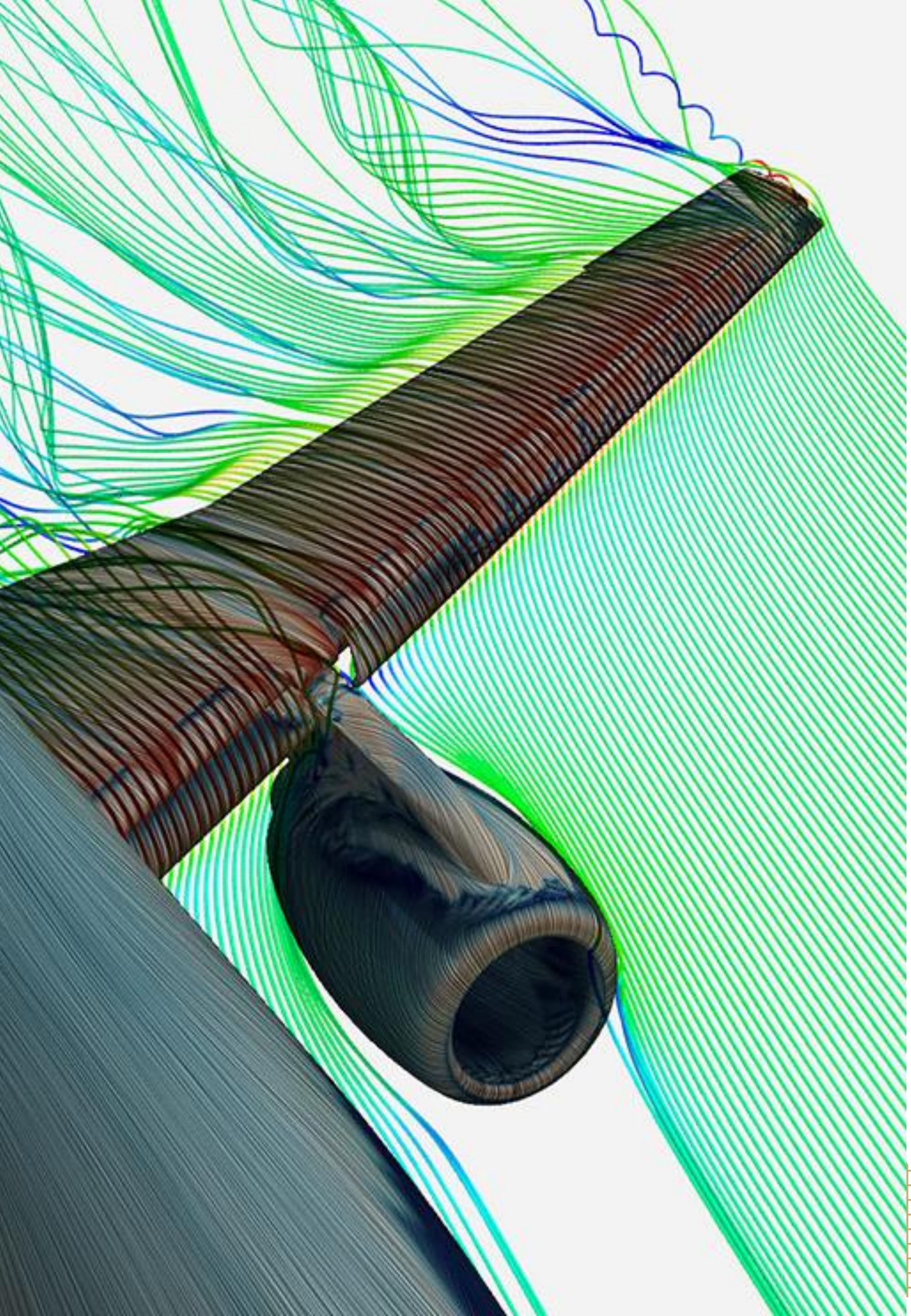
u: Velocity vector

p: Pressure

μ: Dynamic viscosity

f: Body force per unit volume

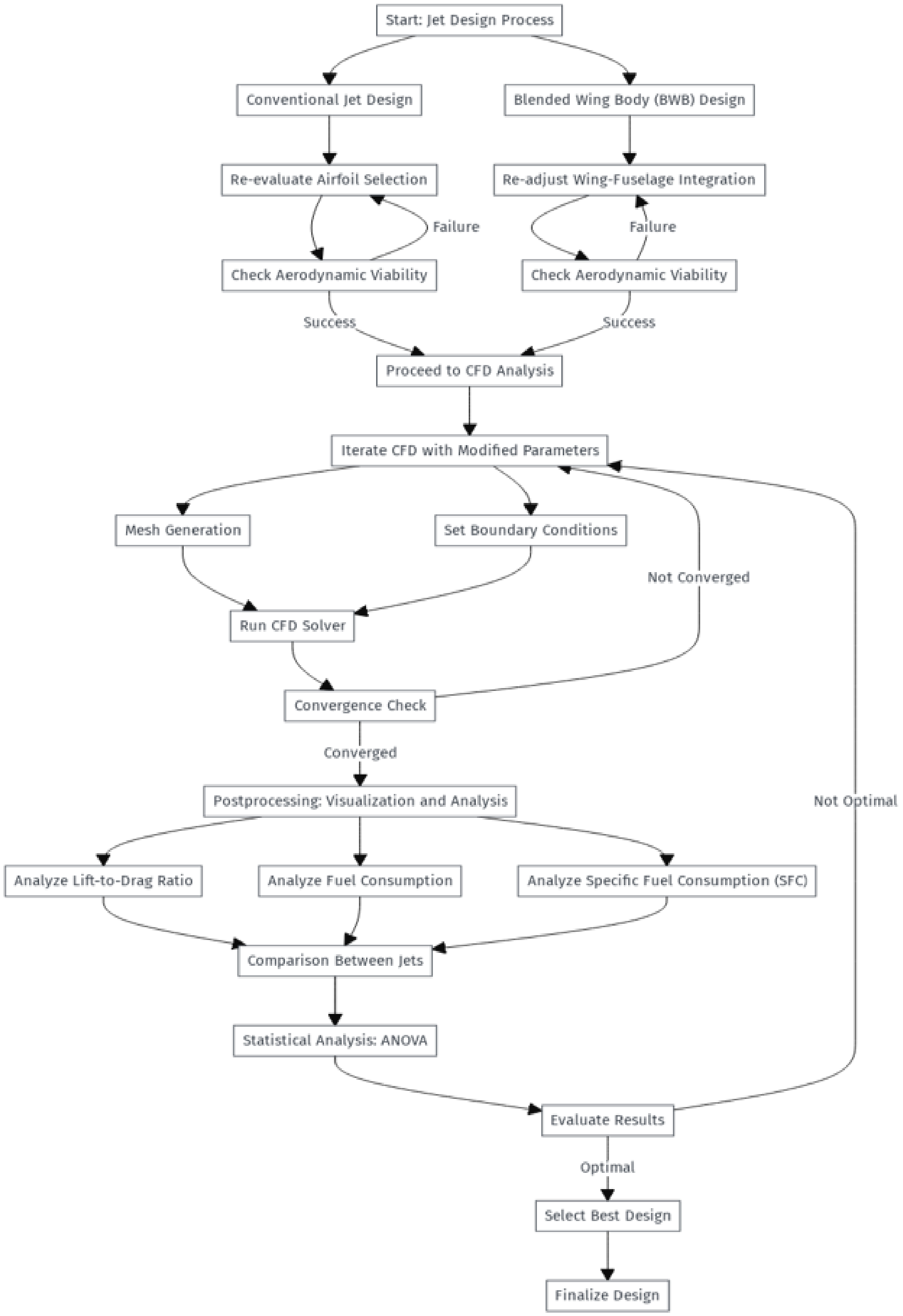
Explanation: This equation describes how momentum is conserved in a fluid, accounting for the effects of pressure, viscous forces, and external forces.



Key Values and Parameters in CFD Simulations

- Takeoff Speeds of 150 knots with angles of attack (AoA) at 0°, 5°, and 10°. Cruise Speeds of 520 knots with angles of attack (AoA) at 0°, 5°, and 10°
- Air density and viscosity set according to takeoff and cruise altitudes
- Reynolds number similarity maintained between scaled and full-scale models.
- Adjustment in fluid density to ensure realistic representation of dynamic conditions.
- Unstructured mesh with tetrahedral elements for capturing complex geometries.
- SST $k-\omega$k−ω turbulence model chosen for boundary layer accuracy.
- Steady-state, pressure-based solver, suitable for subsonic aerodynamic analysis.

Methodology



Methodology Overview

Research Approach: A combination of computational modeling, CFD analysis, and statistical validation to compare conventional and BWB designs.

Tools Used:

- CAD Design: SolidWorks for creating 3D models of both configurations
- CFD Software: ANSYS Fluent for performing simulations and analyzing flow characteristics.
- Statistical Analysis: ANOVA for validating performance metrics across different conditions.

Key Steps: Design of models → Mesh generation → CFD setup → Simulation → Analysis of results → Statistical validation.

Conventional Tube and wing design

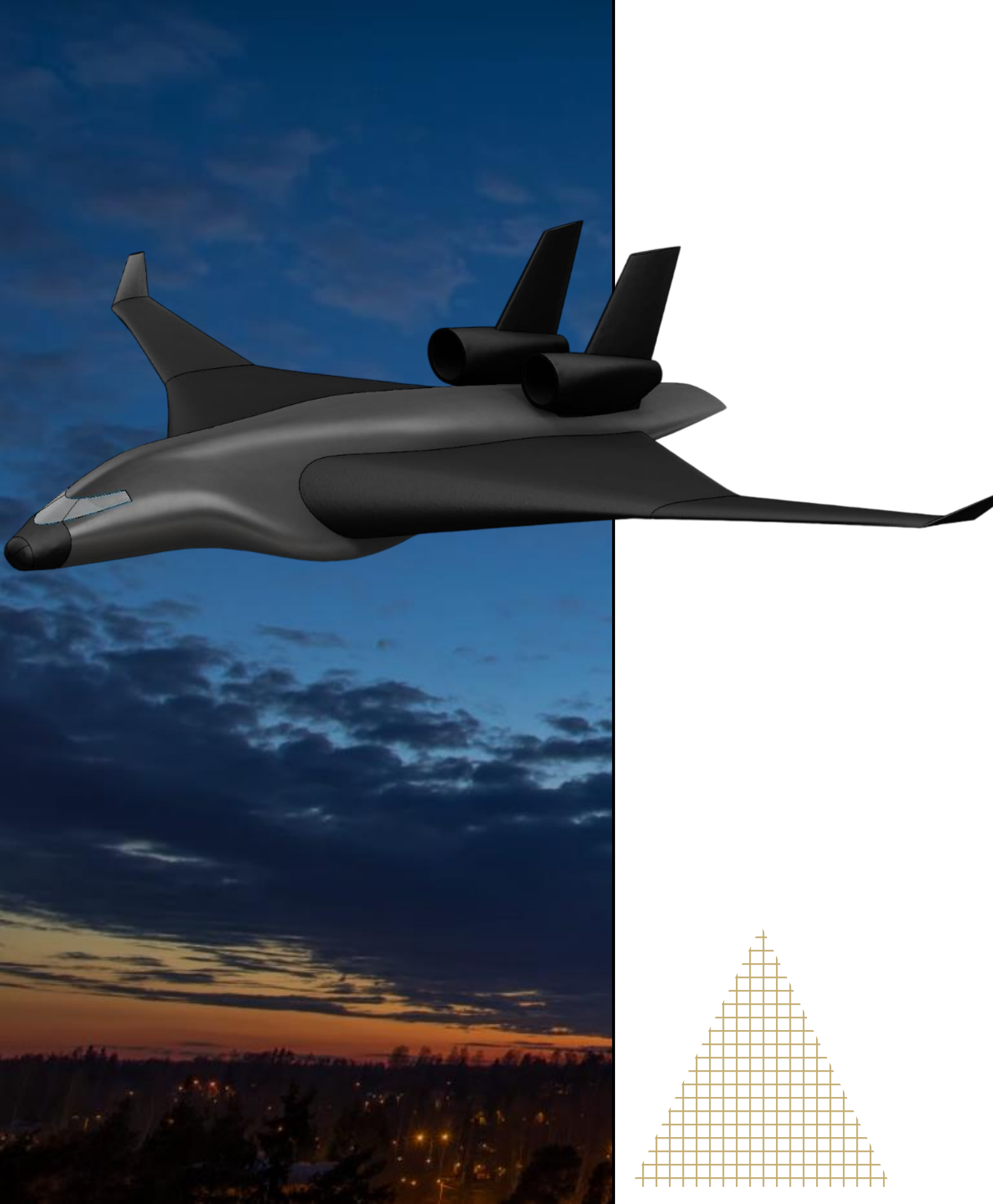
Design Details:

- Fuselage Length: 107.5 feet
- Wing Span: 93.5 feet
- Wing Area: 950 square feet
- Engine Placement: Two rear-mounted turbofan engines (GE Passport, 18,000 lbs thrust each)
- Cruise Speed: Mach 0.88, with service ceiling of 51,000 feet

Software:

- SolidWorks for creating the 3D model based on traditional tube-and-wing configuration.

Design Rationale: Emphasis on a stable and reliable configuration with proven efficiency at high subsonic speeds.



BWB Jet Design Setup

Design Details:

- Overall Length: 95 feet
- Wing Span: 144.91 feet
- Wing Area: 2,100 square feet
- Engine Placement: Two embedded Rolls-Royce Pearl 15 engines (15,000 lbs thrust each)
- Cruise Speed: Mach 0.90, with service ceiling of 51,000 feet

Software:

- SolidWorks used to create an integrated fuselage and wing model for optimized lift distribution and drag reduction.

Design Rationale: High fuel efficiency and aerodynamics achieved through a seamless body-wing integration, aimed at long-range business flights.

CFD Simulation Setup Using L12 Orthogonal Array

L12 Orthogonal array

Run	Aircraft type(A)	Flight Phase(B)	Angle of Attack(C)	Speed(D)
1	Conventional	Take-off	0°	150 knots
2	Conventional	Take-off	5°	160 knots
3	Conventional	Take-off	10°	170 knots
4	Conventional	Cruise	0°	510 knots
5	Conventional	Cruise	5°	520 knots
6	Conventional	Cruise	10°	540 knots
7	Blended Wing Body	Take-off	0°	150 knots
8	Blended Wing Body	Take-off	5°	160 knots
9	Blended Wing Body	Take-off	10°	170 knots
10	Blended Wing Body	Cruise	0°	520 knots
11	Blended Wing Body	Cruise	5°	530 knots
12	Blended Wing Body	Cruise	10°	540 knots

Key Factors:

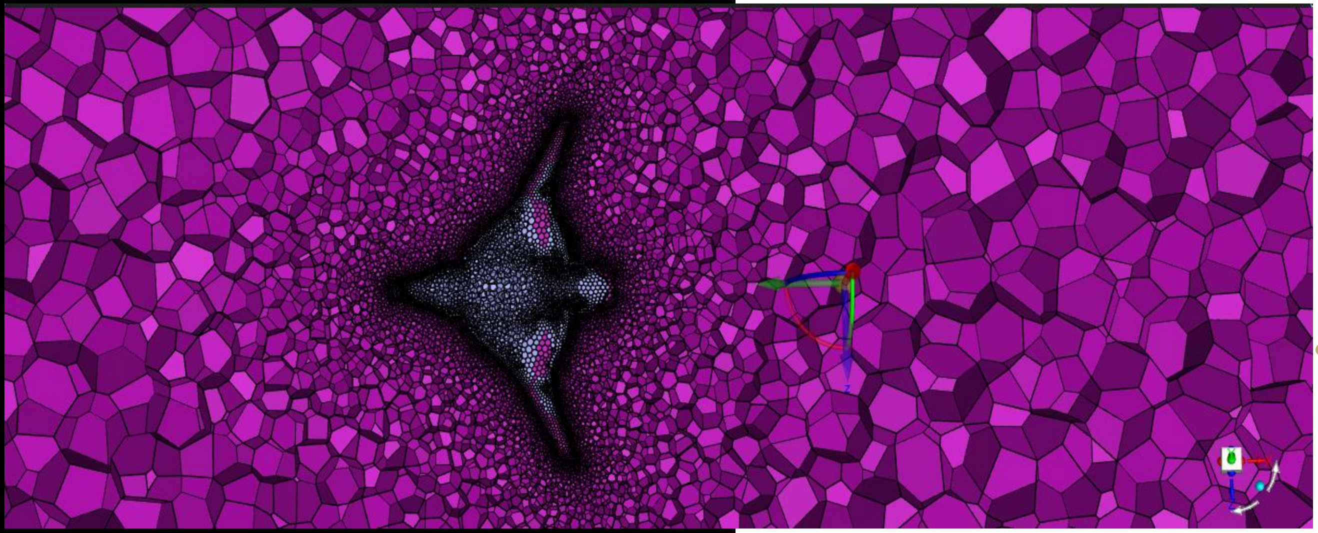
- Aircraft Type: Conventional vs. BWB
- Flight Phase: Takeoff and Cruise
- Angle of Attack (AoA): 0°, 5°, 10°

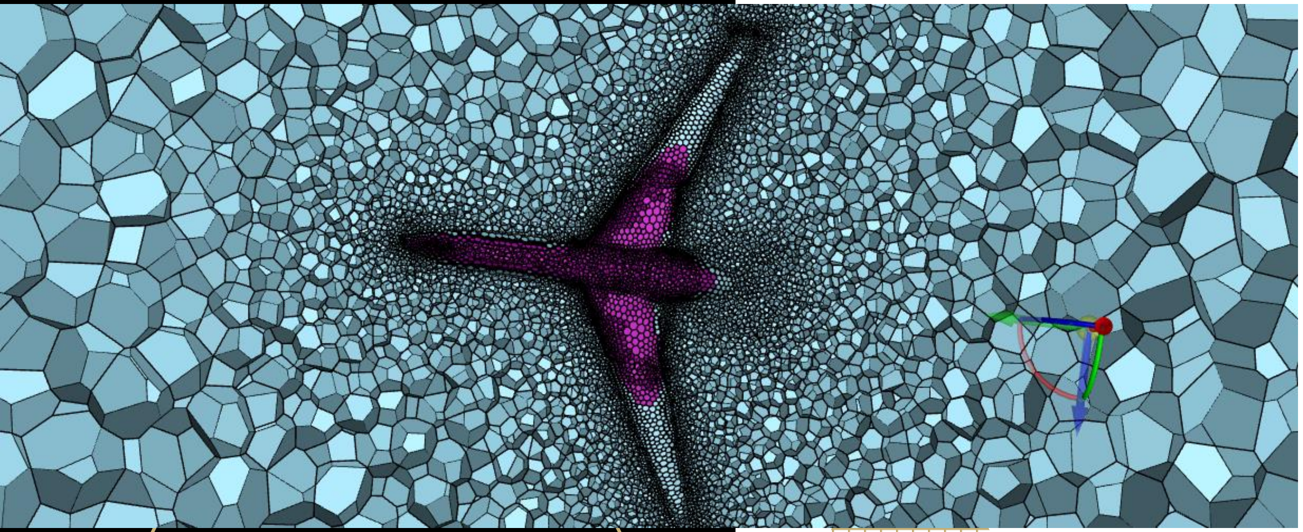
Speed: Specific values for takeoff (150–170 knots) and cruise (520–540 knots)

Rationale for Orthogonal Array: Minimizes simulation runs while ensuring all factor combinations are explored effectively.

Output Metrics: Lift-to-Drag Ratio (Cl/Cd), Specific Fuel Consumption (SFC), lift, and drag.

CFD Setup – Geometry and Mesh Generation





- Geometry: The 3D models of both aircraft were imported into ANSYS DesignModeler and spaceclaim. Attention was given to ensure that the models were clean, watertight, and that all surface details were captured.
- Mesh Generation: Unstructured Mesh: Generated with tetrahedral elements for the overall volume and prism layers near the surfaces to accurately capture boundary layer flows.
- Element Size: Fine mesh was applied to leading edges, trailing edges, and wingtips for both designs.
- Prism Layers: Added to ensure accurate near-wall predictions, with a total of 15 layers and a growth rate of 1.2.

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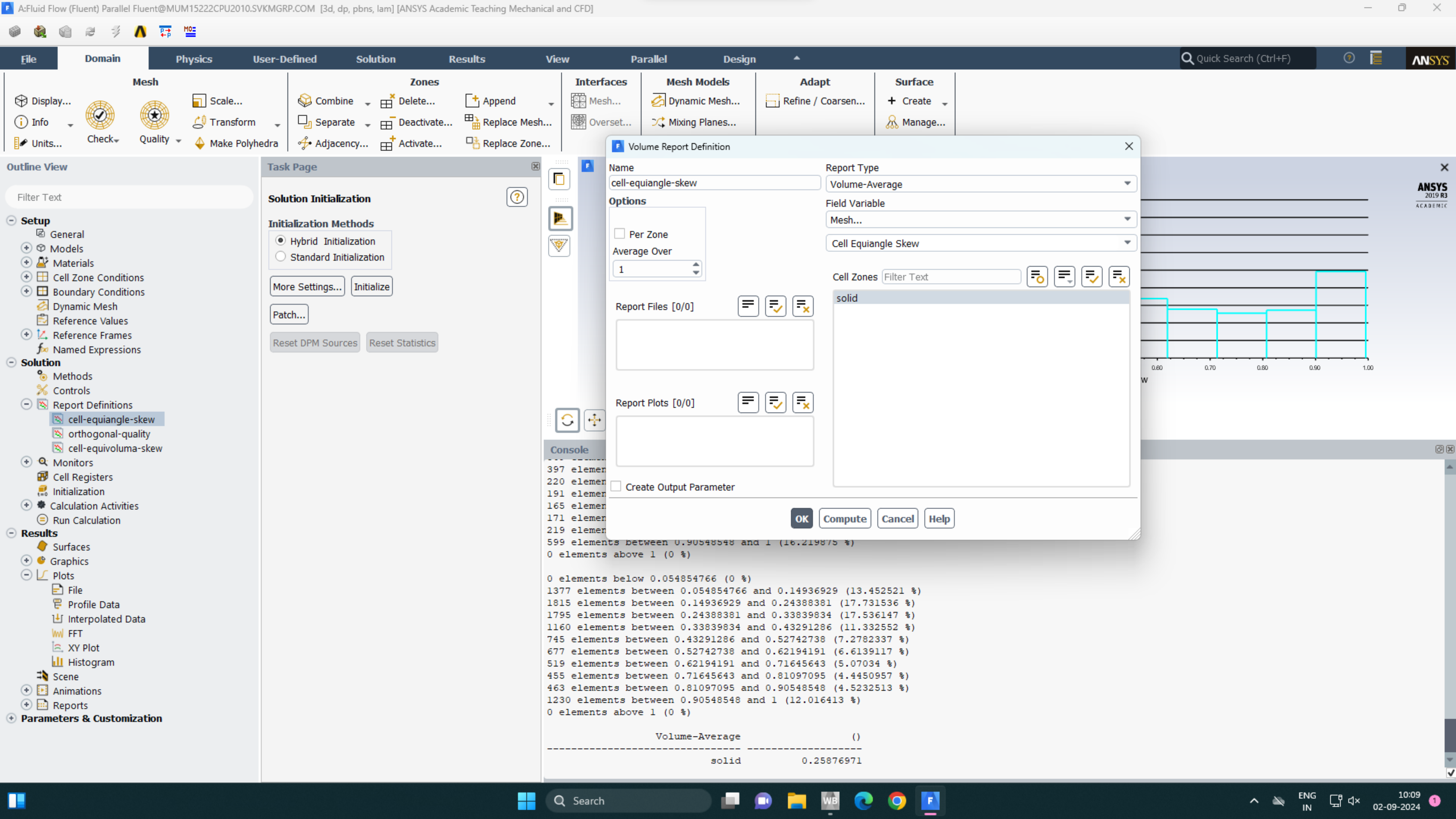
A:Fluid Flow (Fluent) Parallel Fluent@MUM15222CPU2010.SVKMGRP.COM [3d, dp, pbns, lam] [ANSYS Academic Teaching Mechanical and CFD]
File
Domain
Physics
User-Defined
Solution
Results
View
Parallel
Design
Quick Search (Ctrl+F)
Mesh
Display...
Info
Units...
Check
Quality
Scale...
Transform
Make Polyhedra
Zones
Combine
Separate
Adjacency...
Delete...
Deactivate...
Activate...
Append
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Replace Zone...
Interfaces
Mesh...
Overset...
Mesh Models
Dynamic Mesh...
Mixing Planes...
Adapt
Refine / Coarsen...
Surface
Create
Manage...
Outline View
Filter Text
Setup
General
Models
Materials
Cell Zone Conditions
Boundary Conditions
Dynamic Mesh
Reference Values
Reference Frames
Named Expressions
Solution
Methods
Controls
Report Definitions
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Initialization
Calculation Activities
Run Calculation
Results
Surfaces
Graphics
Plots
File
Profile Data
Interpolated Data
FFT
XY Plot
Histogram
Scene
Animations
Reports
Parameters & Customization
Task Page
Solution Initialization
Initialization Methods
Hybrid Initialization
Standard Initialization
More Settings...
Initialize
Patch...
Reset DPM Sources
Reset Statistics
Volume Report Definition
Name
cell-equiangle-skew
Report Type
Volume-Average
Options
Per Zone
Average Over
1
Field Variable
Mesh...
Cell Equiangle Skew
Cell Zones
Filter Text
solid
Report Files [0/0]
Report Plots [0/0]
Create Output Parameter
OK
Compute
Cancel
Help
Console
397 elemen
220 elemen
191 elemen
165 elemen
171 elemen
219 elemen
599 elements between 0.90548548 and 1 (16.219875 %)
0 elements above 1 (0 %)
0 elements below 0.054854766 (0 %)
1377 elements between 0.054854766 and 0.14936929 (13.452521 %)
1815 elements between 0.14936929 and 0.24388381 (17.731536 %)
1795 elements between 0.24388381 and 0.33839834 (17.536147 %)
1160 elements between 0.33839834 and 0.43291286 (11.332552 %)
745 elements between 0.43291286 and 0.52742738 (7.2782337 %)
677 elements between 0.52742738 and 0.62194191 (6.6139117 %)
519 elements between 0.62194191 and 0.71645643 (5.07034 %)
455 elements between 0.71645643 and 0.81097095 (4.4450957 %)
463 elements between 0.81097095 and 0.90548548 (4.5232513 %)
1230 elements between 0.90548548 and 1 (12.016413 %)
0 elements above 1 (0 %)
Volume-Average ()
solid 0.25876971
ANSYS 2019 R3 ACADEMIC
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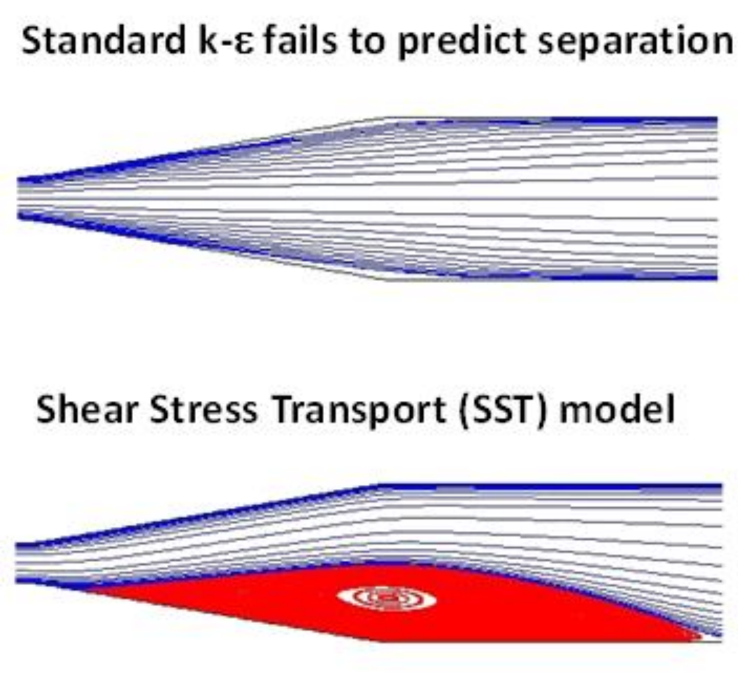
CFD Setup – Turbulence Models



- **Turbulence Model**: The **SST k-ω turbulence model** was chosen for its ability to handle **boundary layers** and **flow separation** accurately, especially near critical areas like the **wing-fuselage junction**.
- Wide Usage in Aircraft Design: The SST k-ω model is a well-established choice in the aerospace industry, particularly in external aerodynamics and aircraft design studies. Its robust prediction capabilities for flow separation, shock waves, and boundary layer behaviors are critical in ensuring the accuracy of the simulations.

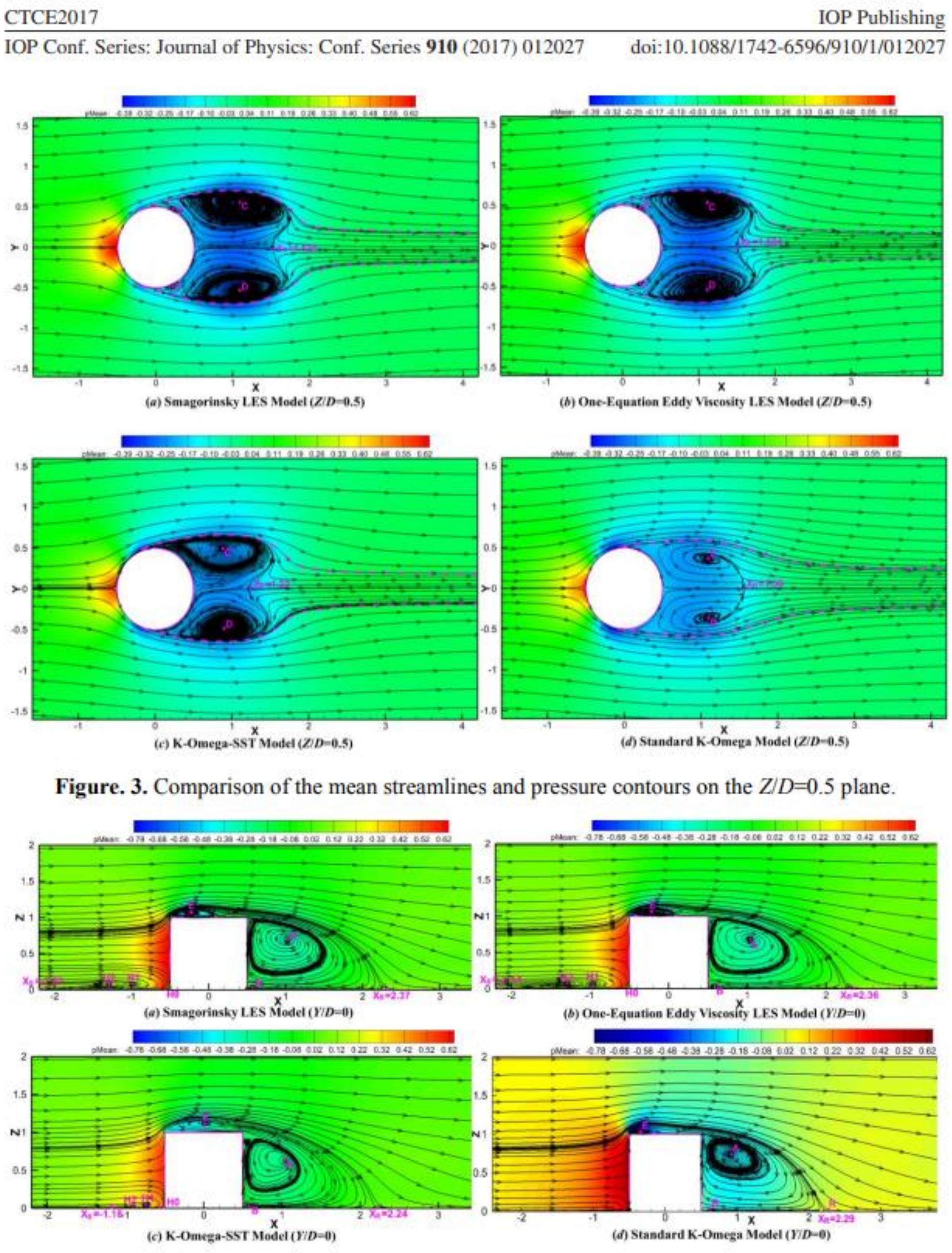
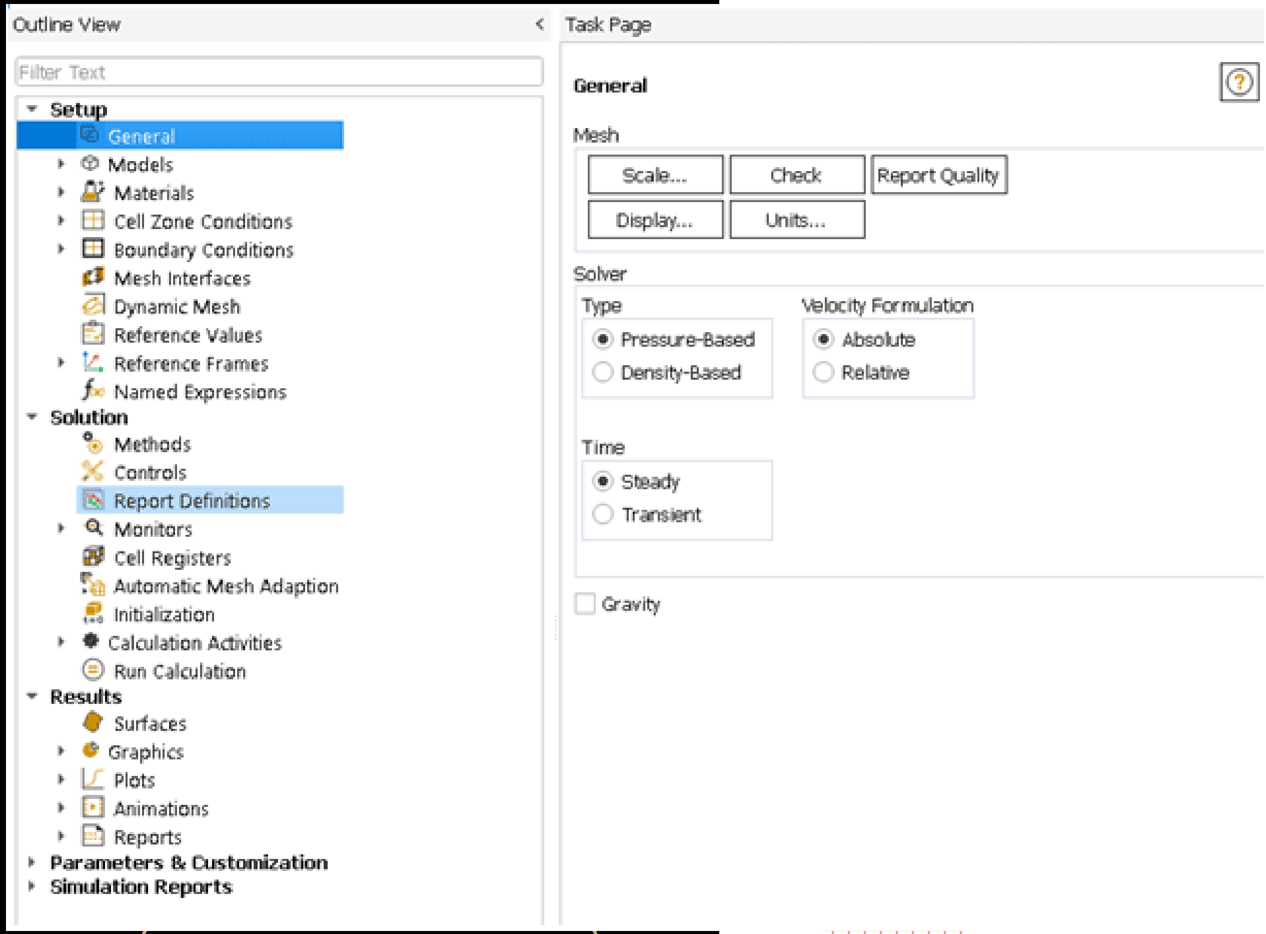

CTCE2017 IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series **910** (2017) 012027 doi:10.1088/1742-6596/910/1/012027

Figure. 3. Comparison of the mean streamlines and pressure contours on the *Z*/*D*=0.5 plane.

CFD Setup – Turbulence Models

- **Why SST k-ω?**
  - It combines the best aspects of the **k-ε** and **k-ω** models, offering accurate **near-wall treatment** while maintaining stability in **far-field regions**.
  - This model is widely used in aircraft design because it provides reliable predictions of **aerodynamic behavior**, even in regions where **flow separation** occurs (such as high angles of attack).



Boundary Conditions and Solver Settings

- **Boundary Conditions**:
  - **Inlet**: For takeoff, a **Velocity Inlet** was used to simulate subsonic flows. During cruise, a **Mach Number Inlet** was used to simulate transonic conditions.
  - **Outlet**: A **Pressure Outlet** was applied with ambient atmospheric conditions.
  - **Walls**: **No-Slip Condition** was applied to all surfaces to simulate the realistic interaction between the airflow and the aircraft surface.
  - **Far-Field Boundaries**: A **Pressure Far Field** was used to simulate the aircraft in an infinite domain, ensuring minimal boundary interaction with the flow.

- **Solver Settings**:
  - **Pressure-Based Coupled Solver**: This solver type was chosen to handle the complex flows around the aircraft.
  - **Spatial Discretization**: Second-Order Upwind was used for **pressure**, **momentum**, and **turbulence parameters**, ensuring accurate representation of aerodynamic characteristics.

Statistical Analysis Using ANOVA

ANOVA ANALYSIS TABLE					
Source of Variation	Degrees of Freedom (Df)	Sum of Squares (SS)	Mean Square (MS)	F-value	p-value (Pr(>F))
Aircraft_Type					
Flight_Phase					
Angle_of_Attack					
Speed					
Aircraft_Type (Interaction)					
Residuals					

Purpose of ANOVA: To statistically validate the significance of differences in performance metrics across flight conditions and configurations.

Variables Analyzed:

- Cl/Cd Ratio: Aerodynamic efficiency for different AoAs and flight phases.
- SFC: Fuel efficiency under various conditions.
- Lift and Drag Forces: Impact of flight phase and AoA on aerodynamic forces.

ANOVA Setup:

- Factors: Aircraft type, flight phase, angle of attack, and speed.
- Significance Level: Statistical threshold set to determine if differences are meaningful (typically 0.05).

Expected Outcome: Identification of the most influential factors on aerodynamic performance, particularly how BWB compares to conventional designs.

ANOVA - RStudio

File Edit Code View Plots Session Build Debug Profile Tools Help

Go to file/function | Addins | ANOVA

anova for aircraft.R | Untitled1* | anova for aircraft.R

Source on Save | Run | Source

```r
# Load necessary libraries
library(ggplot2)
library(dplyr)
library(tidyr)
library(car)

# Manually create the data frame
data <- data.frame(
  Run = 1:12,
  Aircraft_Type = c("Conventional", "Conventional", "Conventional", "Conventional", "Conventional", "Conventional",
                    "Blended Wing Body", "Blended Wing Body", "Blended Wing Body", "Blended Wing B
  Flight_Phase = c("Takeoff", "Takeoff", "Takeoff", "Cruise", "Cruise", "Cruise",
                   "Takeoff", "Takeoff", "Takeoff", "Cruise", "Cruise", "Cruise"),
  Angle_of_Attack = c(0, 5, 10, 0, 5, 10, 0, 5, 10, 0, 5, 10),
  Speed_knots = c(150, 160, 170, 510, 520, 540, 140, 150, 160, 520, 530, 540),
  Cl_Cd = c(7.5, 8, 7, 17, 16.5, 15, 9, 10, 9.5, 21, 20.5, 19),
  SFC = c(0.58, 0.57, 0.56, 0.55, 0.54, 0.53, 0.57, 0.56, 0.55, 0.52, 0.51, 0.50),
  Lift = c(1125, 1280, 1190, 8670, 8580, 8100, 1260, 1500, 1520, 10920, 10865, 10260),
  Drag = c(20, 20, 24.29, 30, 31.52, 36, 15.56, 15, 16.84, 24.76, 25.85, 28.42)
)

# Convert Angle_of_Attack, Flight_Phase, and Aircraft_Type to factors for ANOVA
data$Angle_of_Attack <- as.factor(data$Angle_of_Attack)
data$Flight_Phase <- as.factor(data$Flight_Phase)
data$Aircraft_Type <- as.factor(data$Aircraft_Type)

# Function to perform and summarize ANOVA
anova_summary <- function(response_var) {
  model <- aov(as.formula(paste(response_var, "~ Aircraft_Type * Flight_Phase * Angle_of_Attack")), data = data)
  summary(model)
```

9:14 | (Top Level) | R Script

Console | Terminal | Background Jobs

R 4.4.1 · ~/ANOVA/

```
>
> # Boxplots for Cl/Cd, SFC, Lift, and Drag by Flight Phase and Aircraft Type
> ggplot(data, aes(x = Flight_Phase, y = Cl_Cd, fill = Aircraft_Type)) +
+   geom_boxplot() +
+   labs(title = "Boxplot of Cl/Cd by Flight Phase and Aircraft Type", x = "Flight Phase", y = "Cl/Cd") +
+   theme_minimal()
>
> ggplot(data, aes(x = Flight_Phase, y = SFC, fill = Aircraft_Type)) +
+   geom_boxplot() +
+   labs(title = "Boxplot of SFC by Flight Phase and Aircraft Type", x = "Flight Phase", y = "SFC (lb/lb/hr)") +
+   theme_minimal()
>
> ggplot(data, aes(x = Flight_Phase, y = Lift, fill = Aircraft_Type)) +
+   geom_boxplot() +
+   labs(title = "Boxplot of Lift by Flight Phase and Aircraft Type", x = "Flight Phase", y = "Lift (L)") +
+   theme_minimal()
>
> ggplot(data, aes(x = Flight_Phase, y = Drag, fill = Aircraft_Type)) +
+   geom_boxplot() +
+   labs(title = "Boxplot of Drag by Flight Phase and Aircraft Type", x = "Flight Phase", y = "Drag (D)") +
+   theme_minimal()
>
```

Environment | History | Connections | Tutorial

Import Dataset | 225 MiB | List

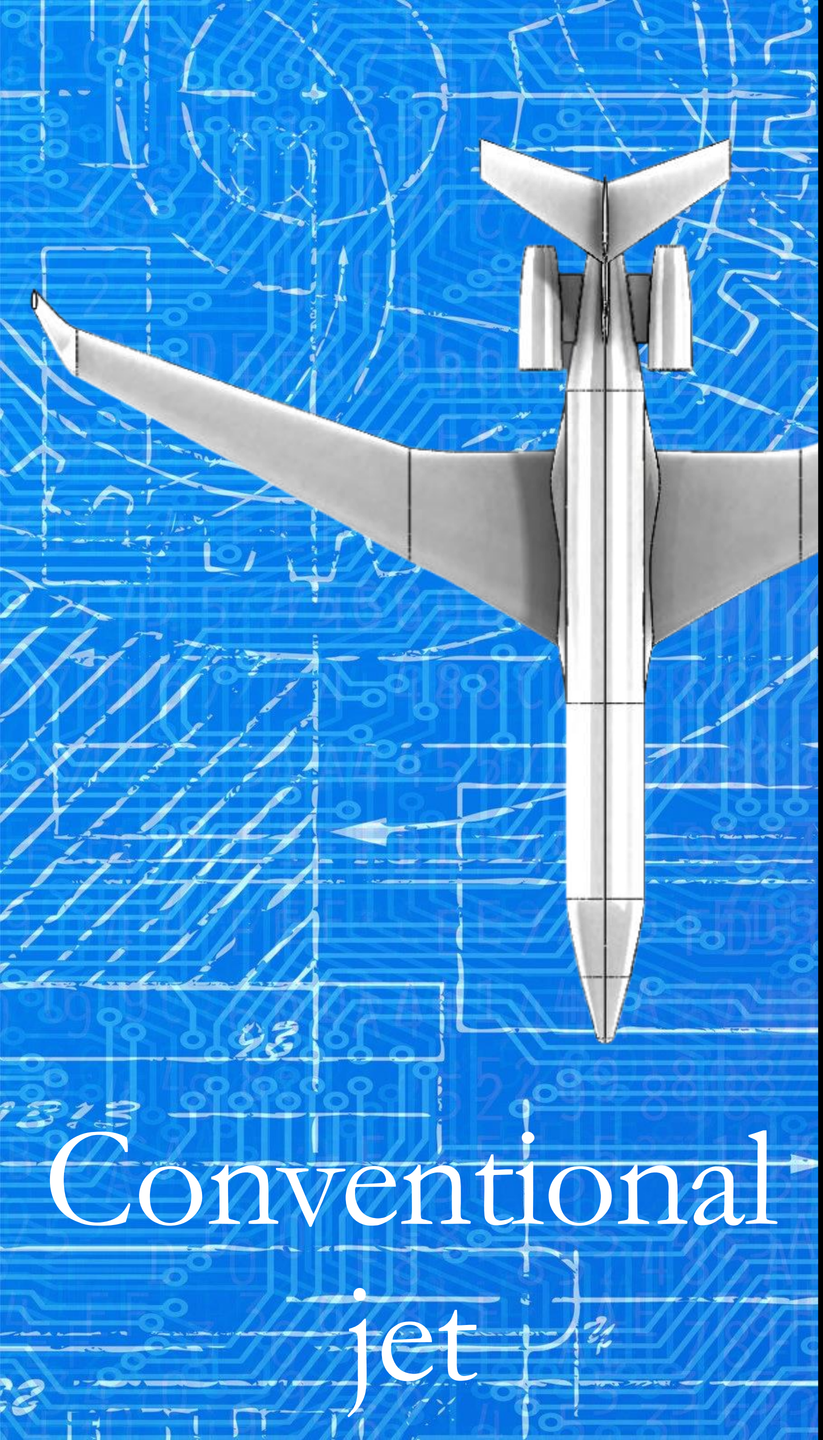
R | Global Environment

Data	
data	12 obs. of 9 variables
Functions	
anova_summary	function (response_var)

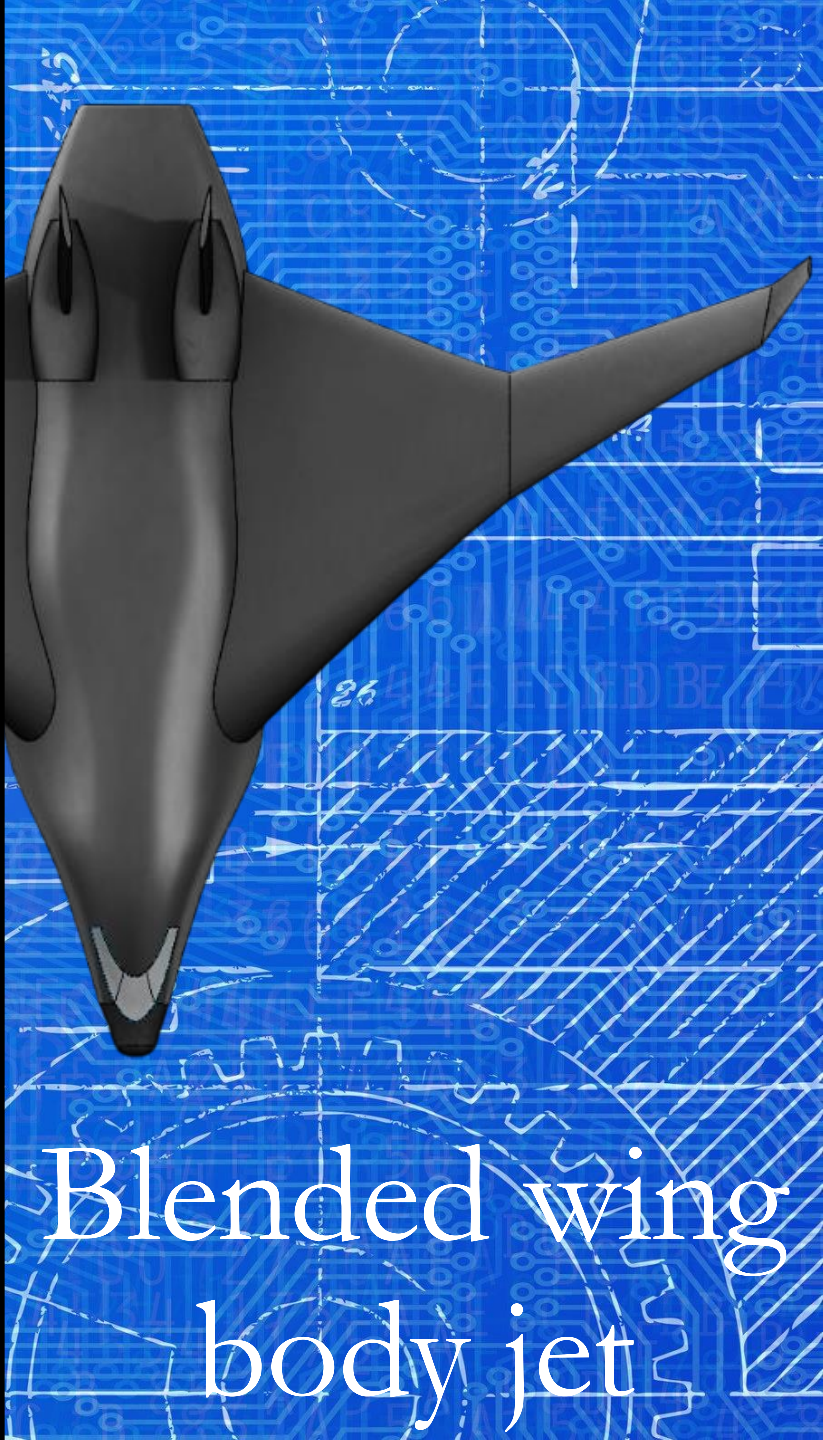
Files | Plots | Packages | Help | Viewer | Presentation

Install | Update

	Name	Description	Version
	User Library		
☐	abind	Combine Multidimensional Arrays	1.4-8
☐	askpass	Password Entry Utilities for R, Git, and SSH	1.2.0
☐	backports	Reimplementations of Functions Introduced Since R-3.0.0	1.5.0
☐	base64enc	Tools for base64 encoding	0.1-3
☐	broom	Convert Statistical Objects into Tidy Tibbles	1.0.7
☐	bslib	Custom 'Bootstrap' 'Sass' Themes for 'shiny' and 'rmarkdown'	0.8.0
☐	cachem	Cache R Objects with Automatic Pruning	1.1.0
☑	car	Companion to Applied Regression	3.1-3
☑	carData	Companion to Applied Regression Data Sets	3.0-5
☐	cli	Helpers for Developing Command Line Interfaces	3.6.3
☐	colorspace	A Toolbox for Manipulating and Assessing Colors and Palettes	2.1-1
☐	cowplot	Streamlined Plot Theme and Plot Annotations for 'ggplot2'	1.1.3
☐	cpp11	A C++11 Interface for R's C Interface	0.5.0
☐	curl	A Modern and Flexible Web Client for R	5.2.3
☐	Deriv	Symbolic Differentiation	4.1.6
☐	digest	Create Compact Hash Digests of R Objects	0.6.37
☐	doBy	Groupwise Statistics, LSmeans, Linear Estimates, Utilities	4.6.24
☑	dplyr	A Grammar of Data Manipulation	1.1.4
☐	evaluate	Parsing and Evaluation Tools that Provide More Details than the Default	1.0.0
☐	fansi	ANSI Control Sequence Aware String Functions	1.0.6
☐	farver	High Performance Colour Space Manipulation	2.1.2
☐	fastmap	Fast Data Structures	1.2.0
☐	fontawesome	Easily Work with 'Font Awesome' Icons	0.5.2
☐	Formula	Extended Model Formulas	1.2-5



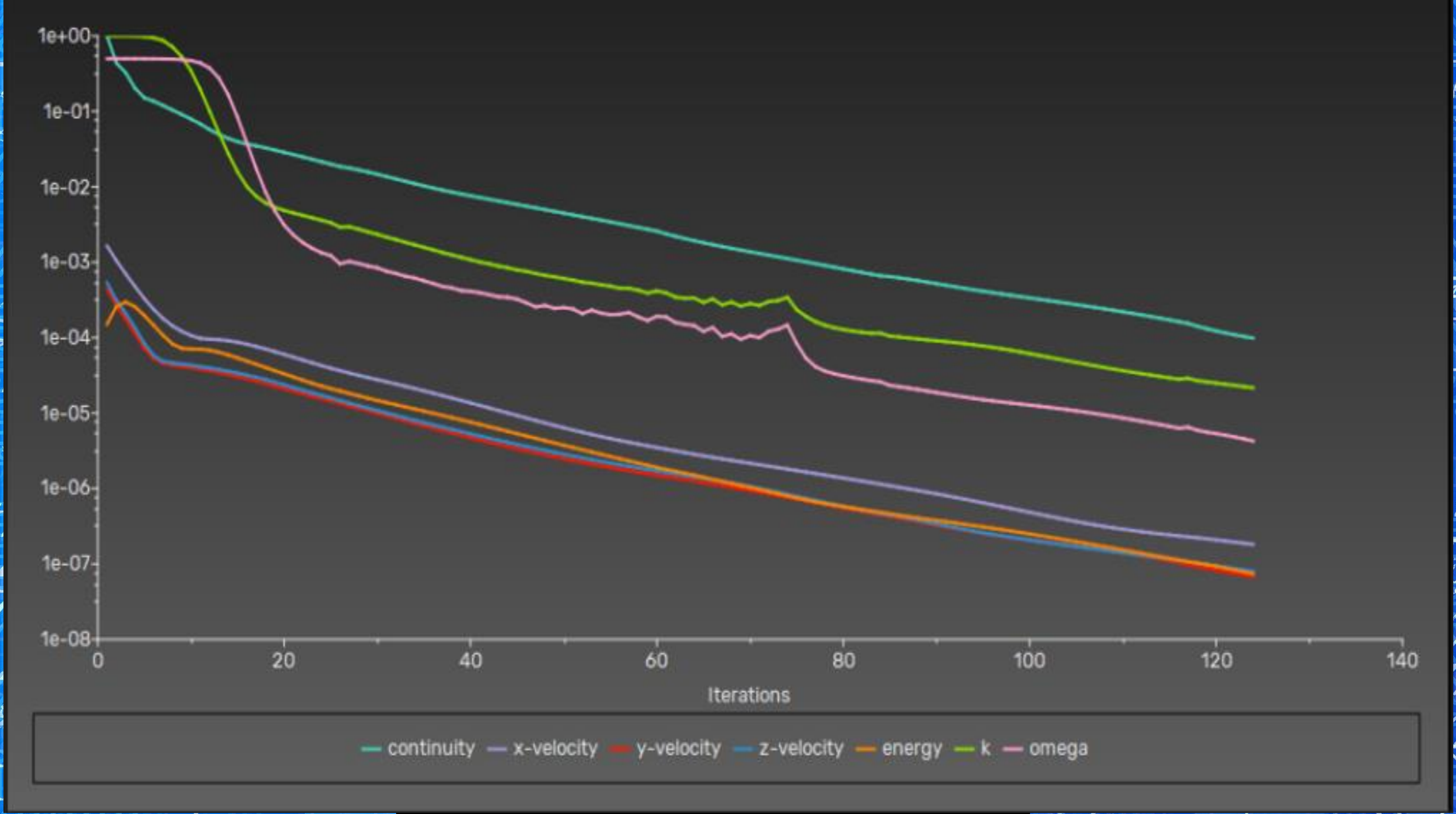
Results



Conventional jet

vs

Blended wing body jet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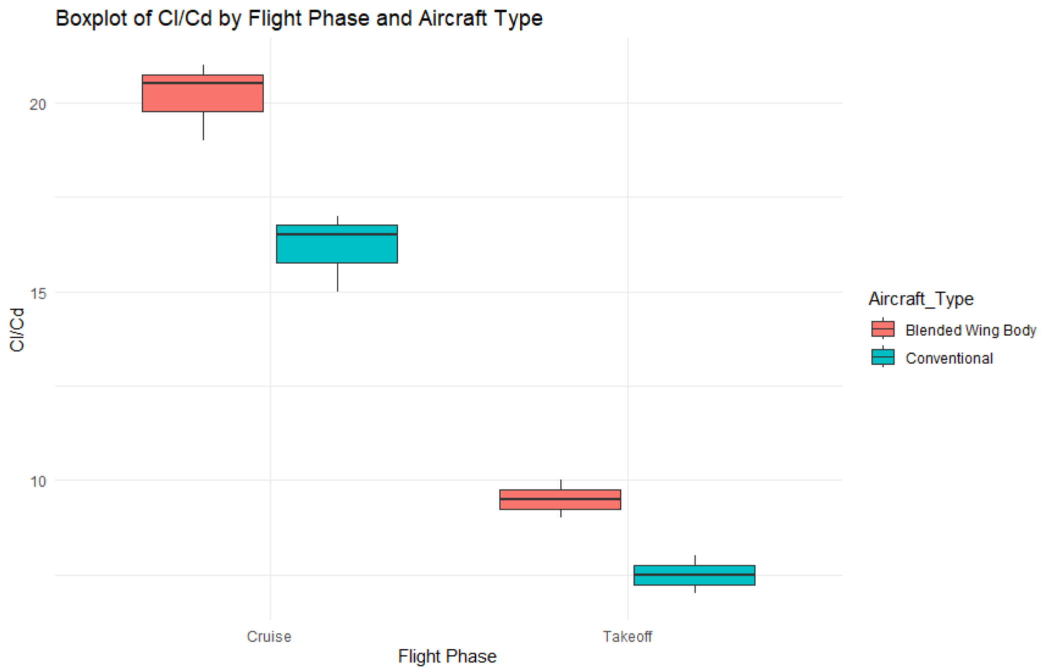
Residuals

CFD Results: Lift-to-Drag Ratio (Cl/Cd)

Result table after all the experimental analysis

Run	Aircraft type	Flight Phase	Angle of Attack	Speed (Knots)	CL/CD	SFC	Lift	Drag
1	Conventional	Take-off	0°	150	7.5	0.58	1125	20
2	Conventional	Take-off	5°	160	8	0.57	1280	20
3	Conventional	Take-off	10°	170	7	0.56	1190	24.29
4	Conventional	Cruise	0°	510	17	0.55	8670	30
5	Conventional	Cruise	5°	520	16.5	0.54	8580	31.52
6	Conventional	Cruise	10°	540	15	0.53	8100	36
7	BWB	Take-off	0°	150	9	0.57	1260	15.56
8	BWB	Take-off	5°	160	10	0.56	1500	15
9	BWB	Take-off	10°	170	9.5	0.55	1520	16.84
10	BWB	Cruise	0°	520	21	0.52	10920	24.76
11	BWB	Cruise	5°	530	20.5	0.51	10865	25.85
12	BWB	Cruise	10°	540	19	0.5	10260	28.42



Objective: Compare the aerodynamic efficiency of the conventional and BWB configurations in terms of Cl/Cd ratio.

Results:

- Conventional Jet: Achieved a maximum Cl/Cd of 17 during cruise at 0° AoA and 510 knots.
- BWB Jet: Achieved a higher maximum Cl/Cd of 21 at 0° AoA and 520 knots during cruise, indicating superior efficiency.

Analysis: BWB's higher Cl/Cd ratio suggests better lift generation relative to drag, making it more fuel-efficient, particularly in cruise conditions.

Conclusion: BWB configuration is aerodynamically more efficient than the conventional design, especially at lower angles of attack.

Result table after all the experimental analysis

Run	Aircraft type	Flight Phase	Angle of Attack	Speed (Knots)	CL/CD	SFC	Lift	Drag
1	Conventional	Take-off	0°	150	7.5	0.58	1125	20
2	Conventional	Take-off	5°	160	8	0.57	1280	20
3	Conventional	Take-off	10°	170	7	0.56	1190	24.29
4	Conventional	Cruise	0°	510	17	0.55	8670	30
5	Conventional	Cruise	5°	520	16.5	0.54	8580	31.52
6	Conventional	Cruise	10°	540	15	0.53	8100	36
7	BWB	Take-off	0°	150	9	0.57	1260	15.56
8	BWB	Take-off	5°	160	10	0.56	1500	15
9	BWB	Take-off	10°	170	9.5	0.55	1520	16.84
10	BWB	Cruise	0°	520	21	0.52	10920	24.76
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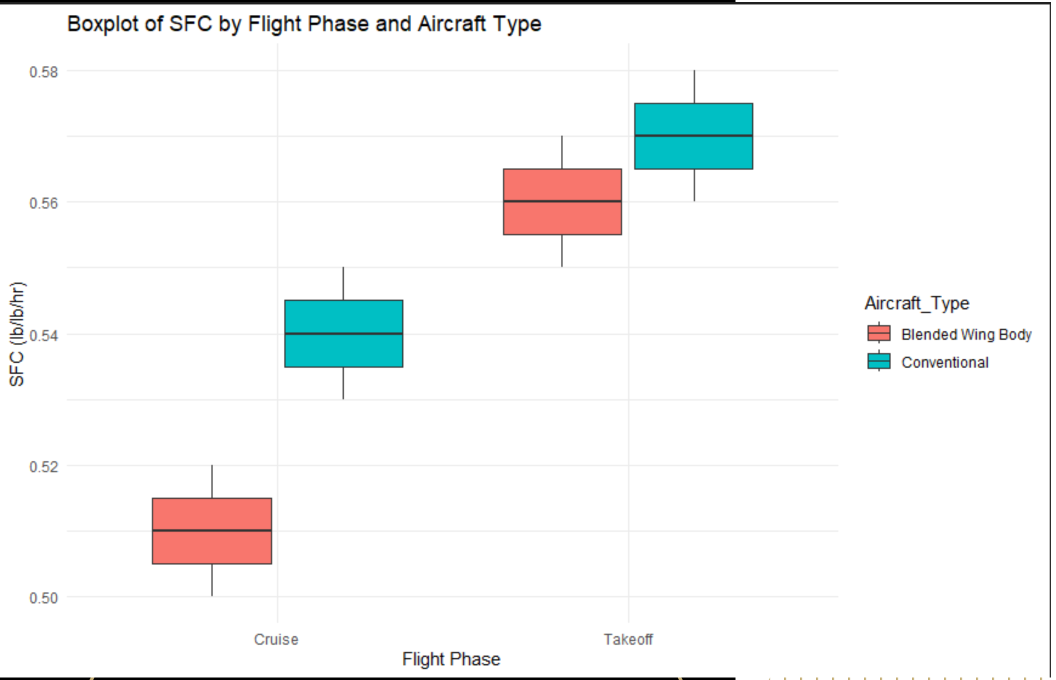


CFD Results: Specific Fuel Consumption (SFC)

Objective: Evaluate the fuel efficiency of both designs by analyzing SFC across flight conditions.

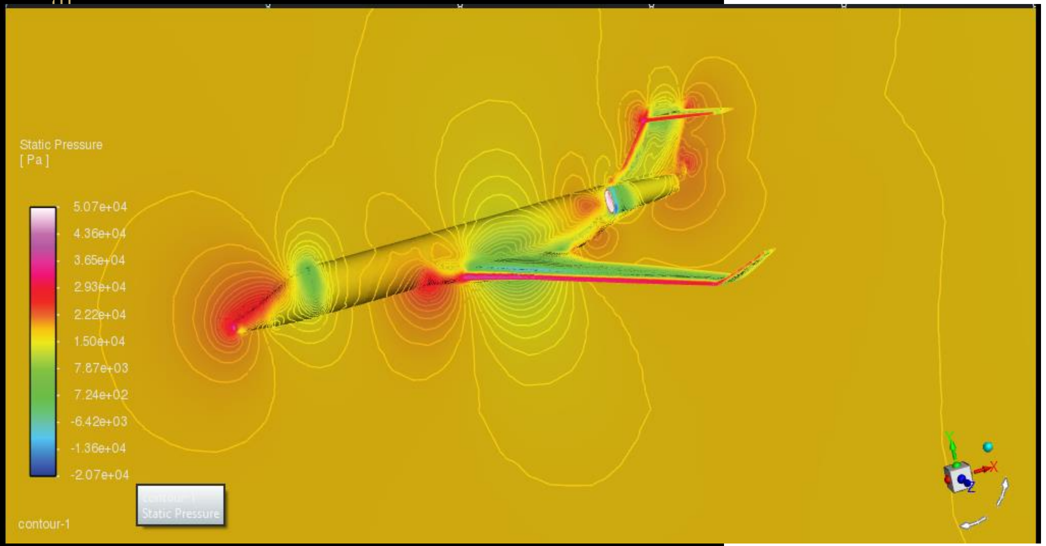
Results:

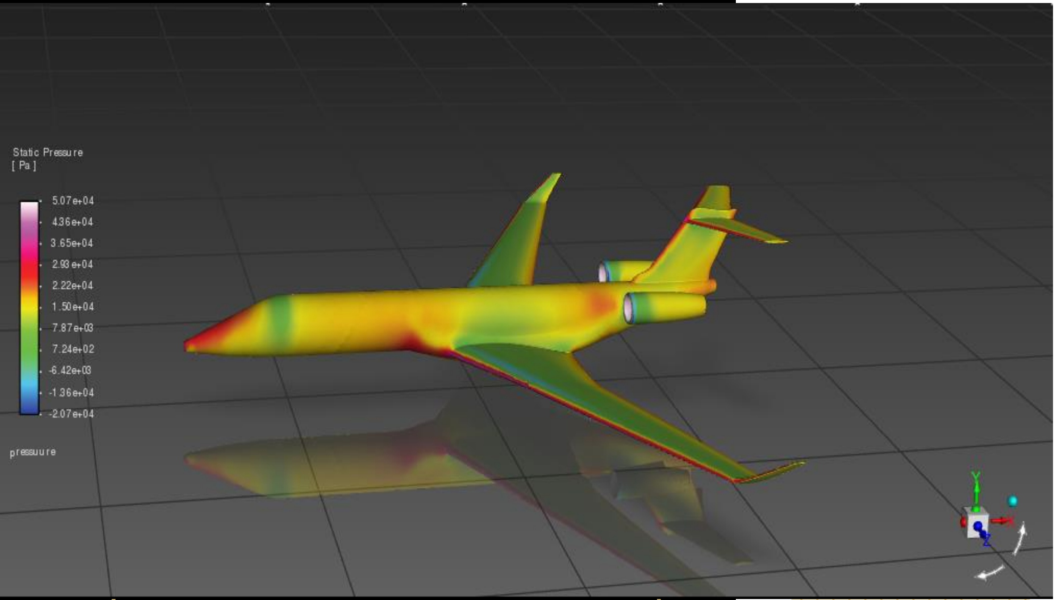
- Conventional Jet: SFC ranged from 0.53 to 0.60 lb/lb/hr across various angles and speeds, with the lowest SFC at 5° AoA and 520 knots during cruise.
- BWB Jet: Demonstrated lower SFC, ranging from 0.50 to 0.55 lb/lb/hr, with the minimum SFC observed at 5° AoA and 530 knots.

Analysis: BWB design shows a 6-8% improvement in fuel efficiency over the conventional jet due to its aerodynamic advantages.

Conclusion: The BWB configuration offers significant fuel savings, aligning with goals for sustainable, long-range business jets.

CFD Results: Pressure Contour - Conventional Jet





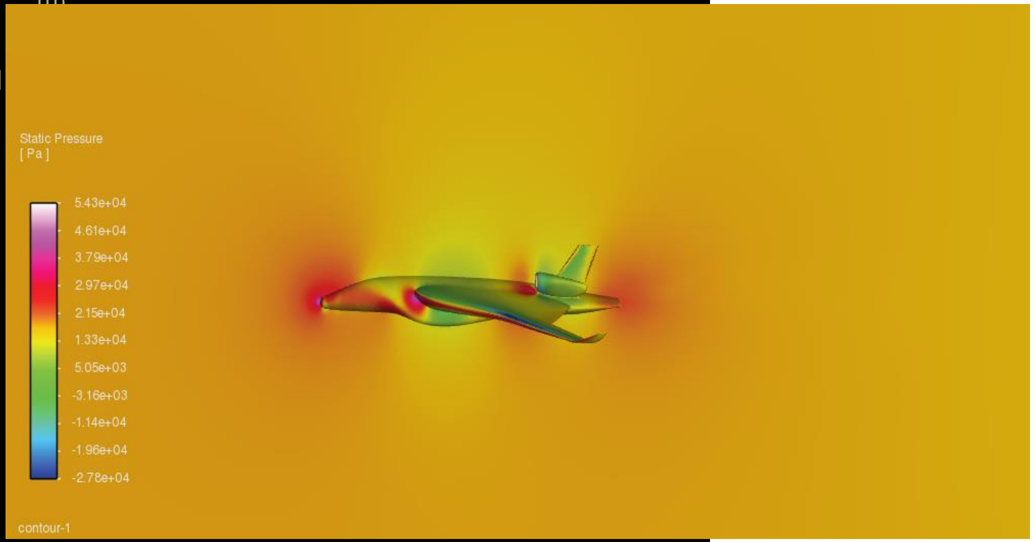
Objective: Visualize and analyze the static pressure distribution around the conventional jet.

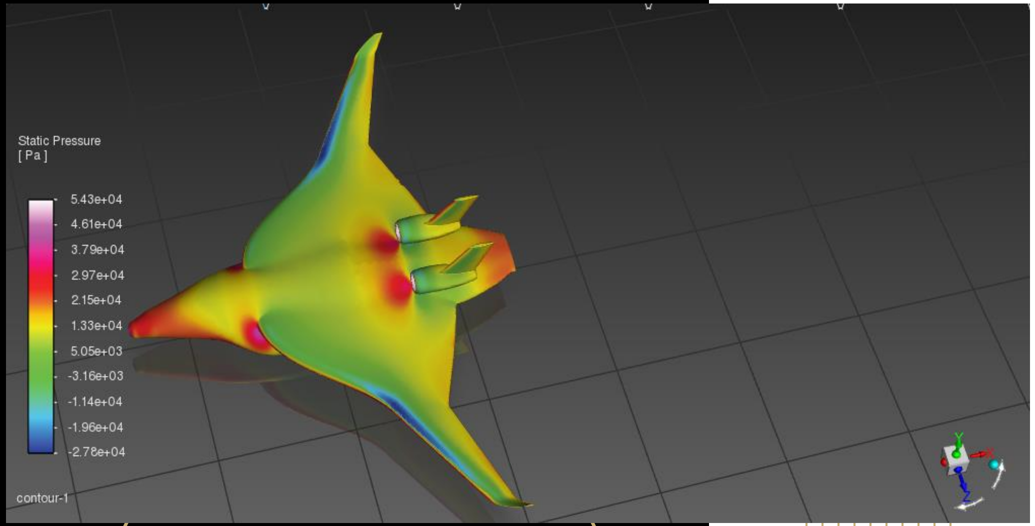
Observations:

- High-pressure regions concentrated around the nose and wing leading edges, indicating areas of lift generation.
- Smooth pressure gradient along the fuselage, contributing to stability at cruise speeds.
- Distinct pressure changes near engine nacelles, which slightly increases drag.

Conclusion: Conventional design has a predictable pressure distribution that supports stability but faces localized drag increases due to protruding engines.

CFD Results: Pressure Contour - Blended Wing Body (BWB) Jet





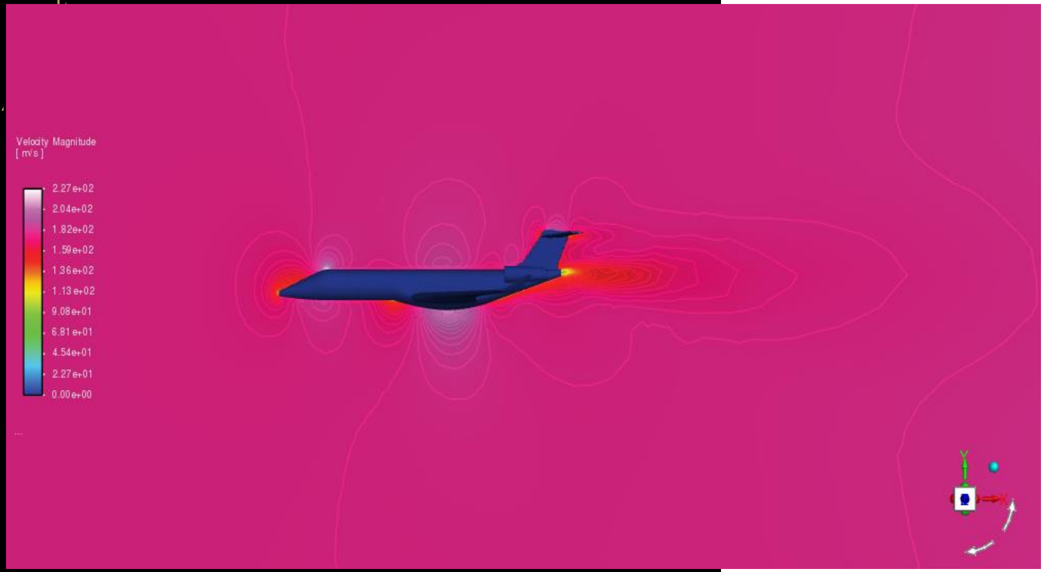
Objective: Visualize and analyze the static pressure distribution around the BWB jet.

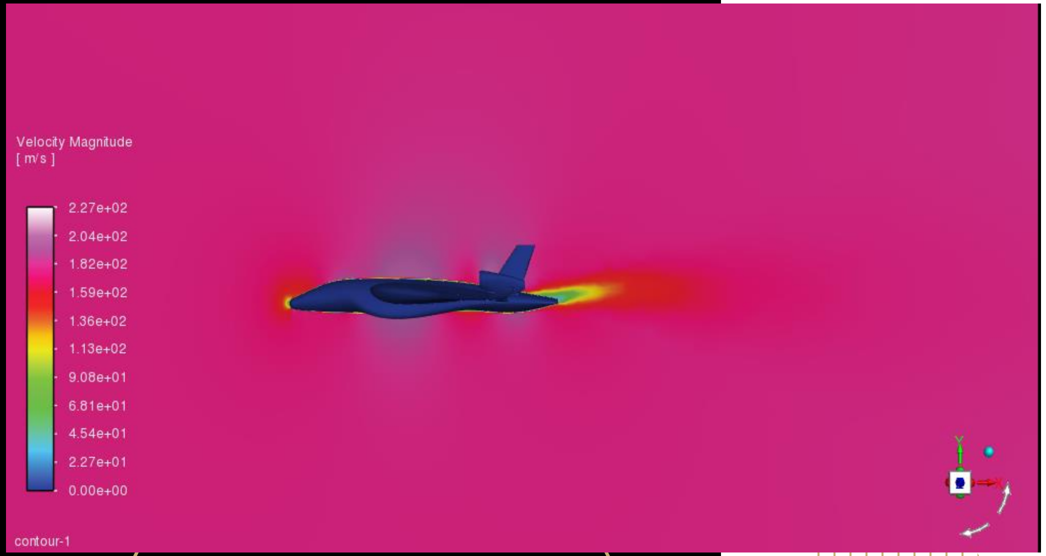
Observations:

- High-pressure zones along the nose and wing roots, smoothly transitioning to low-pressure zones over a wider surface area.
- Reduced pressure peaks around embedded engines, minimizing drag and noise.
- Overall smoother pressure distribution compared to conventional design, which contributes to lower drag and better fuel efficiency.

Conclusion: BWB design shows a more aerodynamically efficient pressure distribution, reducing form and induced drag.

CFD Results: Velocity Contour Comparison





Objective: Compare the airflow and velocity distribution around the conventional and BWB jets.

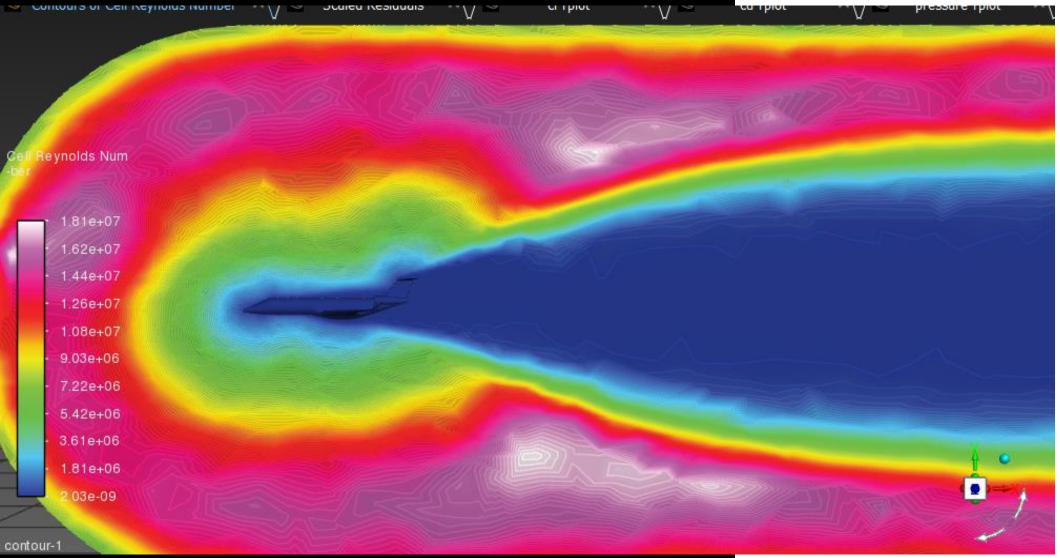
Observations for Conventional Jet:

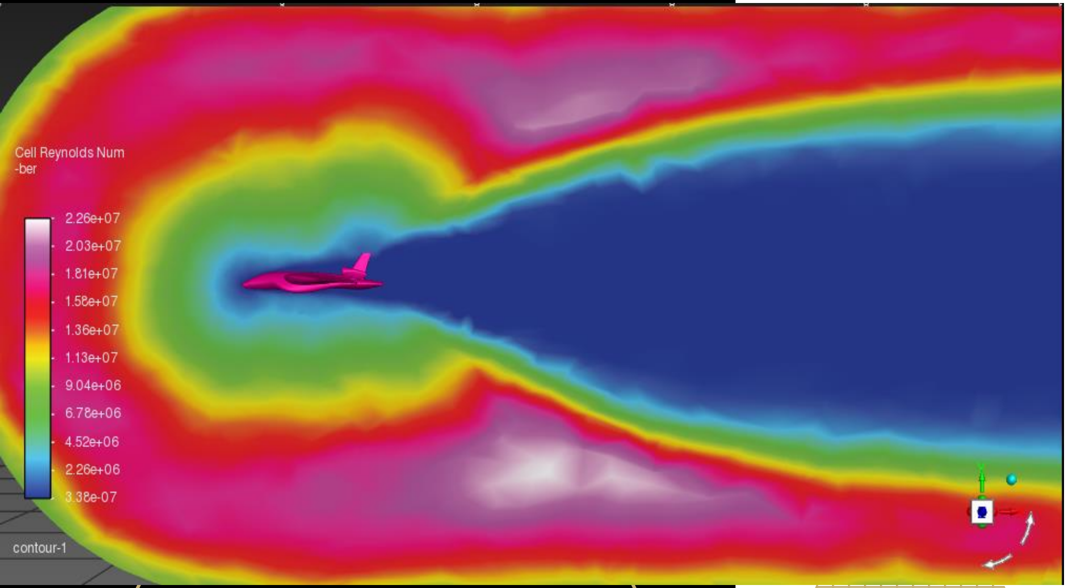
- High-velocity zones concentrated along the wing leading edges and trailing edges.
- Slightly turbulent wake behind the engines, which increases drag.

Observations for BWB Jet:

- Smoother velocity distribution across the wing-body structure.
- Laminar flow sustained over a larger area, resulting in less wake turbulence and lower parasitic drag.

Conclusion: BWB design demonstrates superior airflow characteristics, with minimized turbulence and drag, enhancing aerodynamic efficiency.Visuals: Side-by-side comparison of velocity contour images for conventional and BWB jets, highlighting areas of turbulence and laminar flow.





CFD Results: Cell Reynold's Number Comparison

Conventional Jet:

- The high Reynolds numbers are concentrated near the fuselage and wings.
- The presence of high Reynolds numbers near the surface says there was predominantly laminar flow with a controlled transition to turbulent in selected regions.
- Controlled, turbulent flow along wing trailing edges and around the engine nacelles enhances aerodynamic stability with simultaneous reduction of skin friction drag. This distribution enhances efficiency in conventional jets because of reduced boundary layer separation and drag.

BWB Jet:

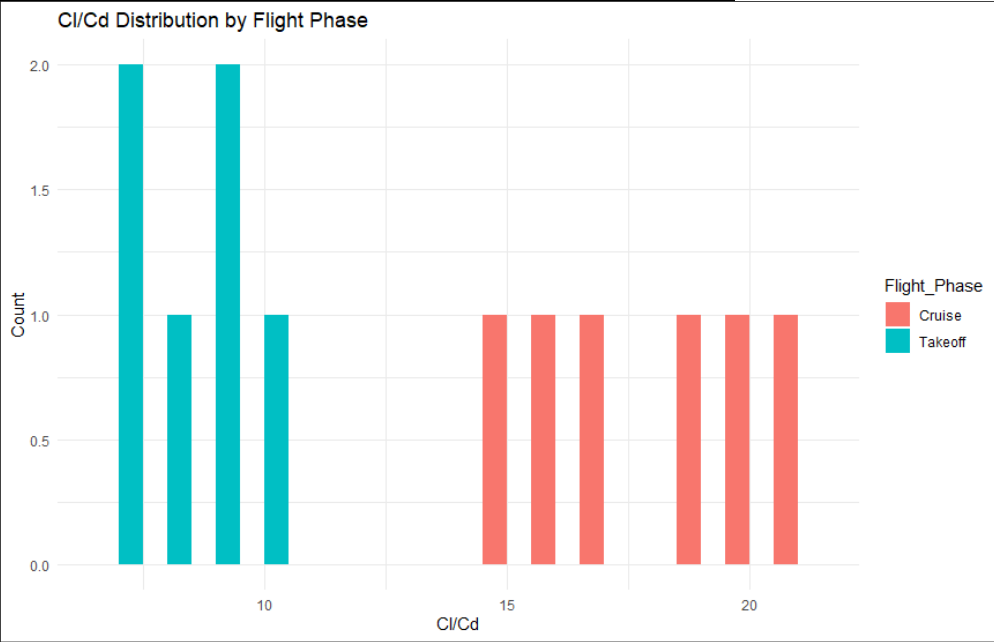
- Locally high Reynolds numbers around the fuselage and wing roots point out zones of laminar flow transitioning into turbulent flow in a controlled manner.
- The aerodynamically streamlined body shape ensures that transition points are predictable and confined only to certain areas; hence, the skin friction drag remains small.
- The Reynolds number contours around the tail section and outer wing areas seem to have indicated that boundary layer development was being managed by the BWB design, further enhancing aerodynamic efficiency by reducing separation zones.

Conclusion: The BWB configuration's cell Reynolds numbers indicate a more refined mesh in complex geometry areas, resulting in more accurate CFD predictions. Both configurations meet the recommended Re *cell* threshold for reliable simulation results.

Anova Results for CL/CD

Anova Results for CL/CD

Source	Df	Sum Sq	Mean Sq
Aircraft_Type	1	27.0	27.0
Flight_Phase	1	280.33	280.33
Angle_of_Attack	2	3.04	1.52
Aircraft_Type	1	3.0	3.0
Aircraft_Type	2	0.13	0.06
Flight_Phase	2	2.04	1.02
Aircraft_Type:Flight_Phase	2	0.13	0.06

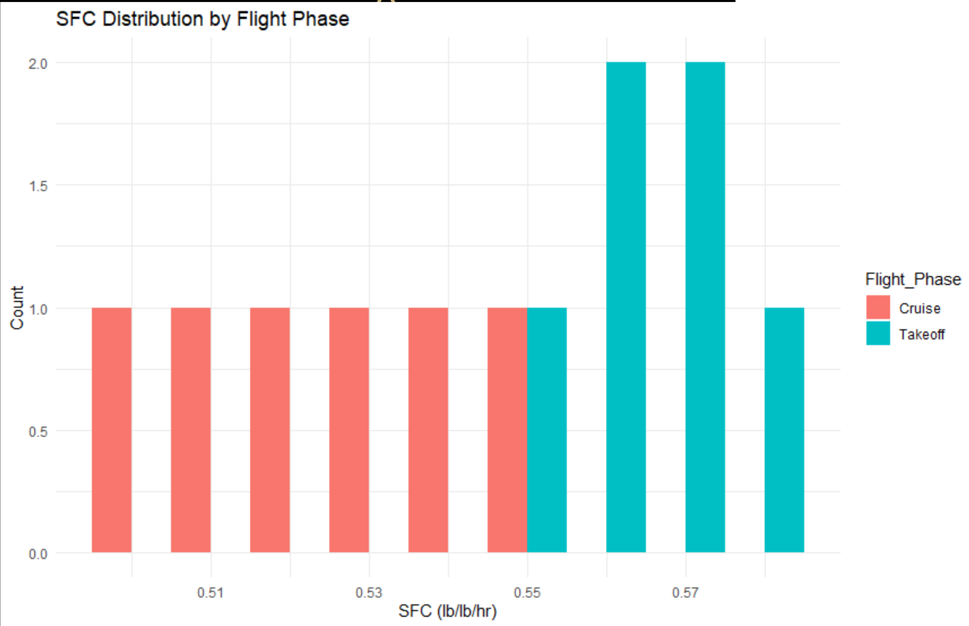


This shows the highest Sum of Squares belongs to Flight Phase (280.33), therefore it is the most influential variable on Cl/Cd. That means there are substantial differences in aerodynamic efficiency, expressed as Cl/Cd, in respect to flight phase between takeoff and cruise phase. Aircraft Type also influences Cl/Cd but much less (Sum Sq = 27.00). Attack Angle and interaction terms like Aircraft_Type have the smaller magnitude of Sum Sq, which indicates, for example, that the influence of this factor on Cl/Cd is not as strong as the main effect of Flight Phase.

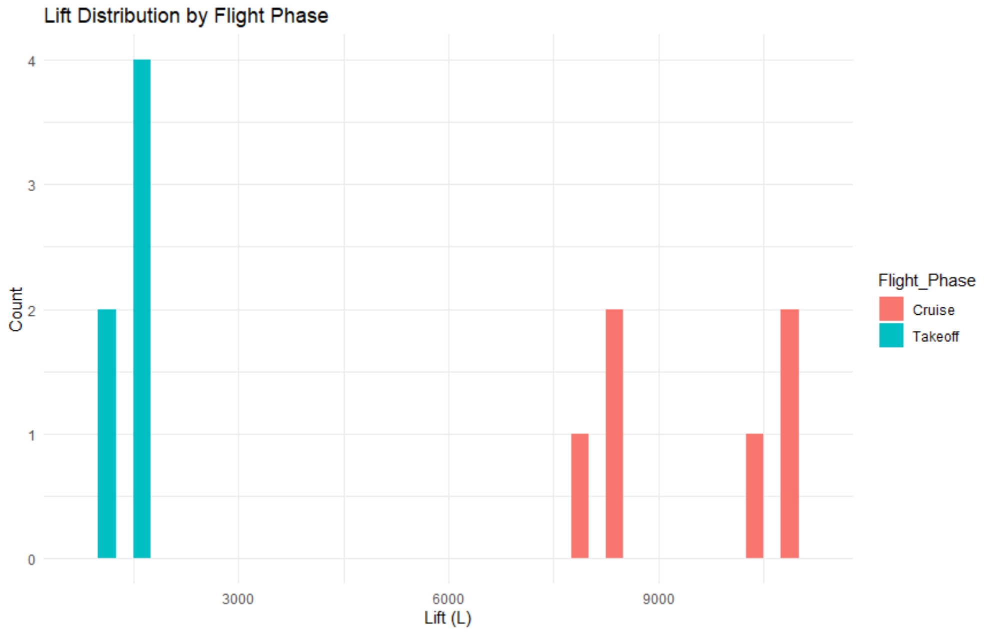
Anova Results for SFC

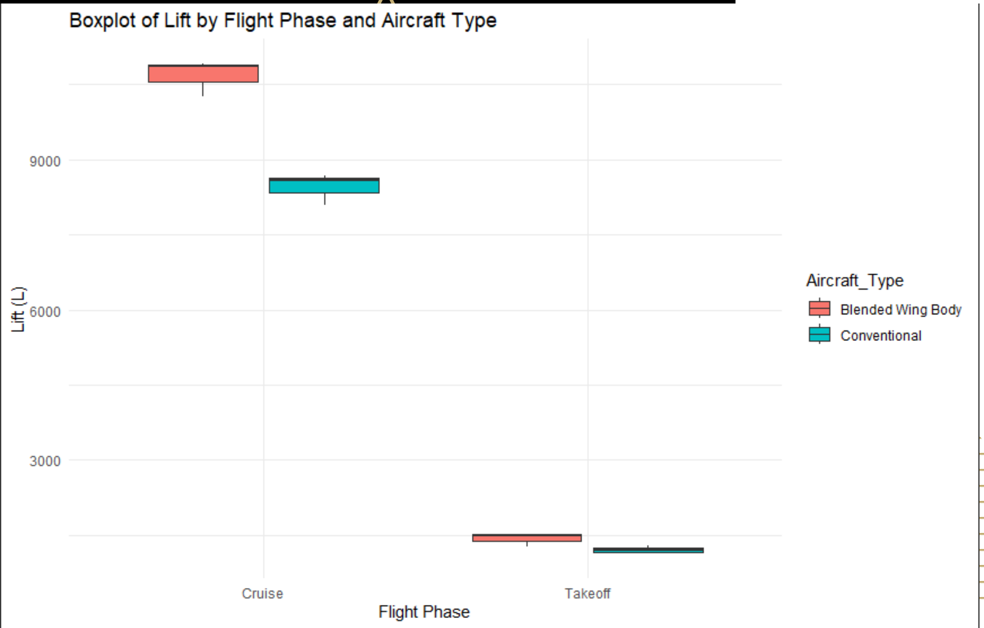
Anova Results for SFC

Source	Df	Sum Sq	Mean Sq
Aircraft_Type	1	0.0012	0.0012
Flight_Phase	1	0.0048	0.0048
Angle_of_Attack	2	0.0008	0.0004
Aircraft_Type	1	0.0003	0.0003
Aircraft_Type	2	0.0	0.0
Flight_Phase	2	0.0	0.0
Aircraft_Type:Flight_Phase	2	0.0	0.0



This shows the highest effect on SFC is due to Flight Phase: Sum Sq = 0.0048, which indicates that the fuel economy is very different between takeoff and cruise. This is followed by Aircraft Type with Sum Sq = 0.0012. Other terms like Angle of Attack and interaction effects are negligible for SFC.



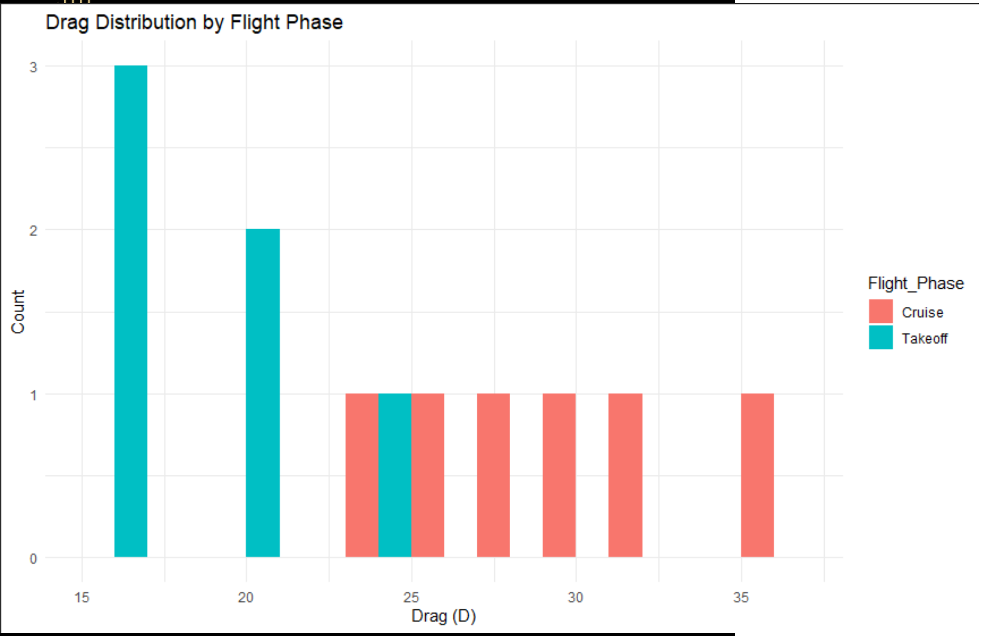


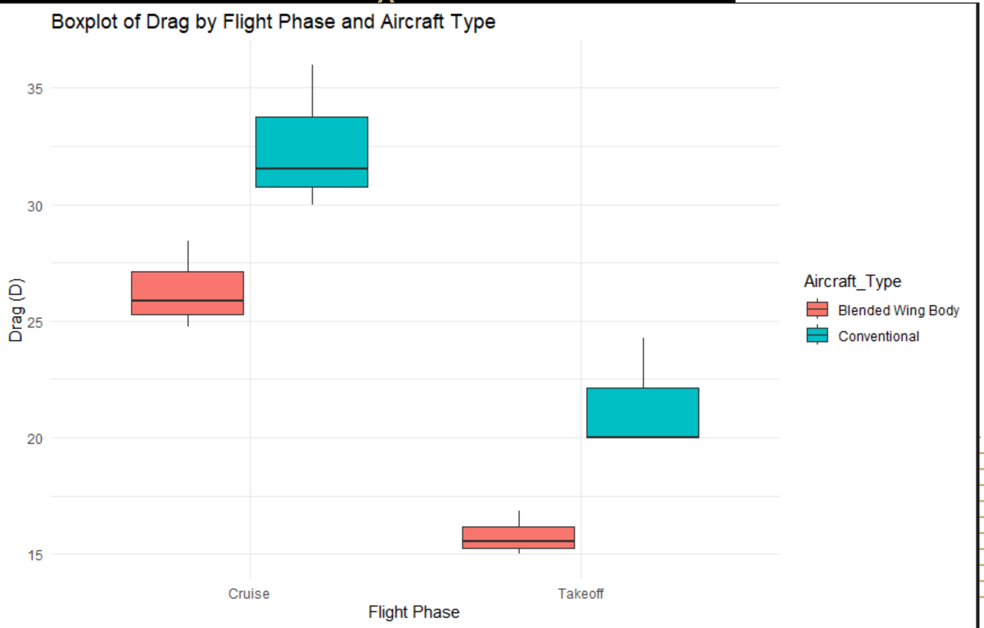
Anova Results for lift

Anova Results for lift

Source	Df	Sum Sq	Mean Sq
Aircraft_Type	1	4538700	4538700
Flight_Phase	1	204352533	204352533
Angle_of_Attack	2	184629	92315
Aircraft_Type	1	3010008	3010008
Aircraft_Type	2	2138	1069
Flight_Phase	2	311654	155827
Aircraft_Type:Flight_Phase	2	11579	5790

- This shows Flight Phase has a highly significant effect on Lift: Sum Sq = 204,352,533 - this reflects that there is an extremely large variability in lift between takeoff and cruise phase. Aircraft Type is also highly influential on lift: Sum Sq = 4,538,700, suggesting lift is highly different between conventional and BWB configurations. Angle of Attack has less of an impact on lift but is relevant, especially in its interaction with Flight Phase.





Anova Results for drag

Anova Results for drag

Source	Df	Sum Sq	Mean Sq
Aircraft_Type	1	104.3	104.3
Flight_Phase	1	350.6	350.6
Angle_of_Attack	2	34.2	17.1
Aircraft_Type	1	0.2	0.2
Aircraft_Type	2	4.1	2.0
Flight_Phase	2	2.3	1.2
Aircraft_Type:Flight_Phase	2	0.1	0.0

- This shows The flight phases, again, are highly significant, Sum Sq = 350.6, suggesting there is a significant difference in drag between takeoff and cruise. Aircraft Type also affects drag significantly, Sum Sq = 104.3, pointing out the amount of difference that exists between the conventional and BWB configurations due to each's level of drag. Angle of Attack impacts the third most but far less than the magnitude of flight phase and aircraft type on drag variation.

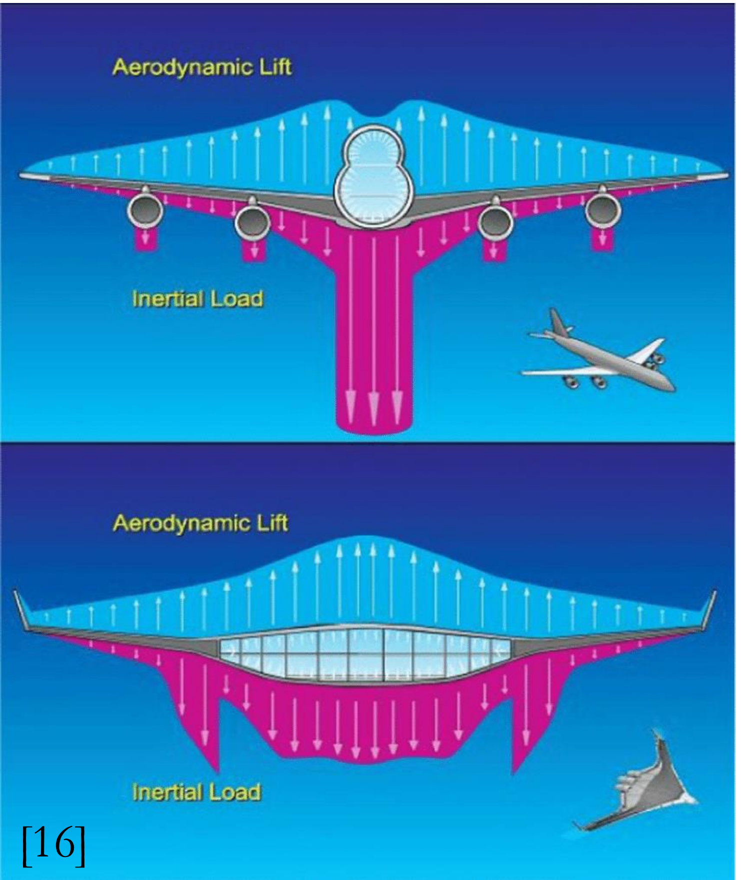
$$\text{Wing Loading} = \frac{MTOW}{S}$$

For the **Conventional Jet** with an MTOW of 80,000 kg and wing area of 950 square feet (88.26 m^2), the wing loading is approximately:

$$\text{Wing Loading}_{\text{Conventional}} = \frac{80000 \times 9.81}{88.26} \approx 8,885 \, N/m^2$$

For the **BWB Jet**, with an MTOW of 85,000 kg and a larger wing area of 2,100 square feet (195.1m^2):

$$\text{Wing Loading}_{BWB} = \frac{85000 \times 9.81}{195.1} \approx 4,272 \, N/m^2$$



[16]

Structural Efficiency Comparison

Objective: Compare the structural efficiency of the conventional and BWB configurations, focusing on weight distribution, wing loading, and structural integrity.

Conventional Jet:

- Weight Distribution: Concentrated in the fuselage and wing root.
- Wing Loading: Higher loading at wing roots, requiring additional structural reinforcement.
- Structural Integrity: Stable but adds weight due to separate fuselage and wing structure.

BWB Jet:

- Weight Distribution: More evenly spread across the integrated wing-body structure.
- Wing Loading: Distributed wing loading reduces the need for heavy reinforcement, enhancing fuel efficiency.
- Structural Integrity: Efficient use of materials allows for lighter and stronger structural elements.

Conclusion: BWB configuration demonstrates superior structural efficiency due to distributed wing loading and weight, allowing for reduced material use and enhanced performance.

Passenger Comfort Features

Objective: Examine passenger comfort features and interior space in both configurations.

Conventional Jet:

- Cabin Layout: Linear cabin with limited headroom near windows.
- Noise Levels: Engines positioned at the rear reduce cabin noise but may still impact rear seating.
- Comfort: Traditional layout offers familiar cabin experience but is limited in customization options.

BWB Jet:

- Cabin Layout: Wide cabin allows for more flexibility in seating arrangements and increased headroom.
- Noise Reduction: Embedded engines reduce external noise, providing a quieter cabin environment.
- Comfort: Spacious cabin with potential for innovative layouts and amenities for luxury business travel.Conclusion: BWB design offers superior passenger comfort features due to its wider cabin and reduced noise levels.

Market Feasibility Analysis

Objective: Assess the market feasibility of adopting BWB design in the business jet market.

Conventional Jet:

- Current Market Acceptance: Widely accepted with well-established infrastructure and maintenance protocols.
- Operational Costs: Proven efficiency but may face limitations in meeting future fuel economy standards.
- Market Feasibility: High due to existing demand and established reputation in business aviation.

BWB Jet:

- Future Market Potential: Novel design offers higher fuel efficiency and aligns with sustainable aviation goals.
- Operational Costs: Reduced fuel consumption could lower operational costs, making it attractive for long-haul business flights.
- Market Feasibility: Growing interest in fuel-efficient, sustainable designs, but requires infrastructure adjustments and pilot retraining.

Conclusion: BWB jet design has strong potential in the long-term business jet market due to its efficiency, though it faces entry barriers.

Limitations and Assumptions

- **Computational Resources Limitations**:
  - Simulations were conducted using **steady-state models**, which provide a snapshot of aerodynamic performance under specific conditions.
  - **Transient analysis** was not conducted due to computational constraints. However, **steady-state analysis** is sufficient to capture key aerodynamic metrics such as **L/D ratio** and **drag**.
- **Modeling Assumptions**:
  - **Ideal Gas Assumption**: Air was modeled as an ideal gas, which may introduce minor inaccuracies in **compressibility effects** at **high subsonic speeds**.
  - **Simplified Geometry**: Certain features, such as **landing gear**, were not included in the simulation to reduce complexity and computational load.
  - **Boundary Layer Assumptions**: Boundary layers were modeled using **enhanced wall functions**, with **y+ values** close to 1, ensuring accurate near-wall flow modeling.

Conclusion

Key Findings:

- Aerodynamic Efficiency: The BWB configuration demonstrated a higher lift-to-drag ratio, particularly in cruise conditions, indicating better aerodynamic efficiency compared to the conventional design.
- Fuel Efficiency: The BWB design showed a lower Specific Fuel Consumption (SFC), resulting in fuel savings of approximately 6-8% over the conventional jet, making it a more sustainable option for long-range flights.
- Structural Efficiency: The distributed weight and wing loading in the BWB design allow for a lighter and more efficient structure, reducing the need for heavy reinforcement and enhancing overall performance.
- Passenger Comfort: The wider cabin and reduced noise levels in the BWB configuration provide an improved passenger experience, offering more space and comfort.
- Market Potential: While the conventional design remains popular and proven, the BWB configuration holds potential for the future of business jets, especially with increasing demand for sustainability and efficiency.

Final Thoughts: The BWB configuration presents significant advantages in terms of fuel efficiency, aerodynamic performance, and passenger comfort, making it a promising candidate for next-generation business aviation. However, challenges in stability and market adaptation must be addressed for successful implementation.

Future Scope

- Control and Stability Improvements: Further research is needed to address the stability challenges in BWB designs, particularly during takeoff and landing phases. Advanced control surface technology and flight control algorithms could enhance maneuverability and safety.
- Real-World Testing and Validation: Future studies should focus on real-world flight testing of BWB configurations to validate CFD results and understand performance under actual flight conditions.
- Sustainable Materials: Research into lightweight, sustainable materials for the BWB structure could further reduce weight and improve fuel efficiency, aligning with environmental goals.
- Infrastructure and Market Adaptation: The aviation industry would need to adapt airport infrastructure, maintenance protocols, and pilot training for the unique requirements of BWB jets.
- Potential Applications Beyond Business Aviation: While this study focused on business jets, the BWB design could be explored for other types of aircraft, such as commercial airliners and military transports, where its fuel efficiency and spacious design would be beneficial.

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Questions?

Thank You