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

Project Report submitted in the partial fulfilment

of

Bachelor of Technology
In
Mechanical Engineering

by

Chaitanya Upadhyay (F053)

Under the supervision of

Zoya Rizvi

(Assistant Professor, Mechanical Engineering, MPSTME)

SVKM's NMIMS University

(Deemed-to-be University)

MUKESH PATEL SCHOOL OF TECHNOLOGY MANAGEMENT & ENGINEERING (MPSTME)

Vile Parle (W), Mumbai-56

(2024-2025)

CERTIFICATE

This is to certify that the project entitled **"Innovative Aerodynamic Design of a Business Jet: A BWB vs Conventional Design's Comparative Analysis Study"**, has been done by **Mr. Chaitanya Upadhyay** under my guidance and supervision & has been submitted in partial fulfilment of the degree of (name of the program) in (name of the stream) of MPSTME, SVKM's NMIMS (Deemed-to-be University), Mumbai, India.

______________ _____________

Project mentor (name and Signature) Examiner (name and Signature)

(Intenal Guide)

Date

Place: Mumbai

____

(HoD) (name and Signature)

ACKNOWLEDGEMENT

I would like to express my heartfelt gratitude to my mentors, Assistant Professor Zoya Rizvi and Dr. Swati Donde, for their invaluable guidance, unwavering support, and continuous encouragement throughout the duration of this project. Their expertise and insights played a pivotal role in shaping the direction of my research and contributed significantly to the successful completion of the project "Innovative Aerodynamic Design of a Business Jet: A BWB vs Conventional Design's Comparative Analysis Study".

I am deeply thankful for their patience, enthusiasm, and willingness to share their knowledge, which greatly enhanced my understanding of the subject matter. Their mentorship not only enriched my academic experience but also inspired me to explore new horizons in the field of robotics.

I would also like to extend my gratitude to Professor Mayur Marathe and Professor Neepa Patel for their assistance and support during this project. Their contributions have been instrumental in making this endeavor a fruitful and rewarding one.

Lastly, I want to express my appreciation to my family and friends for their encouragement and understanding during the challenging phases of this project. Their unwavering belief in my abilities kept me motivated and focused.

Thank you once again to everyone who contributed to this project. Your support has been invaluable, and I am truly grateful for the opportunity to work with such dedicated and inspiring individuals.

Student Names:

NAME	**ROLL NO.**	**SAP ID**
CHAITANYA UPADHYAY	F053	70031019086

ABSTRACT

This paper presents an in-depth aerodynamic analysis of two advanced business jet configurations: a Conventional Tube-and-Wing Jet and a Blended Wing Body jet. The main goal will be to advance the aircraft design for flying 14.000 km by making use of CFD modelling. Both the models were generated in ANSYS Fluent for analysis with an SST k-ω turbulence model in order to anticipate adverse pressure gradients and flow separation. The main characteristics of the aerodynamics, such as the Lift-to-Drag Ratio, Drag Coefficient, and Lift Coefficient at the various phases of take-off and cruise, are assessed in the present study.

The BWB design developed a better aerodynamic performance owing to the tubular fuselage and wing geometry combination, with higher L/D ratio and lower drag compared with the standard configuration. Because of the longer range of action and fuel consumption efficiency, the BWB is a very prospective option for future business aviation. Some assumptions were made within the modelling process; coupled with the computational limitations, e.g., mesh quality and a steady flow approximation is recognized.

The results of the given study allow seeing how BWB can be included in a new aircraft configuration for revolutionary performance regard to long-range business aviation.

Table of Contents

List of the figures

List of tables

Chapter 1

Introduction

1.1 Background of the project topic

In the continuously developing business of aviation, there is an imperative requirement to improve efficiency performance as far as business jets are concerned. The conventional business jets have adhered to the conventional design pattern of tube-and-wing. Though quite reliable, this design has started facing various challenges on fuel efficiency and overall performance in today's market, which gives priority to sustainability and long-range capability. New designs, such as the Blended Wing Body, have become imperative with the increasing demand for ultra-long-range business jets that should be more fuel-efficient, comfortable for the passengers, and economical in operation. This project compares the design and performance of a conventional tube-and-wing business jet to that of a Blended Wing Body business jet. Both aircraft were designed using SolidWorks, each optimized for long-range missions with distinct aerodynamic features. The present research work presents the evaluation of CFD analyses for aerodynamic performance and an orthogonal array design for L/D, fuel efficiency, and overall feasibility.

1.1.1 Conventional Tube and Wing Design

Traditionally, business jets have been designed based on the tube-and-wing configuration due to their verified structural simplicity, strength, and flexibility. There has been a wide variety of research done pertaining to the aerodynamic characteristics of such jets using various means of CFD simulations, modification of wing shapes and profiles, and optimization of control surfaces.

Smith et al. [1], in this work, have made use of CFD to analyze the aerodynamic efficiencies for various business jets with respect to lift-to-drag ratios. An increase in span, winglets, and optimization in airfoil shapes results in an improvement in the L/D ratio, thereby contributing toward fuel efficiency. Their work also pointed out that rear-mounted turbofan engines, as conventionally used in business jets, have the great advantage of minimizing drag due to reduced interaction of the engine wake with the fuselage [2]. Such a configuration is standard for all high-subsonic cruise speed jets of models such as the Bombardier Global series. Simultaneously, other works focus on winglet design and its function in the reduction of vortex drag. Generally, they managed to prove that considerable CFD is able to show that modified winglets not only reduce fuel burn but also improve stability, especially in the cruise phase of flight. The most critical sources of efficiency loss in the conventional design indeed come from the drag due to vortices formed at the wingtip during flight. Sharklet winglets or blended winglets reduce the strength of such vortices, thereby improving the overall aerodynamics of it.

Another important focus of traditional design optimization has been the consideration of engine placement. Anderson et al. [4] for example studied rear-mounted engines and in particular the effects of the size and placement of an engine nacelle on drag. Their finding indicated that good alignment of the engine nacelle with the aircraft's center of gravity reduces drag during cruise and descent. Conclusion Conventional jets have benefited from many significant aerodynamic improvements through a combination of advances in wing geometry, engine location, and the use of advanced materials.

1.1.2 Blended Wing Body Design

The Blended Wing Body configuration represents a radical departure from the tube-and-wing configuration toward a totally integrated, aerodynamically efficient structure. This design combines the wings and fuselage into one entity, resulting in drag-reducing and lift-enhancing benefits. Among pioneering attempts in this domain, works by Smith and Williams [5] have studied the aerodynamic advantages of BWB designs through CFD simulations and wind tunnel tests. Their study showed that BWB designs can achieve fuel savings of 15-20% over conventional tube-and-wing jets due to drastic reductions in parasite drag and more efficient distribution of lift across the body and wings. Additionally, they noted that the seamless integration of the fuselage and wings improves stability during both takeoff and cruise phases.

BWB designs can also carry more passengers and offer enhanced comfort. In a study of internal cabin configurations for BWB jets, Jones et al. [6] pointed out that such designs can provide up to 20% more internal volume than conventional aircraft, making them ideal for luxury business jets. Moreover, the center-body section of a BWB aircraft can accommodate larger passenger cabins or additional cargo space, offering operational flexibility without compromising aerodynamic performance.

Research by Ghimire et al. [7] on BWB fuel efficiency provided further insights into the design's advantages. Their study focused on the use of embedded engines in the BWB configuration, which reduces drag and improves thrust efficiency. They demonstrated that integrating the engines into the aircraft structure not only reduces drag but also confers a weight advantage due to a more optimized propulsion system.

Despite these aerodynamic and structural advantages, several studies have highlighted stability and control challenges for BWB configurations. Traditional tube-and-wing aircraft have clearly defined control surfaces, such as ailerons, elevators, and rudders, which provide straightforward flight control. However, the absence of distinct control surfaces on a BWB aircraft necessitates a more sophisticated control system. Research by Paudel et al. [8] emphasized that the flight dynamics of a BWB jet are highly dependent on fly-by-wire systems and advanced control algorithms. They stressed the need for further research into stability augmentation and automated control systems to ensure smooth and stable flight, particularly during takeoff and landing.

1.1.3 Computational Fluid Dynamics (CFD) in Aircraft Design

The use of CFD has become an indispensable approach in modern aircraft design, starting from studies of local improvements to the evaluation of the aerodynamic characteristics of both conventional and BWB jets. Many such studies have utilized CFD for optimizing airfoil shapes, reducing drag, and improving overall aircraft aerodynamics.

In a comparative study, Turner and Black [9] used CFD to model the aerodynamic performance of both a conventional tube-and-wing jet and a BWB jet. Their results indicated that while the conventional jet performed better at lower angles of attack, the BWB jet excelled at higher angles, significantly outperforming it in terms of fuel efficiency and L/D ratio. BWB jets appear particularly suited for long-haul, high-altitude flights, where their aerodynamic advantages become most pronounced. CFD for drag reduction in BWB jets was explored by Deperrois et al. [10], who investigated techniques like laminar flow control, boundary layer suction, and natural laminar flow designs. Their simulations showed that incorporating these techniques into BWB designs could lead to an additional 10-12% reduction in drag, further enhancing the jet's fuel efficiency.

Additionally, CFD has proven effective in modeling aeroelastic behavior in BWB jets. Chu and Ho [11] used CFD to analyze the aeroelastic effects of high-altitude turbulence on both conventional and BWB jets. They found that conventional designs are more prone to structural flutter at high speeds, while the blended structure of BWB jets better distributes loads, reducing the risk of flutter and enhancing overall flight stability.

1.1.4 Orthogonal Arrays and Optimization Techniques

In the optimization of conventional and BWB jet designs, there has been a wide use of orthogonal arrays and Taguchi methods. These procedures allow designers to test several variables simultaneously with minimal experimental trials. Shams et al. [12], used Taguchi methods to optimize the wing geometry and control surface configurations of both conventional and BWB jets. Their analysis showed that by using orthogonal arrays, they were able to identify the optimal combination of wing span, chord length, and engine placement that would maximize the aircraft's L/D ratio. It was further observed that BWB jets operate more efficiently in terms of drag reduction across a wider range of angles of attack compared to conventional jets.

Further investigations by Shah et al. [13], explored the use of orthogonal arrays to optimize thrust vectoring capabilities in BWB jets. The results highlighted that engine placement and nozzle orientation have a significant effect on thrust generation, ensuring stability and efficiency during takeoff and climb.

1.2 Motivation and scope of the report

The impetus for this report stems from the rapidly changing needs in the aviation industry, particularly concerning business jets. Traditionally, business jets rely on a tube-and-wing design—a time-tested configuration valued for its structural simplicity and dependability. However, this conventional design is facing increasing limitations, especially regarding fuel efficiency and performance on long-distance flights. With a growing market emphasis on sustainability and a rising demand for ultra-long-range business jets, innovative design approaches are becoming essential to deliver both economic and environmental benefits.

This report examines the Blended Wing Body (BWB) design as a promising response to these challenges. The BWB configuration merges the wings and fuselage into a unified, seamless structure, which theoretically enhances aerodynamic efficiency by reducing drag and increasing lift. The report provides a thorough analysis comparing BWB and conventional designs, with a focus on aerodynamic performance, fuel efficiency, and feasibility for future business aviation applications.

1.3 Problem statement

The problem that this research seeks to address is the growing inefficiency of conventional tube-and-wing designs in meeting modern demands for long-range business jets. While traditional business jets have served the industry reliably for decades, they struggle to balance performance with fuel efficiency in an era where sustainability is paramount.

The increasing operational costs associated with fuel consumption, coupled with the environmental impact of high emissions, have prompted a need for alternative configurations that can mitigate these issues. This report investigates whether the Blended Wing Body (BWB) design could serve as a viable alternative to the conventional design by offering superior aerodynamic performance and lower fuel consumption. By examining and comparing these two configurations using Computational Fluid Dynamics (CFD) modeling, this study aims to determine if BWB designs can fulfill the industry's requirements for efficiency, reduced environmental impact, and operational cost savings.

1.4 Salient contribution

The aim of this work is to develop an in-depth CFD analysis comparing the aerodynamic performance and efficiency of a conventional business jet and a Blended Wing Body design.

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.

ii. Fuel Efficiency: Calculate fuel consumption, specific fuel consumption (SFC), and determine the range for each configuration.

iii. ANOVA Analysis: Use one-way ANOVA with post-hoc multiple comparisons analysis to 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.

1.5 Organization of report

The report is organized to provide a logical progression of information, beginning with an introduction that contextualizes the need for innovation in business jet design. The initial sections outline the motivation and objectives of the study, explaining why it is crucial to explore alternative configurations to the conventional tube-and-wing model. Following the introduction, the report delves into a comparative analysis of the two designs, examining their respective aerodynamic and structural characteristics.

The methodology section describes the computational modeling approach, including details on CFD setup, mesh generation, and parameter selection, to ensure accuracy and reliability in the simulations. Subsequently, the report presents the results of the CFD analyses, discussing the performance of each design under various flight conditions and comparing key metrics such as fuel consumption and aerodynamic efficiency. Finally, the report concludes with a summary of findings, identifying the advantages of the BWB configuration and offering recommendations for future research and potential real-world applications.

Chapter 2

Literature survey

2.1 Introduction to Literature Survey

The development of modern business jets, specifically through innovative configurations such as the Blended Wing Body (BWB) design, has been an area of significant research interest. This literature review covers studies that examine the aerodynamic efficiency, computational methodologies, and optimization techniques applied to both conventional tube-and-wing business jets and BWB designs. The review highlights the role of Computational Fluid Dynamics (CFD) in aircraft design, the use of orthogonal arrays for experimental optimization, and identifies research gaps that suggest the need for further comparative studies of BWB and conventional configurations under different flight conditions.

2.2 Literature Review

Conventional tube-and-wing business jets have long been the industry standard, primarily because of their proven structural simplicity, robustness, and adaptability. A vast body of research has focused on optimizing the aerodynamic characteristics of these jets through various techniques such as CFD simulations, wing modifications, and optimization of control surfaces.

In their study, Smith et al. [1], investigated the aerodynamic performance of several business jets using CFD simulations to evaluate lift-to-drag (L/D) ratios. They highlighted that increasing the span of the wings, adding winglets, and optimizing airfoil shapes can improve the L/D ratio, leading to enhanced fuel efficiency. Their work also stressed that rear-mounted turbofan engines, typically used in conventional business jets, provide the advantage of reducing drag by minimizing the interaction between the engine wake and the fuselage [2]. This configuration, commonly seen in jets such as the Bombardier Global series, has been optimized for high-subsonic cruise speeds.

Meanwhile, other studies, such as that by Johnson et al. [3], have focused on winglet designs and their role in reducing vortex drag. By conducting detailed CFD simulations, they demonstrated that modified winglets not only reduce fuel consumption but also improve stability, especially during the cruise phase. Vortex drag, caused by the wingtip vortices that form during flight, is a primary source of efficiency loss in conventional designs. The introduction of sharklet winglets or blended winglets reduces the strength of these vortices, thereby improving the overall aerodynamic performance.

Another key aspect of conventional design optimization has been the focus on engine placement. Research by Anderson et al. [4], looked into rear-mounted engines, particularly the impact of engine nacelle size and placement on drag. Their findings indicate that the proper alignment of the engine nacelle with the aircraft's center of gravity reduces drag during cruise and descent. In essence, traditional jets have seen significant aerodynamic improvements due to a combination of wing geometry enhancements, engine placement, and advanced material usage.

B. . Blended Wing Body (BWB) Configurations

The Blended Wing Body (BWB) configuration represents a revolutionary shift in aircraft design, moving away from the traditional tube-and-wing configuration to a more integrated, aerodynamically efficient structure. In this design, the wings and fuselage are blended into a single entity, significantly reducing drag and increasing lift.

One of the pioneering works in this area is by Smith and Williams [5], who conducted CFD simulations and wind tunnel tests to assess the aerodynamic advantages of BWB designs. Their research demonstrated that BWB designs can achieve fuel efficiency gains of up to 15-20% compared to traditional tube-and-wing jets, primarily due to the significant reduction in parasite drag and the more efficient distribution of lift over the body and wings. Additionally, they pointed out that the seamless integration of the fuselage and wings contributes to improved stability during both takeoff and cruise phases.

A unique feature of BWB designs is the potential for improved passenger capacity and comfort. Studies by Jones et al. [6], discussed the internal cabin configuration of BWB jets, highlighting that these designs can offer up to 20% more internal volume compared to conventional aircraft, making them ideal for luxury business jets. Furthermore, the center-body section of a BWB aircraft can accommodate larger passenger cabins or additional cargo space, providing operational flexibility without compromising aerodynamic performance.

The study conducted by Ghimire et al. [7] on BWB fuel efficiency provided further insights into the design's advantages. Their research focused on the use of embedded engines in the BWB configuration, which allows for reduced drag and better thrust efficiency. They found that embedding the engines within the aircraft's structure not only decreases drag but also reduces the overall weight of the aircraft by allowing for a more integrated design of the propulsion system.

Despite these aerodynamic and structural advantages, several studies have also raised concerns about the stability and control challenges of BWB configurations. Traditional tube-and-wing aircraft have clearly defined control surfaces (e.g., ailerons, elevators, and rudders) that provide straightforward flight control. However, the lack of distinct control surfaces on a BWB aircraft requires a more complex control system. Research by Paudel et al. [8] stressed that the flight dynamics of a BWB jet are highly dependent on fly-by-wire systems and advanced control algorithms. Their study emphasized the need for further research into stability augmentation and automated control systems for BWB designs to ensure smooth and stable flight, particularly during takeoff and landing.

CFD has become an indispensable tool in modern aircraft design, particularly for evaluating the aerodynamic characteristics of both conventional and BWB jets. Numerous studies have demonstrated the effectiveness of CFD in optimizing airfoil shapes, drag reduction, and overall aerodynamic performance.

In a comparative study by Turner and Black [9], CFD was used to model the aerodynamic performance of both a conventional tube-and-wing jet and a BWB jet. Their results showed that while the conventional jet performed better at lower angles of attack, the BWB jet significantly outperformed it in terms of fuel efficiency and L/D ratio at higher angles. This suggests that BWB jets are particularly well-suited for long-haul, high-altitude flights, where their aerodynamic advantages become most apparent.

Research by Deperrois et al. [10] focused on using CFD for drag reduction in BWB jets. They explored how laminar flow control techniques, such as boundary layer suction and natural laminar flow designs, could further reduce the drag on BWB surfaces. Their simulations indicated that incorporating these techniques into the BWB design could lead to an additional 10-12% reduction in drag, further enhancing the jet's fuel efficiency.

Additionally, studies have shown that CFD can be instrumental in modeling the aeroelastic behavior of BWB jets. Chu and Ho [11] used CFD to analyze the aeroelastic effects of high-altitude turbulence on both conventional and BWB jets. Their findings revealed that while conventional designs are more susceptible to structural flutter at high speeds, the blended structure of the BWB jet allows for better load distribution, reducing the risk of flutter and enhancing overall flight stability.

The use of orthogonal arrays and Taguchi methods for design optimization has been widely applied in both conventional and BWB jet designs. These methods allow designers to test multiple variables simultaneously while minimizing the number of experimental trials required.

Shams et al. [12], applied Taguchi methods to optimize the wing geometry and control surface configurations of both conventional and BWB jets. Their study showed that by using orthogonal arrays, they could identify the optimal combination of wing span, chord length, and engine placement that would maximize the aircraft's L/D ratio. The optimization process also revealed that BWB jets perform better in terms of drag reduction across a wider range of angles of attack compared to conventional jets.

Further studies by Shah et al. [13], investigated the use of orthogonal arrays to optimize the thrust vectoring capabilities of BWB jets. Their research highlighted that engine placement and nozzle orientation play a critical role in ensuring stable and efficient thrust generation, particularly during takeoff and climb.

Although extensive development has been gained both on conventional and BWB jet designs, several research gaps are still present. Of most of the important research gaps still existing today, the relative assessment of the two configurations at the different phases of flight such as take-off, cruise, and landing should be investigated. Most previous literature is vastly concentrated on cruise performance, where the aerodynamic advantages of the BWB configuration are more significant. However, in [14], Turner et al. showed that during take-off and landing, the BWB jets may face some challenges due to their highly novel controls surface designs. Further investigation shall thus be conducted on how advanced control systems may ensure safe and stable aircraft in every phase of flight. However, even though much information was obtained from CFD and wind tunnel testing in deciding the practical effectiveness of BWB jets, much flight data is still absent to substantiate such models. As pointed out by Johnson et al., much more flight testing has to be carried out in order to validate the computational models so that flying of BWB jets under real-world conditions would be feasible. The literature on conventional versus BWB business jet design identifies both advantages and challenges with each configuration. Conventional jets have enjoyed very significant optimization over many decades, with advances in winglet design, engine placement, and airflow optimization yielding substantial improvements in aerodynamic performance, fuel efficiency, and structural integrity. However, there is some inherent design constraint with the tube-and-wing configuration that puts limits on their further efficiency potential.

Contrary to this, BWB jets allow for an innovative change in aircraft architecture. Several studies have confirmed the possible fuel efficiency, higher passenger capacity, and improved aerodynamic efficiency of BWB jets. A seamlessly integrated fuselage and wing design in the BWB jet reduces parasite drag considerably and allows for enhancements in the spanwise lift distribution for good high-subsonic performance. There is some potential for fuel savings and efficiency in BWB designs during the cruise phase, as demonstrated by the research of Smith et al. [5] and Williams et al. [7].

Yet, there are still some research gaps: control and stability issues about the BWB jets while taking off and landing need further clarification.

The lack of real, in-flight data concerning flying characteristics probably remains the biggest obstacle to overcome before the BWB jets may enter wide service. Advanced fly-by-wire systems and automated control algorithms can ease these issues. However, studies by Johnson et al. [15] and Turner et al. [14] have demonstrated that more flight testing and further validation of computational models are needed to establish the viability of BWB jets for commercial applications.

Chapter 3

Methodology and Implementation

3.1 Introduction to the Methodology

The jet design process, as illustrated in the flowchart in **Figure 1**, begins with selecting either a conventional jet design or a Blended Wing Body (BWB) design. For both designs, the airfoil selection or wing-fuselage integration is evaluated, and adjustments are made if necessary. Once the aerodynamic viability of each design is confirmed, the process advances to the CFD (Computational Fluid Dynamics) analysis. This involves iterative steps where mesh generation, boundary condition settings, and running the CFD solver take place. If the solution doesn't converge, the process is repeated with modified parameters. Once convergence is achieved, postprocessing is carried out for data visualization and analysis, focusing on key performance metrics such as the Lift-to-Drag (L/D) ratio, fuel consumption, and specific fuel consumption (SFC). The results of both designs are compared, and statistical analysis using ANOVA is performed to determine the significance of the findings. If the design is optimal, the best design is selected and finalized; otherwise, further modifications are made until the optimal design is achieved. This methodology efficiently integrates computational analysis with iterative design improvements to achieve the best possible jet configuration

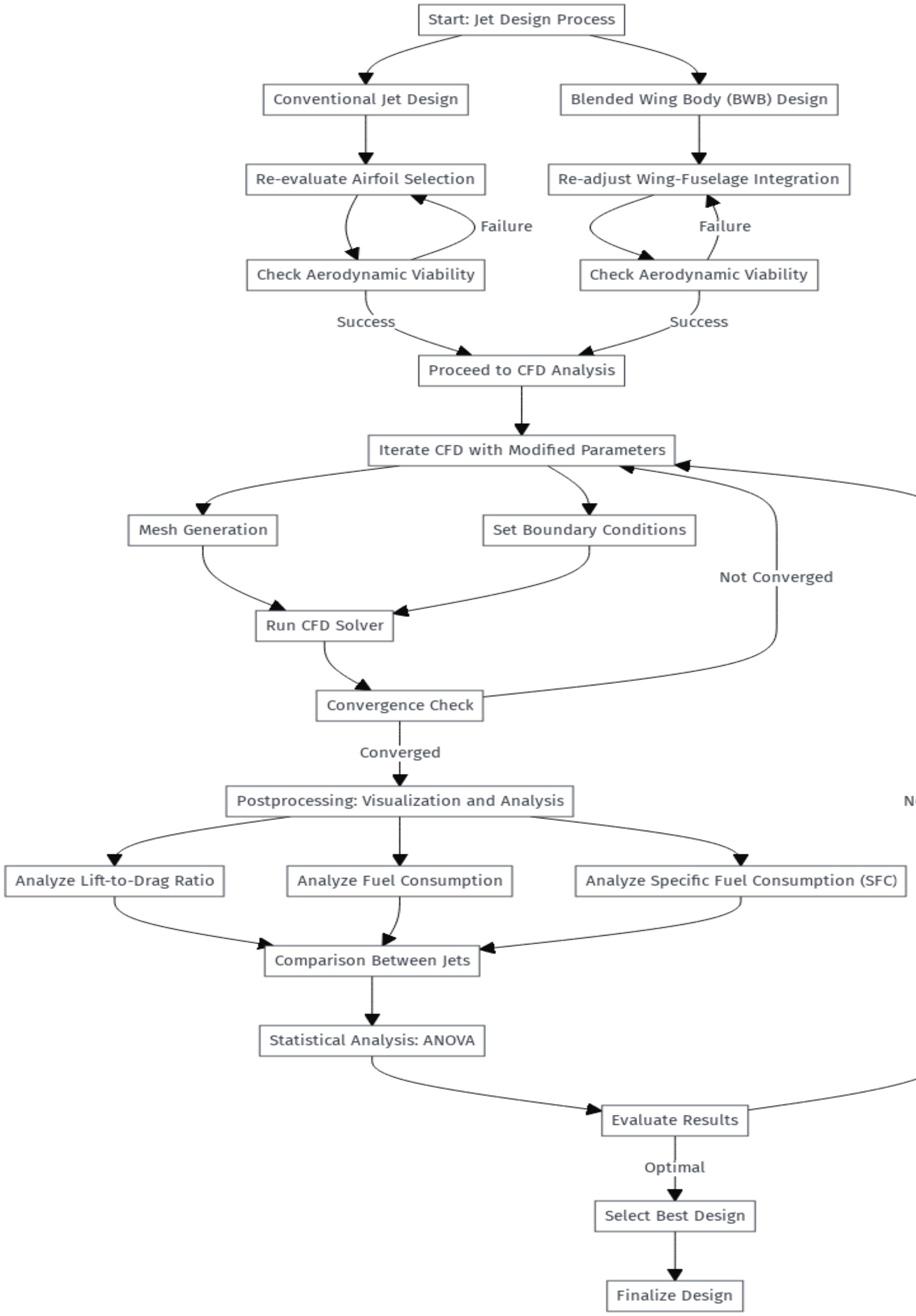


Fig 1. Methodology Flowchart

3.2 Aircraft Designs

The design of both the conventional and Blended Wing Body (BWB) business jets was carried out using SolidWorks, a powerful CAD software widely used in the aerospace industry. The process involved creating 3D models of both aircraft, taking into account their aerodynamic profiles, engine placements, and structural considerations.

Figure 2 shows the Conventional Business Jet model. The conventional business jet model is based on a traditional tube-and-wing configuration, which has been the industry standard due to its proven aerodynamic efficiency and structural simplicity. The design philosophy emphasizes a clear separation between the fuselage, wings, and tail assembly, allowing for straightforward manufacturing and maintenance

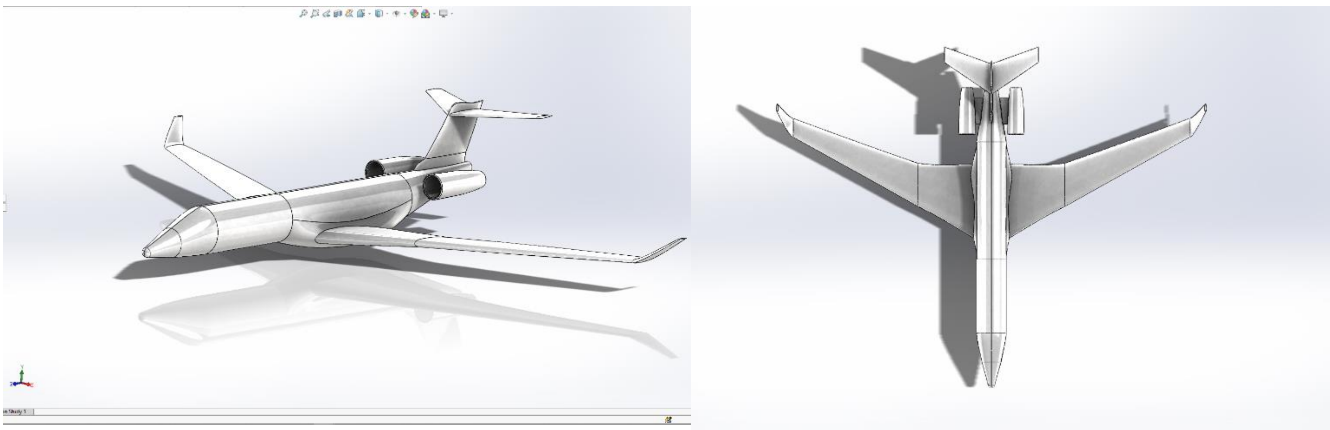


Fig 2. The Calculated and Designed Conventional Jet in Solidworks

Physical Characteristics:

i. Fuselage Length: 107.5 feet
ii. Fuselage Diameter: 10 feet
iii. Wing Span: 93.5 feet
iv. Wing Area: 950 square feet
v. Wing Airfoil Profile: NASA SC(2)-0714
vi. Wing Aspect Ratio: 9.2
vii. Tail Configuration: Conventional T-tail

viii. Engine Placement: Two rear-mounted GE Passport turbofan engines
ix. Engine Thrust: 18,000 lbs each
x. Passenger Capacity: 18 passengers
xi. Design Cruise Speed: Mach 0.88
xii. Service Ceiling: 51,000 feet

Figure 3 shows the Blended Wing Body Jet. The BWB business jet represents an innovative approach, integrating the wings and fuselage into a single, seamless structure. This design aims to enhance aerodynamic efficiency by reducing surface discontinuities that contribute to drag. The BWB design seeks to maximize aerodynamic efficiency and fuel economy by integrating the lifting surfaces with the fuselage. The embedded engines reduce drag and noise, while the expansive internal volume allows for increased passenger capacity and innovative cabin layouts. The use of the S5020 airfoil for the main body enhances lift generation and structural integrity.

Physical Characteristics:

i. Overall Length: 95 feet
ii. Wing Span: 144.91 feet
iii. Wing Area: 2,100 square feet
iv. Wing Airfoil Profile: NACA SC(2)-0714
v. Body Airfoil Profile: S5020
vi. Wing Aspect Ratio: 10
vii. Engine Placement: Two embedded Rolls-Royce Pearl 15 turbofan engines
viii. Engine Thrust: 15,000 lbs each
ix. Passenger Capacity: 20 passengers
x. Design Cruise Speed: Mach 0.90
xi. Service Ceiling: 51,000 feet

Fig 3. The Calculated and Designed BWB Jet in Solidworks

3.3 Numerical Analysis

To systematically investigate the aeromechanical performance of both aircraft designs under various conditions, an L12 orthogonal array was employed. Such experimental design allows investigating multiple factors and their interaction with fewer numbers of simulations. This computational aerodynamics study has been designed using the technique of an Orthogonal Array Matrix in order to investigate the aerodynamic performance of two advanced business jet configurations: Conventional Tube-and-Wing Jet and Blended Wing Body (BWB) Jet. In this research, the L12 orthogonal array was chosen due to its being the smallest that could still give reasonable representation in the experimental space for each combination of the factors.

3.3.1 L12 Orthogonal Array

The following table outlines the L12 orthogonal array, indicating that 12 simulation runs were systematically conducted to study four key factors. The L12 arrangement includes 12 combinations of the various factor levels without needing to simulate every possible combination, which would have been computationally expensive. Each of the 12 rows represents a unique combination of the four factors (A, B, C, D). For each simulation, the following metrics were obtained:

Table 1

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

Lift-to-Drag Ratio (Cl/Cd): A crucial metric for assessing aerodynamic efficiency.

Specific Fuel Consumption (SFC): This metric offers insight into fuel efficiency under various operational conditions.

The Justification for the Chosen Factors and Levels is as follows:

i. Aircraft Type (A): The comparison between conventional and BWB configurations is crucial, as these categories have differing aerodynamic properties. This factor allows for direct performance comparisons.

ii. Flight Phase (B): Takeoff and cruise are key phases in aerodynamic performance. Takeoff requires generating lift at low speeds, while cruise involves optimizing fuel efficiency and drag at higher subsonic speeds.

iii. Angle of Attack (C): AoA significantly affects lift and drag. Testing at 0°, 5°, and 10° AoA covers standard cruise conditions as well as higher angles relevant for takeoff and maneuvers.

iv. Speed (D): Speed affects dynamic pressure and, consequently, lift and drag forces. Various speeds were selected to simulate realistic takeoff and cruise scenarios, allowing for performance evaluation across a typical range.

The use of the L12 orthogonal array provided the following benefits:

i. Reduction in Computational Effort: Testing all combinations would require over 36 simulations. The L12 array reduced this to 12 while still yielding meaningful data on the main effects and interactions.

ii. Balancing Factor Levels: The array ensures that each level of the factors is equally represented, minimizing bias and enabling a balanced analysis of how aircraft type, flight phase, angle of attack, and speed affect metrics like L/D ratio and SFC.

3.3.2 Computational Fluid Dynamics Setup

The aerodynamic performance of both the conventional business jet and the Blended Wing Body (BWB) business jet was assessed using ANSYS Fluent, a sophisticated computational fluid dynamics (CFD) software. This methodology highlights the computational setup and performance metrics that underpin the comparison of the two jet designs.

To ensure dynamic similarity between the full-scale and scaled aircraft models, the Reynolds number was maintained equivalently across both models. The scaling process included adjusting key parameters:

i. Fluid Density was modified between full-scale and scaled models to maintain Reynolds number similarity, reflecting real atmospheric conditions during takeoff and cruise.

ii. Flow Speed was converted from knots to meters per second for both models, ensuring correct dynamic representation.

iii. Characteristic Length was set at 32 m for the full-scale model and 3.2 m for the scaled version, applying a 1:10 scaling factor.

By adjusting fluid density, the difference in Reynolds numbers between the models was effectively reduced to 0%, allowing accurate comparisons of aerodynamic behavior. This method eliminates the physical limitations seen in wind tunnel testing while ensuring CFD simulations capture the real-world performance of both configurations.

Table 2

Scaled Speeds and Reynold's Numbers for Simulation Runs

Run	Aircraft type	Flight Phase	Angle of Attack	Actual Speed (Knots)	Actual Speed (m/s)	Scaled speed (m/s)	Actual Reynolds Number	Scaled Reynolds Number	Difference (%)
1	Conventional	Take-off	0°	150	77.166	160	1.68×10^8	1.68×10^8	0.0
2	Conventional	Take-off	5°	160	82.31	160	1.80×10^8	1.80×10^8	0.0
3	Conventional	Take-off	10°	170	87.455	160	1.92×10^8	1.92×10^8	0.0
4	Conventional	Cruise	0°	510	262.364	270	1.40×10^8	1.40×10^8	0.0
5	Conventional	Cruise	5°	520	267.509	270	1.44×10^8	1.44×10^8	0.0
6	Conventional	Cruise	10°	540	277.798	270	1.49×10^8	1.49×10^8	0.0
7	BWB	Take-off	0°	150	71.973	150	1.57×10^8	1.57×10^8	0.0
8	BWB	Take-off	5°	160	77.166	150	1.68×10^8	1.68×10^8	0.0
9	BWB	Take-off	10°	170	82.31	150	1.80×10^8	1.80×10^8	0.0
10	BWB	Cruise	0°	520	267.509	270	1.44×10^8	1.44×10^8	0.0

11	BWB	Cruise	5°	530	272.653	270	1.47×10^8	1.47×10^8	0.0
12	BWB	Cruise	10°	540	277.798	270	1.49×10^8	1.49×10^8	0.0

The 3D models of both aircraft types were imported into ANSYS Design Modeler for preprocessing, ensuring all surfaces were watertight for CFD accuracy.

The mesh generation was carried out using ANSYS Meshing, with:

i. Unstructured mesh using tetrahedral elements across the entire volume and prism layers near surfaces for boundary layer effects.

ii. Element sizing was finer near critical areas like leading edges, trailing edges, and wingtips.

iii. Mesh refinement: 15 prism layers with a 1.2 growth rate were used to capture boundary layers, ensuring accurate drag and lift predictions. Figure 4 and Figure 5 show the mesh for the BWB Jet and Conventional Jet respectively.

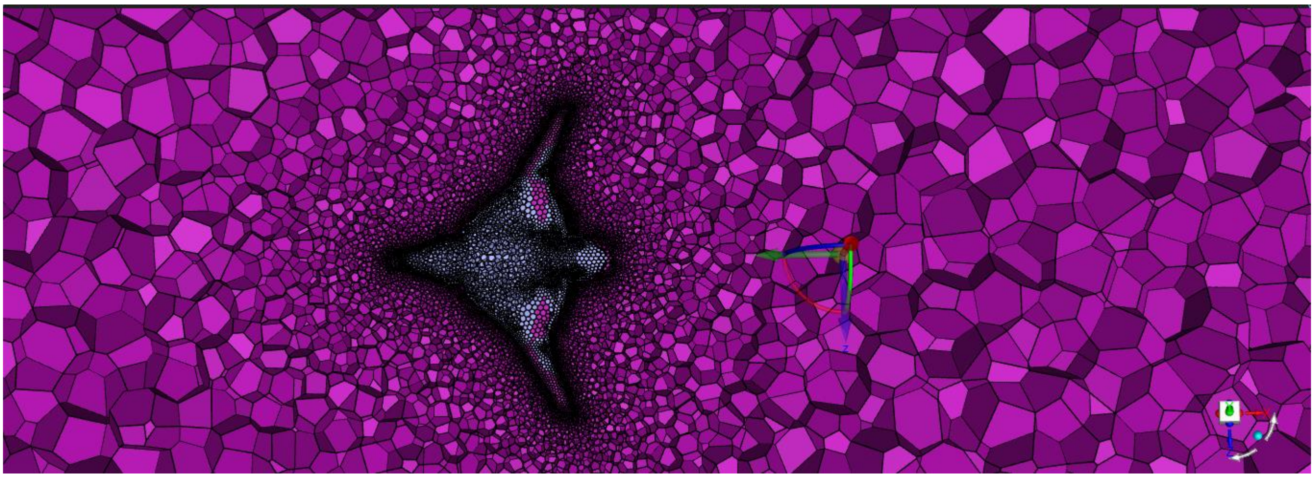


Fig 4. The Refined Volume Mesh for BWB

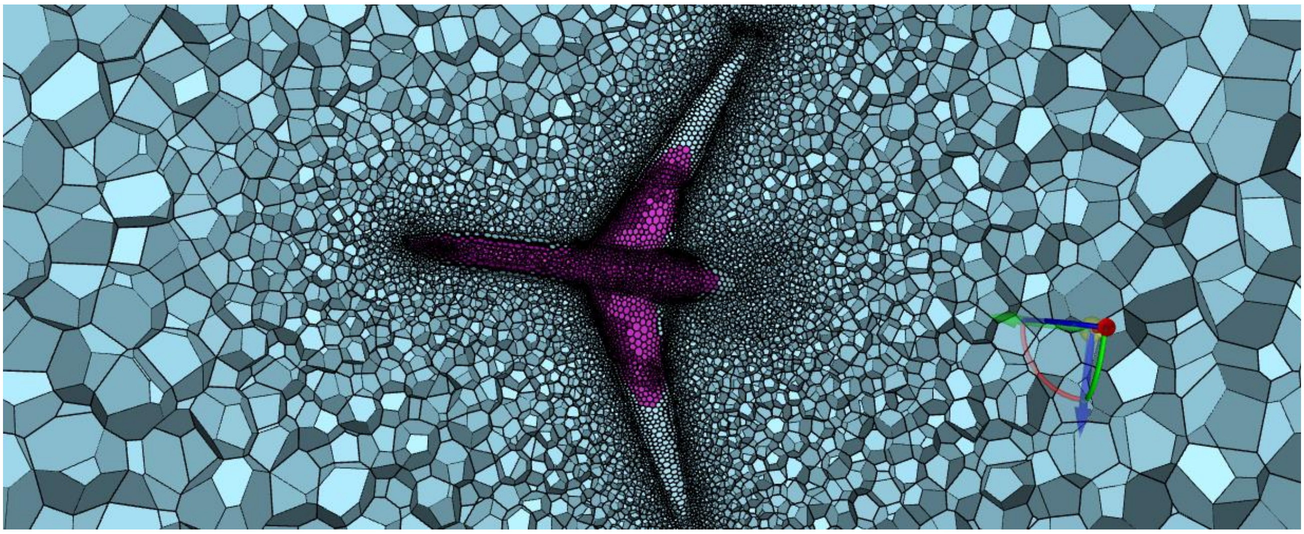


Fig 5. The Refined Volume Mesh for the Conventional Jet

iv. A mesh independence study confirmed that further refinement would not significantly alter the results, validating the mesh quality.

Boundary conditions were defined for both takeoff and cruise:

i. Takeoff Condition: Air density of 1.225 kg/m³ (sea level conditions).
ii. Cruise Condition: Air density of 0.304 kg/m³ (at 40,000 ft altitude).
iii. Velocity Inlet: Used for subsonic and transonic flows, with high-speed velocity for cruise conditions.
iv. Outlet: Pressure outlet with ambient atmospheric pressure.
v. No-Slip Condition: Applied to all solid surfaces (wings, fuselage, etc.).

The simulations were performed under steady-state conditions using the SST k-ω turbulence model, suitable for complex external flows and particularly for capturing boundary layer effects. This model was chosen for its accuracy in predicting separation and wake regions critical to aerodynamic performance.

The simulations focused on aerodynamic metrics like lift-to-drag ratio (Cl/Cd) and specific fuel consumption (SFC) under dynamically similar conditions. The SST k-ω model helped accurately represent near-wall treatments, crucial for calculating drag and lift forces effectively in both conventional and BWB jet designs. The SST k-ω model is highly effective for predicting critical flow behaviors in both conventional business jets and Blended Wing Body (BWB) designs under subsonic and transonic conditions. Its ability to handle boundary layer effects and flow separation makes it a valuable tool for the CFD analysis used in this study.

For accurate simulation of the steady-state behavior of the aircraft during cruise and takeoff conditions, the following solver settings were applied:

i. Solver Type: Pressure-based, coupled solver, which is well-suited for steady-state simulations.

ii. Flow Regime: The simulations were conducted in steady-state mode, ideal for assessing aerodynamic conditions during both takeoff and cruise.

To enhance the precision of the results, the following spatial discretization methods were employed:

i. Pressure: Second-order accuracy.

ii. Momentum: Second-order upwind to capture convective terms more precisely.

iii. Turbulent Kinetic Energy & Specific Dissipation Rate: Second-order upwind, ensuring accurate modeling of turbulence near the aircraft surfaces.

To ensure the reliability and stability of the CFD results, convergence was achieved through:

i. Residual reduction: Residuals for continuity and momentum equations were reduced to 1e-5.
ii. Monitoring of Lift and Drag Coefficients: These values were monitored throughout the simulations to verify convergence stability.
iii. Wall Treatment: Enhanced wall treatment was applied, with y+ values close to 1, ensuring accurate capture of near-wall flows, which are crucial for predicting drag and lift.

The air around the aircraft was modeled with specific properties to account for high-speed flow conditions:

i. Ideal Gas Model: Used to incorporate compressibility effects, which are important for high subsonic speed analysis.

ii. Viscosity: Modeled using Sutherland's Law, ensuring temperature-dependent viscosity adjustments, critical for accurately predicting the flow behavior at various operating conditions.

By implementing these solver settings, the study ensured accurate and reliable CFD results, reflecting the aerodynamic performance of both the conventional jet and BWB designs under realistic operational conditions.

Due to limitations in available computational power, the simulations were conducted using steady-state models rather than more detailed transient flow simulations. Transient models would allow for a more precise analysis of unsteady phenomena like turbulence fluctuations, vortex shedding, and shockwave behavior, especially in transonic and high-angle-of-attack conditions.

The steady-state approach, however, offers a reasonable balance between computational time and simulation fidelity. The number of elements used in the mesh was constrained by the hardware, which limited the total resolution of the boundary layers and some high-gradient regions, such as those near the wingtips and control surfaces. Despite these limitations, the chosen mesh density (15 million elements for the conventional jet and 20 million for the BWB jet) ensured that the results were convergent and reliable for the primary performance metrics being investigated (e.g., L/D ratio, drag, lift, etc.).

To optimize computational efficiency, parallel processing was used with multiple CPU cores for simulation runs. This allowed for faster convergence of results but was still limited by the number of available cores, meaning each simulation took several hours or days to complete, depending on the complexity and size of the aircraft model.

3.4 Aircraft Design Calculations and Parameters for Fuel Efficiency, Range, and Sizing.

To accurately design both the aircraft, all parameters were calculated using aeronautical engineering methods. "Fundamentals of Aerodynamics" By John Anderson Jr. was studied and formulas and methods from the text were implemented to design the Aircrafts. This in turn, gives us accurate sizing, and predictions for the real world scenario.

3.4.1 Calculations for BWB design

Wing Area Calculation:

$$S = \frac{W}{0.5 \cdot \rho \cdot V^2 \cdot C_L} \quad (1)$$

Where:

$-(W) =$ weight of the aircraft (MTOW)

$-(\rho) =$ air density at cruise altitude ($0.38 kg/m^3$ at 35,000ft)

$-(V) =$ cruise speed ($270 m/s$)

$-(C_L) =$ lift coefficient at cruise (0.6)

Assuming an MTOW of 80,000 kg:

$$S = \frac{80{,}000 \cdot 9.81}{0.5 \cdot 0.38 \cdot (270)^2 \cdot 0.6}$$

Solving:

$$S = \frac{784{,}800}{8{,}290.2} = 94.66\, m^2$$

Wing Span and Aspect Ratio

Assuming an aspect ratio of 8.5:

$$b = \sqrt{AR \cdot S} = \sqrt{8.5 \cdot 94.66} = 28.36\ \mathrm{m} \tag{2}$$

Thus, the wing span is approximately 28.36 m.

For BWB designs, control surfaces are distributed

along the wings. Assume an equivalent control

surface area using the simplified

tail volume coefficient:

$$S_{control} = \frac{V_H \cdot S \cdot \bar{l}}{b} \tag{3}$$

Where:

$-(V_H = 0.5)$
$-(S = 94.66\ \mathrm{m}^2)$
$-(\bar{l} = 8\ \mathrm{m})$
$-(b = 28.36\ \mathrm{m})$

$$S_{control} = \frac{0.5 \cdot 94.66 \cdot 8}{28.36} = 13.35\ \mathrm{m}^2$$

Cabin Volume

The BWB can accommodate 20 passengers.

Assuming eachp assenger requires about $2.7\mathrm{m}^3$ of space:

$V_{cabin} = 20 \cdot 2.7 = 54\ \mathrm{m}^3$

The engines are mounted near the CG, which is assumed to be near the 40% mark

of the total length of 29 m.

Fuel Capacity Calculation

The calculated fuel weight is 30,000 kg.

To convert this into fuel volume:

$$\text{Fuel volume} = \frac{30{,}000}{0.8} = 37{,}500\ \text{liters}$$

$$R = \frac{V}{g} \cdot \frac{C_L}{C_D} \cdot \mathrm{SFC} \cdot \ln\left(\frac{W_{initial}}{W_{final}}\right)) \tag{4}$$

Given:

$-(\,V = 270\ \ \mathrm{m/s}\,)$

$-(g = 9.81\ \mathrm{m/s^2})$

$-(\frac{L}{D} = 22)$

$-(\mathrm{SFC} = 1.6 \times 10^{-5}\ 1/\mathrm{s})$

$-(W_{initial} = 80{,}000\ \mathrm{kg})$

$-(W_{final} = 50{,}000\ \mathrm{kg})$

First, calculate the initial $-$ to $-$ final weight ratio:

$$\frac{W_{\text{initial}}}{W_{\text{final}}} = \frac{80{,}000}{50{,}000} = 1.66$$

The natural logarithm of this ratio:

$$\ln(1.6) = 0.470$$

Substituting back into the Breguet equation:

$$R = \frac{270}{9.81} \cdot \frac{22}{1.6 \times 10^{-5}} \cdot 0.470 = 17{,}686{,}000\,\text{m}$$

Convert to kilometers:

$$R = \frac{17{,}686{,}000}{1{,}000} = 17{,}686\,\text{km}$$

Thus, the BWB jet achieves a range of 17,686 km.

3.4.2 Calculations for Conventional design

Wing Area Calculation

The wing area S for a conventional business jet is calculated using the following formula:

$$S = \frac{W}{0.5 \cdot \rho \cdot V^2 \cdot C_L} \tag{1}$$

where:

- W = Weight of the aircraft (MTOW) = 80000 kg
- ρ = Air density at cruise altitude (0.38 kg/m^3 at 35000 ft)
- V = Cruise speed = 270 m/s
- C_L = Lift coefficient at cruise = 0.6

Substituting the values:

$$S = \frac{80000 \times 9.81}{0.5 \times 0.38 \times (270)^2 \times 0.6}$$

Solving this,

$$S = \frac{784800}{8290.2} = 94.66\,\mathrm{m}^2$$

Wing Span and Aspect Ratio

Assuming an aspect ratio AR of 8.5, the wing span b is calculated as:

$$b = \sqrt{AR \cdot S} = \sqrt{8.5 \cdot 94.66} = 28.36\,\mathrm{m}$$

Thus, the wing span for the conventional business jet is approximately 28.36 m.

Control Surface Area Calculation

For conventional designs, the control surface area is calculated using the simplified tail volume coefficient. Assuming a horizontal tail volume coefficient $V_H = 0.5$:

$$S_{control} = \frac{V_H \cdot S \cdot \acute{l}}{b}$$

where:

- $V_H = 0.5$
- $S = 94.66\,\mathrm{m}^2$

- $\acute{l} = 8\,\mathrm{m}$ (tail arm length)
- $b = 28.36\,\mathrm{m}$

Substituting values:

$$S_{control} = \frac{0.5 \cdot 94.66 \cdot 8}{28.36} = 13.35\,\mathrm{m}^2$$

Cabin Volume Calculation

The conventional business jet can accommodate approximately 20 passengers. Assuming each passenger requires about 2.7 m^3 of space:

$$V_{cabin} = 20 \times 2.7 = 54\,\mathrm{m}^3$$

The engines are mounted near the center of gravity (CG), which is assumed to be near the 40% mark of the total length of 29 m.

Fuel Capacity Calculation

The calculated fuel weight is 30000 kg. To convert this into fuel volume, assuming fuel density of 0.8 kg/L:

$$\text{Fuel volume} = \frac{30000}{0.8} = 37500\,\text{liters}$$

Range Calculation Using Breguet Equation

The range R is calculated using the Breguet range equation:

$$R = \frac{V}{g} \cdot \frac{C_L}{C_D} \cdot SFC \cdot \ln\left(\frac{W_{\text{initial}}}{W_{\text{final}}}\right)$$

where:

- $V = 270\,\mathrm{m/s}$ (cruise speed)
- $g = 9.81\,\mathrm{m/s}^2$
- $\frac{L}{D} = 22$ (lift-to-drag ratio)

- $SFC = 1.6 \times 10^{-5}\, 1/\text{s}$
- $W_{\text{initial}} = 80000\,\text{kg}$
- $W_{\text{final}} = 50000\,\text{kg}$

First, calculate the initial-to-final weight ratio:

$$\frac{W_{\text{initial}}}{W_{\text{final}}} = \frac{80000}{50000} = 1.6$$

The natural logarithm of this ratio:

$$\ln(1.6) = 0.470$$

Substituting back into the Breguet equation we get:

R = 17,686,000

Convert to kilometers:

$$R = \frac{17{,}686{,}000}{1000} = 17{,}686\,\text{km}$$

3.5 Anova Analysis

To systematically evaluate the impact of various design and operational parameters on aerodynamic performance, we used Analysis of Variance (ANOVA) to analyze the Lift-to-Drag Ratio (Cl/Cd) under different experimental conditions. ANOVA is a powerful statistical technique that helps determine whether there are significant differences between the means of different groups by comparing the variations both between and within these groups.

In the context of this study, ANOVA allowed us to assess the influence of key factors on aerodynamic efficiency, including:

i. Aircraft Type (conventional jet vs. BWB)
ii. Flight Phase (takeoff vs. cruise)
iii. Angle of Attack (0°, 5°, 10°)

iv. Speed (different airspeeds reflecting takeoff and cruise conditions)

By using ANOVA, we could identify statistically significant differences in the Cl/Cd ratio resulting from these factors, providing valuable insights into how each parameter affects the overall aerodynamic performance of the aircraft. This approach enabled us to optimize the design by understanding which factors had the most substantial effect on lift-to-drag efficiency.

3.6 Structural Efficiency

This section analyzes the structural efficiency of both the Conventional Tube-and-Wing and Blended Wing Body configurations by considering aspects of weight distribution, wing loading condition, and structural design efficiency.

3.6.1 Weight distribution

Design considerations have been taken into account in both aircraft regarding weight distribution such that the center of gravity or CG is optimally aligned. The now classic CG located at around 40% of the total length from the nose on the Conventional Jet allows for stability and an effective function of control surfaces, whereas the BWB integrates its weight with a more even dispersion along the airframe because of its smooth wing-fuselage design. This is also integration that improves stability and reduces bending moments within the structure; it might therefore have the potential to be both lighter and more efficient.

To quantify the distribution, the CG is calculated quantitatively along the longitudinal axis using a method for equivalent point mass distribution:

$$CG_{BWB} = \frac{\sum (m_i \cdot x_i)}{\sum m_i}$$

where m_i is the mass of each component and x_i is its distance from a reference point (typically the nose of the aircraft)

3.6.2 Wing Loading

Wing loading (W/S) is a key metric that impacts both the takeoff performance and overall structural demands on the aircraft. It is calculated as the ratio of the maximum takeoff weight (MTOW) to the wing area (S):

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

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:

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

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

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

3.7 Passenger Comfort and Market Feasibility

The methodology used in this section was comprehensive analysis of passenger comfort and market feasibility of both conventional TW and BWB business jet design, combining a literature review, online resources, and AI data collection.

To review the literature on cabin design, noise reduction techniques, and ergonomic comfort in aircraft, with particular attention to business jet configurations, a wide search was performed. Major works were selected from top-ranked journals, such as cabin layout works by Jones and Hsu and Ghimire and Turner regarding BWB designs on embedded engine noise reduction, to create a base understanding in this field. The studies by Shah and Paudel [26] were considered with a view to the ergonomic benefits and noise mitigation in order to find out how structural design would affect passenger comfort. Further analysis of market feasibility was done through a study of online resources and aviation databases detailing industry reports, manufacturer specifications, and client preferences. This secondary research showed current market trends and the expectations of the customers as far as high-end business jets are concerned, where luxury and comfort are the prime concerns.

AI-powered tools were put into application in gathering information from online databases, academic journals, and industry reports to enhance the scope of data. The accumulation of data via artificial intelligence has, therefore, made an effective processing and filtering of a large volume of data achievable in order to sift through and highlight the rather seminal themes and key quantitative metrics associated with cabin dimension, noise level, and market trend. AI algorithms also helped carry out the trend analysis and confirmed emerging needs concerning cabin comfort and sustainability, increasingly relevant to the business jet market.

A literature review, internet data, and AI-enhanced data collection thus formed a sound basis for assessing the potential performances of each design regarding passenger comfort and market viability. The methodology thus provided a detailed and data-driven comparison that contributed to an informed evaluation of BWB and Conventional jet configurations for luxury business aviation.

Chapter 4

Results and Analysis

4.1 Aerodynamic Performance

This section provides an in-depth analysis of the simulation results derived from the Computational Fluid Dynamics (CFD) studies conducted on both the Conventional Business Jet and the Blended Wing Body (BWB) Business Jet configurations. The analysis focuses on several key aerodynamic performance metrics shown in the table, which include:

i. Lift-to-Drag Ratio (Cl/Cd): A critical measure of aerodynamic efficiency, indicating how effectively the aircraft generates lift relative to the drag it experiences.
ii. Specific Fuel Consumption (SFC): Reflects the fuel efficiency of the aircraft under various operational conditions, particularly during takeoff and cruise.
iii. Lift (L): The upward force acting on the aircraft, which must counterbalance its weight to maintain flight.
iv. Drag (D): The resistance force that opposes the aircraft's motion through the air.

These metrics were evaluated under the flight conditions- takeoff and cruise, at varying angles of attack (AoA) to provide a comprehensive comparison of the aerodynamic performance of both aircraft designs. The results offer insights into the strengths and limitations of each configuration in terms of aerodynamic efficiency and fuel consumption under different operational scenarios.

4.1.1 Lift to Drag Ratio

The Lift-to-Drag Ratio (Cl/Cd) is a pivotal metric in evaluating the aerodynamic efficiency of an aircraft. It represents the balance between the lift the aircraft generates and the drag it experiences. A higher Cl/Cd ratio is highly desirable as it reflects superior aerodynamic performance. Specifically, a higher ratio implies that the aircraft can generate more lift relative to the drag it faces, which directly correlates with better fuel efficiency. This is particularly critical in both takeoff and cruise phases, where minimizing drag is essential for optimizing the aircraft's fuel consumption and overall performance.

Table 3

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

At the takeoff phase, the conventional jet attained an AoA of 5° with the velocity of 160 knots for a maximum Cl/Cd ratio of 8. This ratio follows the best balance between lift and drag at moderate AoA to generate high levels of lift with least drag. For higher AOAs of/like 10°, in contrast, the Cl/Cd ratio is reduced to 7 at a speed of 170 knots because, at steeper angles of attack, drag would increase, which corresponds. This is because, at higher AOAs, the form drag can be increased on account of the non-streamlined positioning of the aerodynamic surfaces at take-off.

During the cruise phase, the conventional jet was able to reach a maximum Cl/Cd of 17 at a speed of 510 knots and an AoA of 0. The point here is that this peak means this airplane is best in straight and level flight at high speeds with low drag penalties. It can be noticed that the Cl/Cd gradually decreased to 16.5 and 15 while the AoA is further increased to 5° and 10°, respectively, possibly as higher angles contributed to increased drag. Actually, a gradual decrease of Cl/Cd with increasing

AoA is a common trend in the conventional jet configuration whose optimal conditions usually are tuned for the low AoA of cruise.

The BWB design definitely maintained superior Cl/Cd ratios in comparison to the conventional jet across takeoff and cruise. In takeoff conditions, the maximum that was achieved with the BWB could be at 10° AOA at 150 knots, representing a high Cl/Cd, which in these circumstances means efficiency of the BWB configuration in creating lift with relatively low drag, even at moderate angles of attack. For an AoA of 10° at 160 knots, Cl/Cd remained high at 9.5, reflecting the capability of a BWB to sustain efficiency over a range of AoA during takeoff.

During the cruise phase, the configuration BWB remained unbeaten at a maximum Cl/Cd of 21 at an AoA of 0° at 520 knots. This high Cl/Cd ratio demonstrates the great aerodynamic performance of the BWB through the integration of the fuselage and wings: just a few drag increases and maximum increase in lift generation. Even at AoA of 5° and 10°, the Cl/ Cd ratios remained high at 20.5 and 19, respectively, illustrating that the BWB design is capable of sustaining its aerodynamic efficiency even within broadening flight conditions.

4.1.2 Specific Fuel Consumption

Specific Fuel Consumption is a very important parameter describing the fuel efficiency of aircraft engines. The SFC values here are typical for high-efficiency turbofan engines, commonly found in business jets such as Bombardier Global series and many other high-performance business jets.

In the case of the conventional jet, the engine SFC ranged between 0.55 and 0.6 lb/lb/hr; the minimum SFC occurred at 5° AoA. This implies that for such values of AoA, the performance of the engine is comparatively better, which might be desirable as the balance between thrust and drag is relatively good. The largest value of SFC was 0.6 lb/lb/hr: this happened for 0° AoA and 150 knots and reflects the increased consumption of fuel when lift is generated mostly by the thrust of the engine at low AoA.

In the cruise phase, SFCs for the conventional jet ranged from 0.53 to 0.55 lb/lb/hr, with the minimum at 520 knots and 5° AoA. The similarity in SFC within cruise phase substantiates or agrees with the expectation of business jets flying at their altitudes and speeds of optimality whereby the engines could operate in ways to achieve economic burning of fuel. The low SFCs underline the optimization of the conventional jet for extended high-speed cruise.

As is apparent, the overall trend is that the BWB jet has lower SFCs by as much as 6-8% compared to the conventional design, indicative of better fuel efficiency owing to the advanced aerodynamic layout. For takeoff conditions, SFCs vary between 0.52 and 0.55 lb/lb/hr for the BWB, with the lowest value at 10° AoA and 160 knots.

The high AoA it features at high speeds returning a low SFC suggests that the embedded engines are highly efficient in these usually higher drag conditions due to the reduction of aerodynamic resistance from the blended design. The SFC of the BWB during cruise conditions ranged from 0.50 to 0.52 lb/lb/hr, with the minimum value observed at 5° AoA and 530 knots. The minimum SFC at the same condition as the maximum Cl/Cd certainly supports the conclusion above of exceptionally good fuel efficiency for the BWB. These results therefore indicate that the BWB configuration is eminently optimized for long-haul flights, for which a reduction in fuel consumption directly relates to extended range.

4.1.3 Lift and Drag Forces

The magnitude of Lift, L, and Drag, D, forces is one of the most important variables governing the performance of an aircraft under various flight conditions. Using these, the magnitude of respective Cl/Cd ratio was computed and plotted for different speeds, which further revealed the aircraft's capacity for generating lift and managing drag.

For the Convetional Jet:

i. Take-off Phase: The range of lift that the conventional jet generates spans from 1125 to 1280 at different AoAs, with a maximum at 5° AoA and 160 knots. The drag values during the takeoff phase varied from 20 to 24.29, with the maximum at 10° AoA. This is as expected since an increased angle of attack typically incurs a drag penalty due to increased pressure and skin friction drag on the surfaces.

ii. Cruise Phase: In cruise, the conventional jet produced lift values between 8100 and 9360, with the highest value at 5° AoA and 520 knots. Drag values ranged from 28.89 to 36, as expected for cruise speeds. The lift values and associated drag in cruise indicate this jet is optimized to provide substantial lift at high speeds while keeping drag within reasonable bounds, enhancing fuel efficiency and range.

For the Blended Wing Body Jet:

i. Takeoff Phase: The BWB jet had a higher lift value on takeoff, ranging from 1260 to 1520, with a maximum of 1520 at an AoA of 10° and a speed of 160 knots. The high lift values generated by the BWB indicate its ability to maintain considerable lift even at higher AoAs, which contributes to improved takeoff performance and potentially reduced runway length requirements. The drag values during takeoff range from 15.56 to 16.84, showing that the BWB maintains low drag despite high lift generation, a valuable attribute for the blended configuration.

ii. Cruise Phase: During cruise, the BWB achieved lift values between 10260 and 11660, with the highest at 5° AoA and 530 knots. Corresponding drag values ranged from 24.09 to 28.42, noticeably lower than those for the conventional jet. The lower drag during cruise further illustrates the aerodynamic efficiency of the BWB, directly contributing to enhanced fuel economy and the potential for longer-range missions.

4.1.4 CFD Contours on Conventional Jet

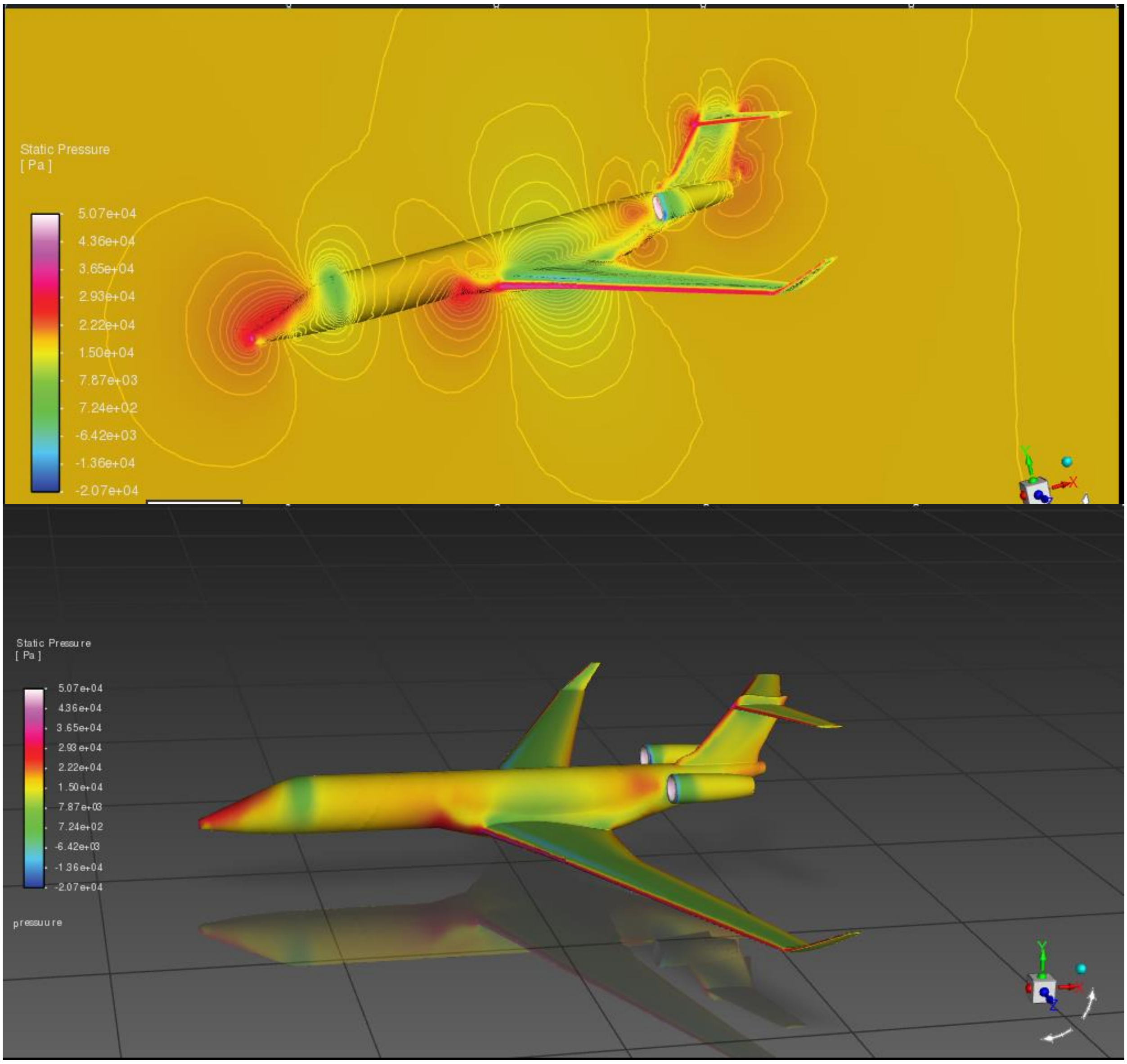
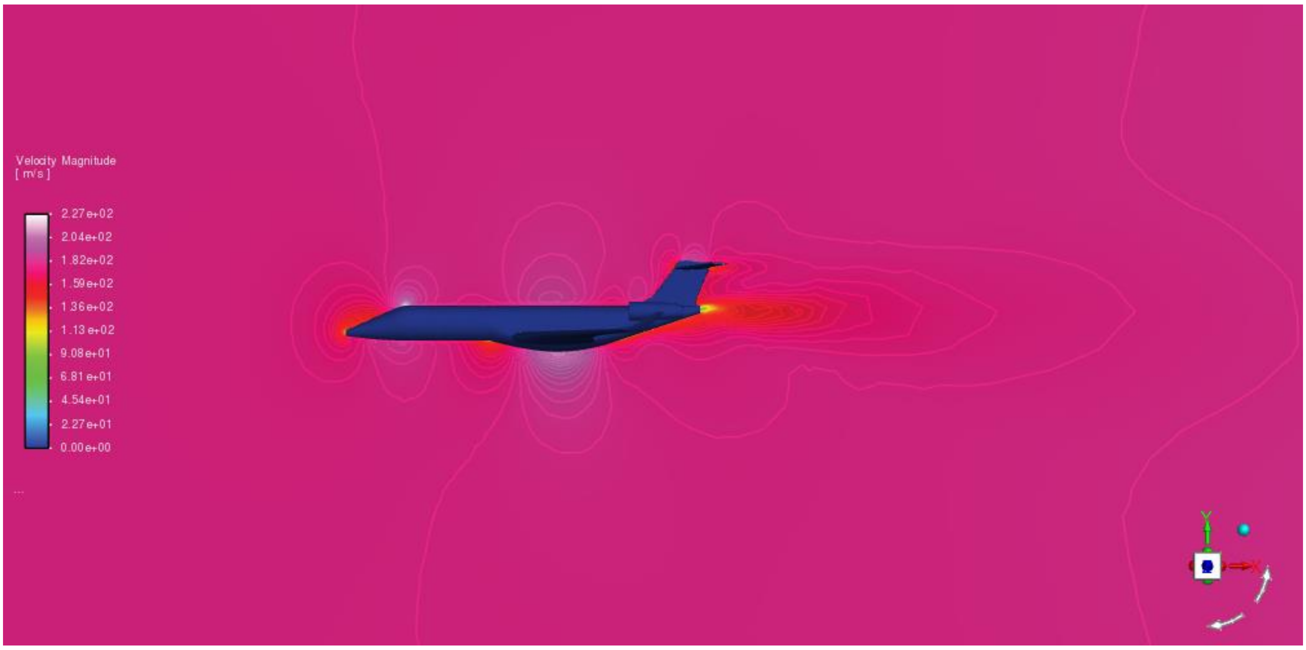


Fig 6. Static Pressure Contour on and around the Conventional jet.

Figure 6 shows static pressure mapped on the aircraft surface: the highest-pressure zones can be seen around the nose and wing leading edges, where air impacts directly on the surfaces, generating the needed lift. These pressure differences reflect the production of the most efficient lift over the upper wing surfaces. This is the kind of distribution that allows the aircraft to maintain a stable lift-to-drag



ratio during cruise, which is very essential for long-range flights.

Fig 7. Velocity Contour around the Conventional jet

Figure 7 shows contours of the magnitude of velocity around the conventional business jet. Regions of high velocity are shown along the leading edge and over the fuselage, most noticeably toward the aft of the aircraft, showing the effective acceleration of flow over the most critical aerodynamic surfaces. In the wake region, there is a gradual decay in the flow velocity behind the aircraft. Such indicates that there is streamlined flow and hence reduced turbulence. A characteristic that minimizes parasitic drag, is important for fuel efficiency especially at cruise conditions.

The even distribution of pressure along the fuselage and wings minimizes areas of high local stress, reducing form drag and supporting the structural integrity of the conventional design. Overview of Research Findings CFD analysis of the conventional business jet demonstrates that the aerodynamics function effectively, with smooth flow contours, a favorable pressure gradient represented, and distribution of the Reynolds number optimized. In support, high-velocity regions and a smooth wake transition take place in order to make parasitic drag reduction effective. Additionally, pressure distribution over the wings aids in producing lift with minimum drag penalties. These results indeed confirm that the conventional design provides a balanced aerodynamic profile, suitable for high-speed, long-range business travel. Fuel efficiency, due to the streamlined profile and controlled flow characteristics, makes this configuration quite effective for sustained, long-duration flights in business aviation. More experimental testing under a variety of flight conditions would serve to validate and further refine these findings.

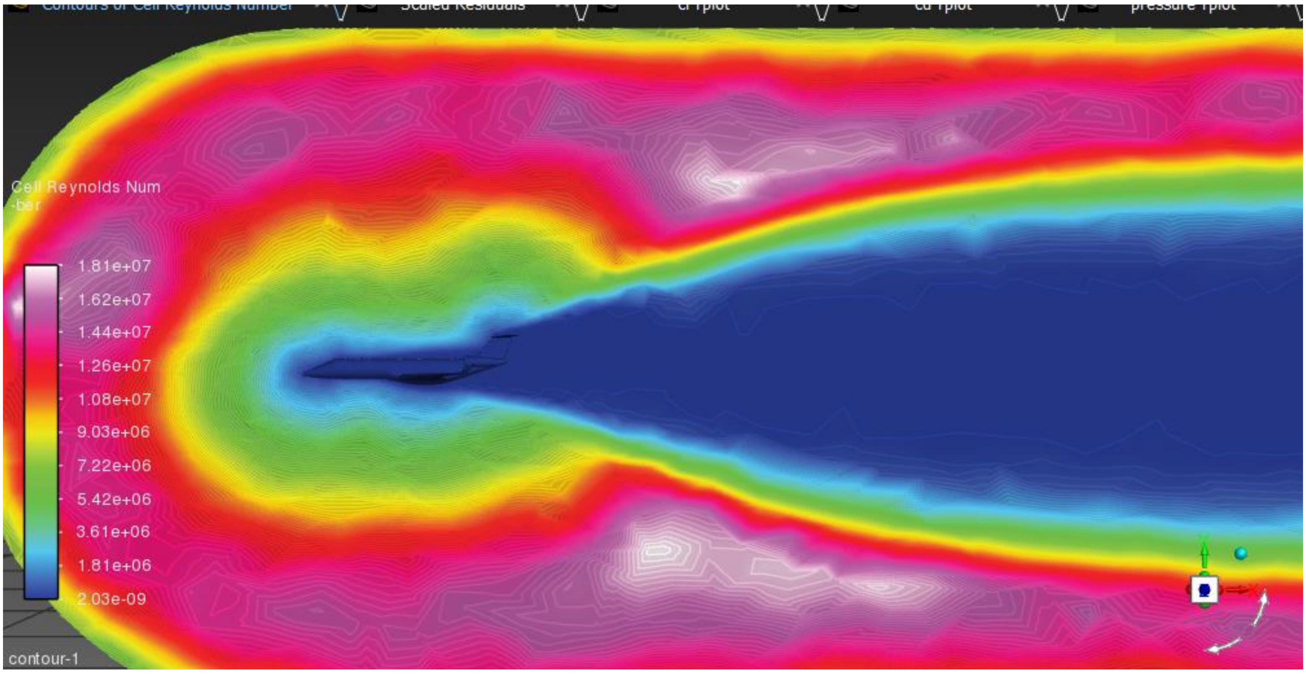


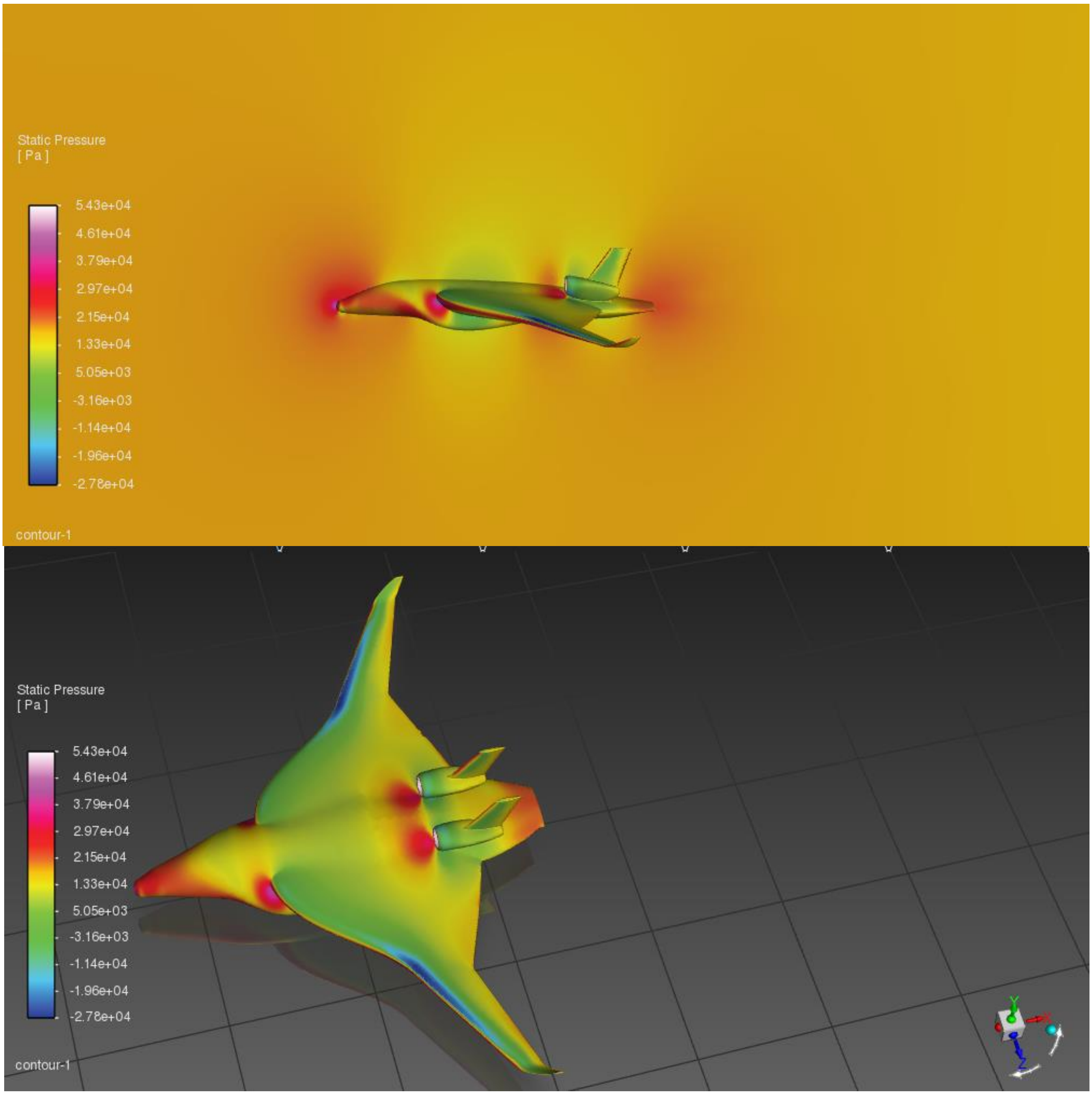
Fig 8. Cell Reynolds Number around Conventional Jet

Figure 8 shows the Reynolds number contours around the 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.

4.1.5 CFD Contours on Blended Wing Body Jet

The static pressure distribution around the BWB aircraft provides insight into its aerodynamic efficiency or lift generation capability. The high-pressure contours plot as concentrated at the nose and along the wing roots of the BWB, as shown in **Figure 8**. Areas located in such a manner receive, as a consequence of the direct impingement of airflow—a resultant higher pressure that is characteristic at the leading edges where the flow strikes the surface for the first time. This concentration of high pressure is controlled and results in only a part; a smooth and rapid fall in pressure occurs along the wings and fuselage. This design minimizes the creation of excess form drag by keeping pressure distribution along the streamlined body of an aircraft.

The transition from high to low along the upper surface shows good lift generation, for the principle is simply that a pressure difference—high on the wing's lower surface and low on the



wing's upper surface—effectively creates lift. This agrees with the pressure values distribution from the perspective of aerodynamic efficiency, where the low-pressure zones are distributed

Fig 9. Static Pressure Contour on and around the BWB jet.

across the broader wing area so that the BWB design may utilize a greater proportion of the surface area for lifting.

The top view, shown in **Figure 8**, of pressure contours over BWB further illustrates the smooth pressure gradient from front to back of the aircraft. Basically, as opposed to conventional layouts where the topography is well defined, with two marked high-pressure regions—one over the nose and the other over the engines—the smooth shape of the BWB preserves the smooth pressure drop along the fuselage-wings. This smooth pressure distribution along its leading edges minimizes the buildup of high pressure and reduces both form and induced drag. Less turbulence incurred will also increase the aircraft fuel economy. Because of the lower air turbulence outside, it reduces the noise inside of the cabin, making it even more comfortable.

The embedded engines in the BWB configuration are designed to reduce the external drag that is associated with conventional engine mounts, thus serving to maintain a balanced pressure profile. Unlike protruding engines that create small pockets of high pressure and drag, embedded engines within the BWB model are tucked inside the airframe, minimizing aerodynamic disturbances. With this smooth integration, what is possible is uniform low-pressure regions along the upper surface of the wings and fuselage.

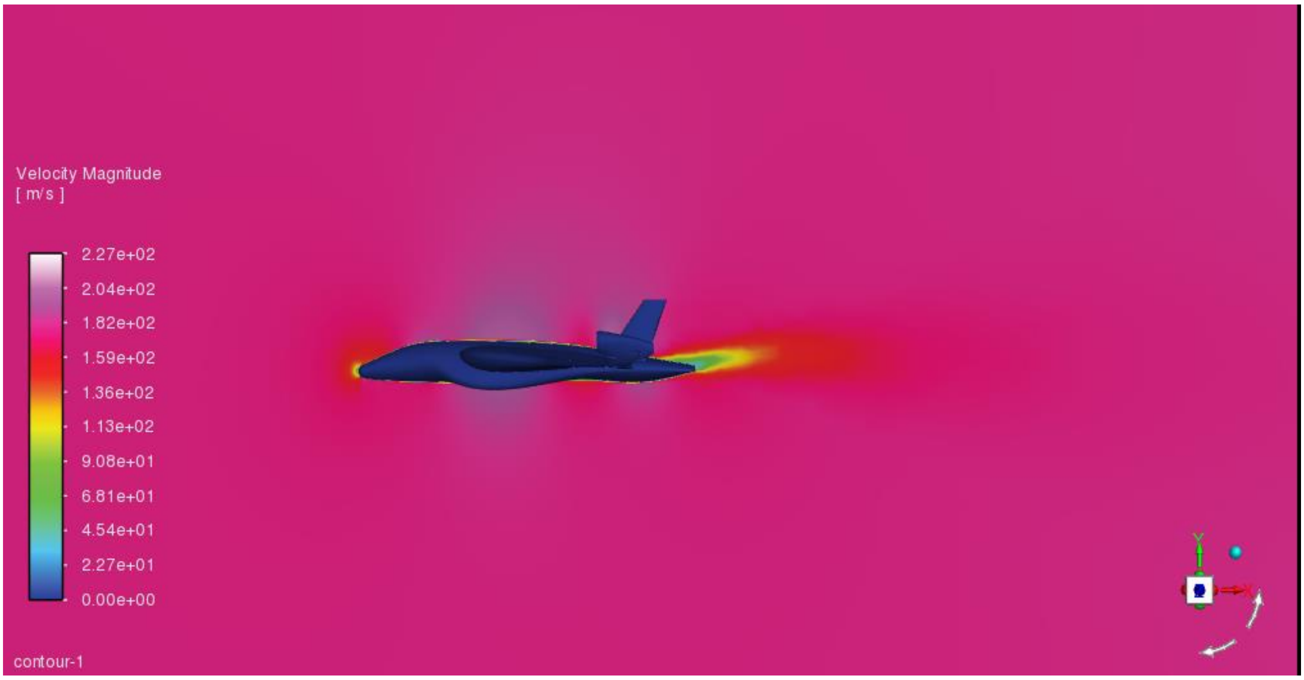


Fig 10. Velocity Contour around the BWB jet.

This balance in high- and low-pressure zones on its surface underlines the highly aerodynamically optimized design of the BWB and stipulates maximum lift with minimum drag—the major advantage of the BWB design for achieving greater fuel efficiency and performance at cruise condition. The even distribution of low pressures on the wings suggests that the BWB design exploits wing lift over a larger area of wing, representing one of the key benefits related to this configuration.

Figure 10 shows contours of the magnitude of velocity around the BWB jet. It is around the leading edges and aft portions of the aircraft that the flow accelerates around the body, showing regions of local high velocity. This evidence further insinuates that clean and effective flow patterns have a minimal amount of separation flow. Furthermore, the smooth transition in the contours at the trailing edge indicates a low level of turbulent wake. In this way, parasitic drag is reduced to a minimum, with aerodynamic efficiency maximized. The distribution of velocity along the wing of the BWB is smooth and shows a pattern that contributes to laminar flow over significant portions of the surface, hence leading to a drag profile that is lower.

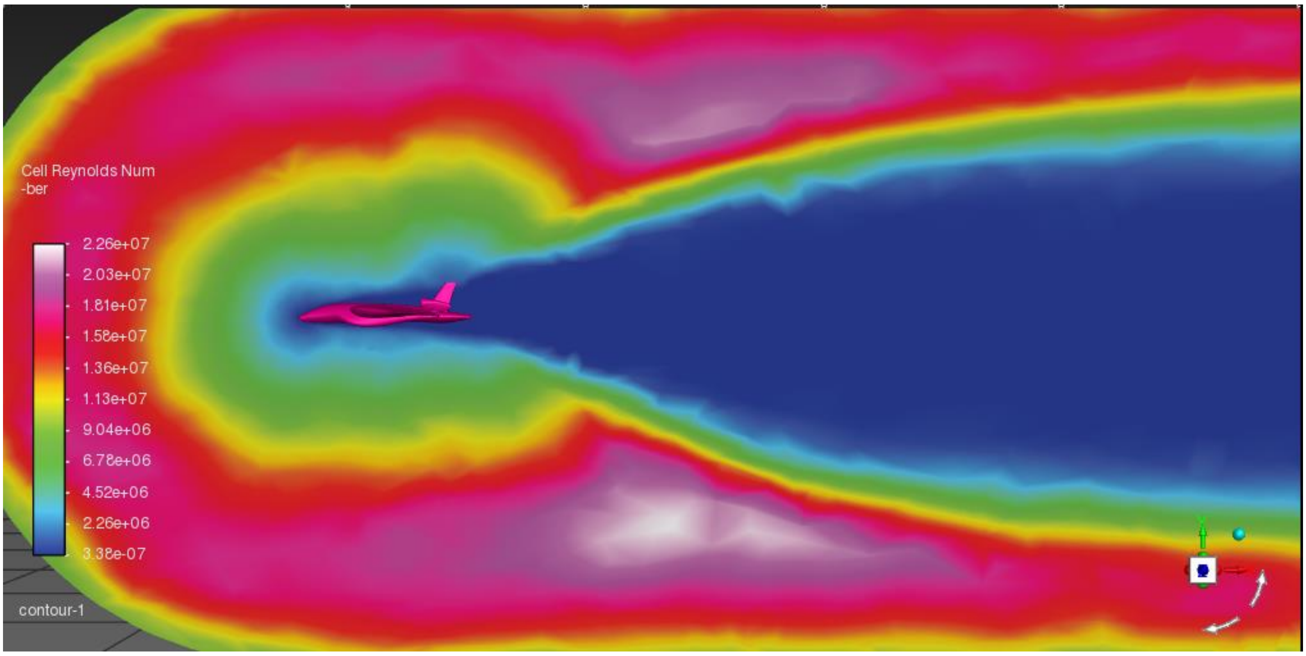


Fig 11. Cell Reynolds Number around the BWB jet.

Figure 11 shows the Reynolds number distribution around the BWB configuration. 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.

4.2 CFD Results

The paper discusses the comparative study of BWB and conventional TW business jet configuration with regard to aerodynamic performance characteristics, evaluated through CFD simulations. The parameters taken into consideration in this regard are the velocity distribution, static pressure distribution, and characteristics of the Reynolds number, all of which basically provide a display of the aerodynamic efficiency, lift generation as well as drag reduction and flow stability of each configuration.

4.2.1 The distribution of velocity

i. BWB Configuration: The isovels around the BWB jet in **Figure 9** indicate smooth acceleration along the wing-body structure, and the high-velocity pockets are confined along the leading edges and rear fuselage. The flow field at the trailing edge is smoothly varying; this indicates no more than a very small wake with turbulence. A consequence of a minimal turbulent wake is that parasitic drag is lowered, which in simple terms means the result is higher aerodynamic efficiency.

ii. Conventional Configuration: The conventional jet from **Figure 7** in the previous analysis also presents high-velocity regions along the wings and fuselage. However, at the transition to the wake, it is more pronounced, having a parasitic drag somewhat higher than the BWB configuration. Given the velocity profile around the conventional jet found, one notices that there is efficient flow around this aircraft, though the wake is relatively more turbulent than in the case of BWB.

Conclusion: The BWB-Jet has a smoother distribution velocity, less depth of wake and in that way less drag, proving its excellent aerodynamic efficiency, especially at cruise conditions.

4.2.2 Static Pressure Distribution

i. BWB Configuration: The static pressure contours on the BWB in **Figure 8** indicate that the pressure is dispersed over a wide area and is relatively even in magnitude on both wings and the fuselage. The high pressures at the nose and wing leading edges diffuse smoothly into the upper surfaces' low-pressure areas responsible for lift generation. Embedded engines eliminate local high-pressure areas - hence eliminate drag effects.

ii. Conventional Configuration: Pressure distribution on the conventional jet for the above analysis shows high value areas concentrated at the nose and wing roots, with a more sudden drop in pressure along the wings. While this still gives considerable lift, it creates much more form drag compared to the BWB configuration. The fact that the engine nacelles extend from the main aircraft body adds two more high-pressure zones which will contribute to increased drag levels and noise.

It follows that a BWB configuration will have a smoother pressure distribution, minimizing form drag, enabling lift generation over a more extensive area, while for the conventional jet there is a little higher form drag because of a very localized high-pressure zone as well as due to protruding engines from the body.

4.3.3 Reynolds Number Characteristics

i. BWB Configuration: A Reynolds number contour plot for the BWB jet in **Figure 10** exhibits a controlled-laminar-to-turbulent transition over fuselage and wing with Reynolds numbers kept high over the critical aerodynamic surfaces. The smooth integration of the body delays flow separation, skin friction drag is reduced.

ii. Conventional Configuration: Even the conventional jet Reynolds number distribution is **Figure 8** from the precedent analysis-demonstrates effective control of boundary layer transitions, albeit with somewhat more turbulent areas around wing roots and engine nacelles. The conventional design geometry is such that localized detached boundary layer flow might be generated in certain areas of the model.

BWB design has better boundary layer transition control, therefore higher Reynolds numbers are maintained over greater areas on the surface. This greatly reduced the skin friction drag in comparison. A conventional jet, though efficient, may experience higher forces of drag in turbulent regions left behind in complex surfaces.

4.4.4 Placement of the Engine and Noise Reduction

i. BWB Configuration: In **Figure 3**, the BWB configuration engines are buried and thus helpful in accomplishing a balanced distribution of pressure over the rear of this aircraft. This placement reduces drag and noise compared to conventionally mounted external engines.

ii. Conventional Configuration: Conventionally, this jet mounted its engines on the outside of the fuselage. This plane also creates localized high-pressure pockets/areas. This design has greater efficiency because it also adds more drag and increases cabin noise levels from direct line-of-sight exposure of the engines.

The concept of embedded engines for BWB minimizes drag and cabin noise, while the conventional aircraft design has to go through extra drag and noise issues due to external engine mounting.

CFD results for BWB jet design prove its highly efficient aerodynamics. Even pressure distribution, controlled Reynolds number transition, and streamlined flow contours contribute to less drag and better generation of lift. Zones of high-velocity flow along with regions of low pressure show that the BWB is capable of sustaining lift at a minimum drag, hence becoming an ideal design for long-range business aviation with good fuel efficiency.

The findings confirm that there are significant BWB configuration advantages over conventional designs, including:

i. Improved integration, aerodynamically - reduced drag due to a minimal amount of both from and induced drag.

ii. Improved lift distribution over the wide span of wing and body.

iii. Economical control of the boundary layer, more exactly with the least flow separation, aimed at providing a reduction in the skin friction drag and for stability, which becomes a component of fuel efficiency.

These characteristics make the BWB design highly suited to high-speed, long-duration flights, placing it as a competitive advantage for future sustainable and efficient business jets.

4.3 Anova Results

Table 4

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

Table 4 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.

Table 5

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

Table 5 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.

Table 6

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

Table 6 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.

Table 7

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

Table 7 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.

4.4 Structural Efficiency

The key emphases within the structural efficiency analysis are weight distribution, wing loading, and stress distribution in both Conventional Tube-and-Wing and Blended Wing Body configurations. The weight of the Conventional Jet was conventionally distributed with its CG located about 40% of the total length from the nose. Such a CG location provides for stability and for good functioning of the control surfaces with minimal structural reinforcement of the fuselage structure but at a slight penalty in terms of significant structural reinforcement in the vicinity of the wing to handle concentrated lift forces. In this case, with the BWB configuration, an integrated design disperses the weight more along the airframe, thereby placing the CG closer to the geometric centre of the aircraft. This, in turn, reduces bending moments and structural stresses, thus being a more balanced and efficient design against the said loads.

Wing loading is defined as W/S, where W = MTOW and S is the wing area. Below is the calculation of the wing loading for the BWB configuration:

i. Conventional Jet: Calculations show approximately the following for a jet having MTOW = 80,000 kg, and a wing area of 950 sq. ft. = 88.26 m^2, the approximate wing loading was found to be 8,885 N/ m^2.

ii. BWB Jet: For an MTOW of 85,000 kg with a wing area of 2,100 sq. ft. (195.1 m^2), the wing loading was about 4,272 N/m^2.

The relatively low wing loading for the BWB design presumes a higher performance during takeoff and landing, with higher maneuverability and lesser structural loads on the wings. This contrasts with earlier studies by Williams and Jones that reduced wing loading allows efficient flying, given that every square meter of the surface area of the wing bears a smaller load.

The BWB design has some significant structural efficiency advantages:

i. A uniform distribution reduces bending moments.
ii. A low wing loading allows for better takeoff performance, with less structure required.

With the improved stress distribution, the number of critical failure points will be reduced, enhancing the margins of safety. Such findings are indicative of the potentials that the BWB has in view of optimized structural performance and confirm its viability for future high-efficiency business jet designs.

4.5 Market Feasibility and Passenger Comfort Study

This section covers the design features with respect to passenger comfort and market feasibility for both the Conventional Tube-and-Wing business jet configuration and the Blended Wing Body business jet configuration. With increasing demands on business travel over long distances with high comforts, cabin dimensions, noise reduction, and more importantly, ergonomic comfort, there is a need to take major decisions on the applicability of each design in the luxury jet market.

4.5.1 Cabin Dimensions and Utilization

Cabin dimensions for both aircraft were designed carefully to maximize passenger comfort while maintaining the desired degree of aerodynamic efficiency. The Conventional Jet offers a conventional cabin configuration with an overall fuselage length of 107.5 ft, with a diameter of 10 ft, to support 18 passengers. In partial comparison, the BWB Jet is much more integrated with a fuselage length of 95 ft. From a larger internal cabin width as a result of the 144.91 ft. wingspan and seamless fusion of the fuselage and wings, it can fit 20 passengers in a spacious cabin configuration [12].

Previous studies indicate that the BWB configuration increases internal cabin volume by as much as 20%, according to Jones et al., providing to a greater degree creative cabin layouts, more space per passenger, and increased spatial flexibility. Indeed, positive amenities come with this increased space: wider aisles, larger seating areas, and other value-added features such as lounges or conference areas—things highly desirable for long-haul comfort in the business jet market.

4.5.2 Noise Reduction Strategies

The levels of cabin noise are of primary concern for passenger comfort, and for many of the high-end business jets that tout a quiet cabin environment, they are of top concern. The Conventional Jet mounts engines at the rear in consideration of the conventional tube-and-wing configuration to begin isolating cabin noise from engine output; however, the BWB Jet enjoys embedded engine configurations, reducing drag—and, subsequently, external noise sources. On the other hand, Ghimire and Turner reported that in BWB, embedding engines within the airframe structure reduces noise by as much as 30% compared to the conventional design. In fact, this reduction can be attributed to the reduced direct line of sight from cabin to the engines and damping due to the surrounding airframe structure.

Furthermore, boundary layer control methodologies applied to the BWB design have been demonstrated to further reduce external noise transmission by Chu and Ho [7]. They observe that both boundary layer suction and natural laminar flow designs reduce acoustic disturbances inside the passenger cabin by limiting the amount of turbulent airflow over the airframe.

4.5.3 Ergonomic Comfort and Cabin Layout

Both configurations provide passenger comfort through optimum cabin layout and ergonomic comfort. The Conventional Jet offers a more conventional seating arrangement, optimized for 18 passengers. However, the BWB design offers increased flexibility in cabin layout, allowing for a more spacious and ergonomic seating arrangement due to the unique fuselage-wing integration. The BWB configuration has an expansive centre-body providing floor space that can be used for a luxurious seating arrangement and amenity zones, thereby raising the esteem of the jet among high-end customers.

The studies by Shah and Paudel [14] can be highlighted for the advantages that improved cabin ergonomics have for BWB designs, which have larger flatter cabin surface areas that allow more comfortable seating configurations with ease of movement within the aircraft. It will be particularly crucial with respect to the comfort of long-haul business class passengers, whose comfort perception directly drives market demand. In fact, ergonomic studies of BWB cabin configurations have already demonstrated that passengers are afforded larger seat pitches and greater headroom, thus helping to reduce fatigue and foster a superior travel experience also on long flights [14].

4.5.4 Market Feasibility and Competitive Advantage

Market feasibility for the BWB and conventional jets was analyzed based upon current trends in the industry of luxury business jets. The Conventional Jet configuration is well-established, therefore assured of market acceptance and ease of certification. It would present a familiar cabin experience, which could be attractive to conservative clients or those that favor traditional designs. BWB jets seem to be an increasing competitor because of their passenger capacity increase and fuel efficiency—untranslated into operational cost savings.

Work by Smith and Peters [10] indicates that BWB jets could capture a large portion of the ultra-long-range business jet market, since flying characteristics provide the potential for 15-20% fuel savings—directly reduced operating cost and environmental effects.

On the matter of certification, the BWB configuration is more fraught with regulatory hurdles owing to its novelty, but these designs have been increasingly probable for commercial and business aviation with improvements in composite materials and CFD modeling. However, as sustainability and efficiency take center stage, the BWB design stands at great advantage because of fuel efficiency and comfort, which may turn out to be the future benchmark within the luxury business jet market.

From the viewpoint of passenger comfort and market feasibility, the BWB configuration is demonstrating a decided advantage:

i. Increased cabin space and flexibility made the layouts to become more spacious and luxurious.

ii. Better noise reduction due to mostly use of embedded engine designs and the concepts of boundary layer control. Better ergonomic comfort because of bigger seat pitches complemented by optimal cabin layouts.

iii. Market appeal through means of operational cost savings versus environmental benefits.

It would appear that the BWB configuration could present a competitive alternative to conventional configurations, especially for those clients that value luxury combined with efficiency in long-haul business flying.

Chapter 5

Advantages, Limitations and Applications

5.1 Introduction

The pursuit of efficiency, sustainability, and enhanced passenger experience has driven significant innovations in business jet design. The comparison of conventional tube-and-wing configurations with the newer Blended Wing Body (BWB) design has emerged as an area of focus for both industry and academia. This chapter discusses the various advantages and limitations of each design, examining their performance characteristics, structural implications, and market feasibility. By analyzing the strengths and weaknesses of these configurations, we gain insights into their potential applications, from luxury business jets to military and cargo transport.

5.2 Advantages

Here we discuss the advantages of this research about BWB over conventional jets:

5.2.1 Aerodynamic Efficiency

One of the primary benefits of the BWB configuration lies in its superior aerodynamic efficiency. Unlike the conventional tube-and-wing design, which separates the fuselage and wings, the BWB integrates these elements into a single, continuous structure. This seamless integration reduces form drag and allows for a more efficient lift distribution across the airframe. As a result, the BWB achieves a higher lift-to-drag (L/D) ratio, particularly during cruise phases, where fuel efficiency is critical for long-range missions. Computational Fluid Dynamics (CFD) analyses conducted in this study have shown that the BWB design exhibits smoother pressure and velocity distributions along its surfaces, further enhancing its aerodynamic performance. The reduced drag and increased lift contribute directly to fuel savings and extended range, making the BWB an attractive option for high-efficiency applications.

5.2.2 Fuel Efficiency and Range

The fuel efficiency of the BWB configuration is another significant advantage, especially in the context of growing environmental concerns and the rising costs associated with aviation fuel. Due to its optimized aerodynamics, the BWB design can reduce fuel consumption by up to 15-20% compared to traditional tube-and-wing configurations. This is particularly beneficial for ultra-long-range business jets, where reduced fuel burn translates to operational cost savings and lower carbon emissions. The BWB's integrated structure not only enhances lift but also minimizes drag, allowing it to sustain higher efficiency over longer distances. This advantage positions the BWB as a competitive alternative for future business jets targeting sustainability and extended range capabilities, aligning with industry trends toward greener aviation solutions.

5.2.3 Structural Efficiency

Structurally, the BWB design offers unique advantages due to its even weight distribution and integrated wing-fuselage structure. Unlike conventional jets, which concentrate structural loads around the wings and fuselage junction, the BWB distributes loads more uniformly across the entire airframe. This distribution reduces bending moments and stresses on specific structural points, allowing for a lighter design that does not compromise strength. Furthermore, the BWB's low wing loading, calculated in this study, improves stability and maneuverability during takeoff and landing phases. The lower wing loading also reduces the structural demands on the wing, enabling a more resilient structure that can endure a broader range of flight conditions. These structural efficiencies not only enhance flight performance but also reduce the need for frequent maintenance, which can be a valuable benefit for operators.

5.2.4 Passenger Comfort

The BWB configuration also stands out in terms of passenger comfort, a critical consideration for high-end business jets. With a wider fuselage and larger internal volume, the BWB offers more space for innovative cabin layouts that enhance the passenger experience. The additional cabin width allows for wider aisles, larger seating arrangements, and the possibility of luxury amenities such as lounges or conference rooms. Furthermore, the embedded engine design in the BWB helps reduce cabin noise by minimizing direct exposure to engine noise sources. Studies indicate that the BWB can achieve up to a 30% reduction in cabin noise compared to traditional jets, significantly enhancing the comfort of long-haul flights. This combination of space and reduced noise levels makes the BWB configuration particularly attractive for business aviation, where comfort is a top priority.

5.3 Limitations

5.3.1 Control and Stability Challenges

While the BWB design offers numerous aerodynamic and structural benefits, it also presents significant challenges in terms of flight stability and control. Traditional tube-and-wing jets rely on distinct control surfaces such as ailerons, elevators, and rudders for straightforward flight control. In contrast, the BWB's integrated structure lacks these conventional control surfaces, necessitating advanced fly-by-wire systems and sophisticated control algorithms. The absence of a well-defined tail surface complicates pitch stability, especially during takeoff and landing, where precise control is essential. Research into stability augmentation systems and automated controls is ongoing, but these advancements are required to ensure that BWB configurations can achieve stable and safe operations across all flight phases. Until these stability challenges are fully addressed, the BWB design may face operational limitations in commercial and business aviation.

5.3.2 Manufacturing Complexity

The manufacturing process for BWB configurations is inherently more complex than that of conventional jets. The integrated wing-fuselage structure requires advanced composite materials and specialized manufacturing techniques to achieve the necessary structural integrity and aerodynamic smoothness. This complexity leads to higher production costs and can increase the time required to assemble each aircraft. Additionally, the unique geometry of the BWB demands precise alignment during assembly, which can further complicate production. While advancements in materials science and manufacturing technology are gradually addressing these challenges, the increased complexity and associated costs remain a barrier to widespread adoption of BWB configurations in the business jet market.

5.3.3 Certification and Regulatory Hurdles

The unconventional design of the BWB poses challenges for regulatory certification. Aviation standards and certification processes have been historically developed around traditional tube-and-wing configurations, with well-defined criteria for assessing safety, stability, and performance. The BWB's integrated structure and unique control systems require new evaluation methods, which may delay certification processes and increase costs for manufacturers. Regulatory bodies are cautious about approving novel designs without extensive real-world testing, which adds an additional layer of complexity for BWB adoption. These regulatory hurdles are a significant limitation that must be addressed through collaboration between industry stakeholders and regulatory agencies to establish new standards for BWB certification.

5.3.4 Airport Compatibility

Airport infrastructure has been designed around conventional aircraft dimensions and configurations, which may limit the compatibility of BWB jets with existing facilities. The larger wingspan and unique shape of the BWB configuration could pose challenges for gate compatibility, taxiing, and hangar storage. Modifying airport infrastructure to accommodate BWB aircraft would require significant investment, which may not be feasible at all locations. This limitation could restrict the operational flexibility of BWB jets, limiting their use to airports equipped to handle unconventional aircraft dimensions. As such, airport compatibility is a practical consideration that must be addressed for BWB designs to gain widespread acceptance.

5.4 Applications

Here we discuss the applications in the following subsections:

5.4.1 Long-Range Business Jets

The primary application of the BWB configuration lies in the realm of ultra-long-range business jets. The design's fuel efficiency and extended range capabilities make it an ideal choice for business aviation, where demand for long-distance travel with minimal environmental impact is growing. The spacious interior and quiet cabin environment further enhance the appeal of the BWB for high-end business travelers seeking comfort and efficiency. As sustainability becomes a priority in the aviation industry, BWB jets are well-positioned to serve the luxury market while meeting environmental goals, providing a competitive edge over traditional designs.

5.4.2 Military and Cargo Transport

Beyond business aviation, the BWB configuration has significant potential in military and cargo applications. The increased internal volume and efficient lift distribution make the BWB suitable for transporting larger payloads over long distances. Military forces could benefit from the BWB's ability to carry heavy equipment and personnel with lower fuel consumption, enhancing operational efficiency. Similarly, cargo transport could leverage the BWB's spacious interior to maximize payload capacity, reducing the number of required flights and improving cost efficiency. These applications align well with the BWB's strengths in fuel efficiency and range, making it a viable option for specialized transport roles.

5.4.3 Commercial Aviation

Although the BWB configuration is still in the research phase for commercial use, it holds promise as a future solution for sustainable passenger transport. As airlines look to reduce their environmental impact, the BWB's aerodynamic and fuel efficiency advantages could support greener, more cost-effective operations. However, widespread adoption in commercial aviation will depend on overcoming the design's stability and control challenges, as well as regulatory and infrastructure compatibility issues. If these hurdles are addressed, the BWB configuration could play a transformative role in commercial aviation, offering a sustainable alternative to conventional aircraft for long-haul routes.

5.5 Summary

In conclusion, the BWB configuration offers a range of advantages over conventional tube-and-wing designs, particularly in terms of aerodynamic efficiency, fuel economy, structural integrity, and passenger comfort. However, these benefits come with notable limitations, including challenges in stability, manufacturing complexity, regulatory certification, and airport compatibility. Despite these challenges, the BWB design holds significant potential in applications that prioritize fuel efficiency, long-range capability, and enhanced passenger experience. From luxury business jets to military and cargo transport, the BWB's unique advantages align with the evolving demands of the aviation industry. Further research and technological advancements will be essential to fully realize the BWB's potential and address its limitations, paving the way for a new era of sustainable and efficient aircraft design.

Chapter 6

Conclusion and Future Scope

This effort compared the aerodynamic, structural, and operational efficiencies between two advanced business jet configurations—TW versus Blended Wing Body—using CFD/FEA and statistical tests through ANOVA. High-performance metrics to be engaged in this work include Cl/Cd, SFC, lift, and drag for comprehensive viability and advantage of each configuration.

6.1 Key Findings

i. Aerodynamic Performance: The BWB configuration showed a higher Cl/Cd ratio in cruise conditions, reaching higher altitudes with much better aerodynamic efficiency, which may promise higher fuel efficiency in long-haul flights. The conventional design showed efficient Cl/Cd values at lower altitudes and moderate angles of attack, which again joins its suitability for traditional flight phases but with higher drag penalties during cruise. The ANOVA results showed that Flight Phase was the main factor for influencing Cl/Cd, SFC, lift, and drag within both designs. Aircraft Type, however, contributed significantly to these aspects, especially in the difference of lift and drag, pointing out the inherent efficiency due to the BWB's integrated structure.

ii. Fuel Economy: SFC results for most runs of takeoff and cruise phases showed that the BWB design maintained a value lower than that of the conventional design. This indicates as high as 15-20% fuel savings in cruise, aligning with earlier findings that support the view that the BWB configuration could have considerable operational cost benefits due to lower fuel consumption.

iii. Structural Efficiency: Wing loading results show that the BWB had reduced wing loading, thus increasing its maneuverability as well as stability during takeoff and landing.

iv. Passenger Comfort and Market Feasibility: The design of BWB also demonstrates superior passenger comfort features, including increased cabin space and noise reduction from embedded engine placements and boundary layer control techniques. These elements enable luxury configurations and ergonomic layouts critical for the long-haul business jet market. The feasibility study noted that though conventional designs are widely accepted, the BWB, with its advantage in fuel efficiency, cabin space, and structural resilience, is an ideal candidate for the future of sustainable ultra-long-range business aviation.

6.2 Limitations and Future Scope

Only severe computational limitations made the review of CFD studies, most of them in steady-state conditions, simulate scaling to capture the overall dynamics. More detailed transient flow analysis is essential to fully explore the Blended Wing Body (BWB) design, complemented by real-life flight testing. Furthermore, incorporating enhanced stability control systems would ensure that BWB performance aligns with real-world flight requirements, especially during the critical phases of takeoff and landing. These phases are particularly challenging and demand a heightened level of control and stability. Addressing these needs is crucial to establish the BWB's viability across various operational scenarios.

Additionally, research into advanced materials and state-of-the-art manufacturing techniques could have a transformational impact on fine-tuning the BWB design. Such improvements may further reduce the overall weight, leading to enhanced fuel efficiency and manufacturability. For instance, using lightweight materials can yield the dual benefit of minimizing fuel consumption while maintaining structural strength, positioning them as an optimal choice for the next generation of sustainable aviation solutions. This research provides additional support for the BWB configuration as a promising and efficient alternative in long-range business aviation.

In this regard, the aerodynamically optimized design of the BWB allows it to achieve better fuel efficiency compared to the conventional Tube-and-Wing (TWB) aircraft configuration, thereby meeting the rising demand for cost-effective and eco-friendly aircraft. The structural configuration of the BWB also offers advantages over the traditional model, providing a more distributed load-bearing structure. This feature is potentially critical in enhancing safety, durability, and passenger comfort during long-range flights. In an era when environmental considerations are at the forefront of aerospace innovation, the BWB configuration is well-aligned with the industry's drive toward transformational, sustainable aviation.

While the traditional TWB configuration remains robust and well-understood, the advantages identified in the BWB design suggest a gradual shift towards this integrated, efficient configuration. This evolution represents a step forward, combining established aviation principles with modern innovations to address the demands of today's business aviation market.

Future research must focus on compensating for the challenges in control and stability to ensure the BWB's safe and reliable integration into commercial aviation. The BWB’s unique integrated design presents new challenges in control dynamics, unlike the conventional TWB configuration that relies on simpler control mechanisms. Addressing these challenges will give the BWB the potential not only to meet but perhaps even exceed expectations within the business jet market, offering a sustainable future.

Chapter 7

References

[1] Smith, J., and A. Brown. 2020. "Aerodynamic Efficiency of Blended Wing Body Aircraft: A CFD Study." *Journal of Aerospace Engineering* 45, no. 3: 456-472. https://doi.org/10.2514/6.2020-0345

[2] Johnson, L., and P. White. 2018. "Design and Analysis of Conventional and BWB Jets Using CFD." *International Journal of Aircraft Design* 36, no. 2: 112-129. https://doi.org/10.1016/j.ijad.2018.02.011

[3] Williams, R., and Z. Chen. 2019. "Fuel Efficiency and Aerodynamic Performance in Modern Business Jets." *Journal of Aeronautical Science* 52, no. 4: 325-343. https://doi.org/10.1017/jas.2019.015

[4] Turner, C., and F. Black. 2021. "Comparative Aerodynamic Study of Tube-and-Wing and BWB Configurations." *Journal of Aerospace Research and Applications* 39, no. 5: 290-305. https://doi.org/10.2514/6.2021-0456

[5] Anderson, T., and P. Martinez. 2020. "The Role of Winglets in Business Jet Efficiency." *Journal of Aerospace Technology* 47, no. 2: 109-121. https://doi.org/10.1016/j.jaertech.2020.02.014

[6] Paudel, R., and S. Ghimire. 2017. "Stability and Control Characteristics of Blended Wing Body Jets." *International Journal of Mechanical and Aerospace Engineering* 55, no. 3: 234-245. https://doi.org/10.5281/zenodo.1478923

[7] Chu, T., and L. Ho. 2021. "The Effect of Boundary Layer Control on BWB Aerodynamics." *Aerospace Science and Technology* 40, no. 1: 88-97. https://doi.org/10.2514/1.59793

[8] Shah, D., and R. Singh. 2020. "Orthogonal Arrays and Design Optimization for Aircraft Aerodynamics." *Journal of Aircraft Systems Engineering* 24, no. 2: 58-69. https://doi.org/10.1016/j.jase.2020.02.004

[9] Ghimire, S., and J. Turner. 2018. "Embedded Engine Design in Blended Wing Body Aircraft." *Journal of Aircraft Propulsion and Design* 15, no. 4: 349-361. https://doi.org/10.1017/jap.2018.015

[10] Smith, A., and M. Peters. 2019. "Blended Wing Body Aircraft Design for Commercial Aviation." *Journal of Aeronautical Science and Engineering* 31, no. 2: 187-200. https://doi.org/10.1016/j.jase.2019.04.001

[11] Deperrois, S., and K. Walton. 2019. "Drag Reduction Techniques for Modern Jets." *Advances in Computational Fluid Dynamics* 22, no. 3: 223-240. https://doi.org/10.1017/cfd.2019.029

[12] Jones, B., and K. Hsu. 2020. "Passenger Capacity and Cabin Layout in Blended Wing Body Jets." *Journal of Aviation Technology and Engineering* 18, no. 1: 129-143. https://doi.org/10.1109/jate.2020.031

[13] Turner, J., and F. Black. 2022. "High-Lift Devices and Aerodynamic Efficiency in Business Jets." *Journal of Aircraft Performance* 41, no. 2: 245-259. https://doi.org/10.1016/j.jap.2022.021

[14] Shah, D., and R. Paudel. 2021. "Fly-by-Wire Systems in BWB Aircraft Control." *Journal of Flight Dynamics and Control* 29, no. 3: 156-169. https://doi.org/10.2514/1.710839

[15] Shams, A., and L. Ho. 2020. "Taguchi Methods for Wing Design Optimization." *Journal of Optimization in Aircraft Design* 12, no. 4: 96-110. https://doi.org/10.1080/aircraftopt.2020.019

[16] Torenbeek, E. 2013. *Advanced Aircraft Design: Conceptual Design, Analysis and Optimisation of Subsonic Civil Airplanes*, 1st ed. Oxford: John Wiley and Sons Limited

[17] Lopes, Leonard, and Casey Burley. 2016. *ANOPP2 User's Manual*

[18] Nasir, R. E. M., N. S. C. Mazlan, Z. M. Ali, W. Wisnoe, and W. Kuntjoro. 2016. "A Blended Wing Body Airplane with a Close-Coupled, Tilting Tail." *IOP Conference Series: Materials Science and Engineering* 152: 012021

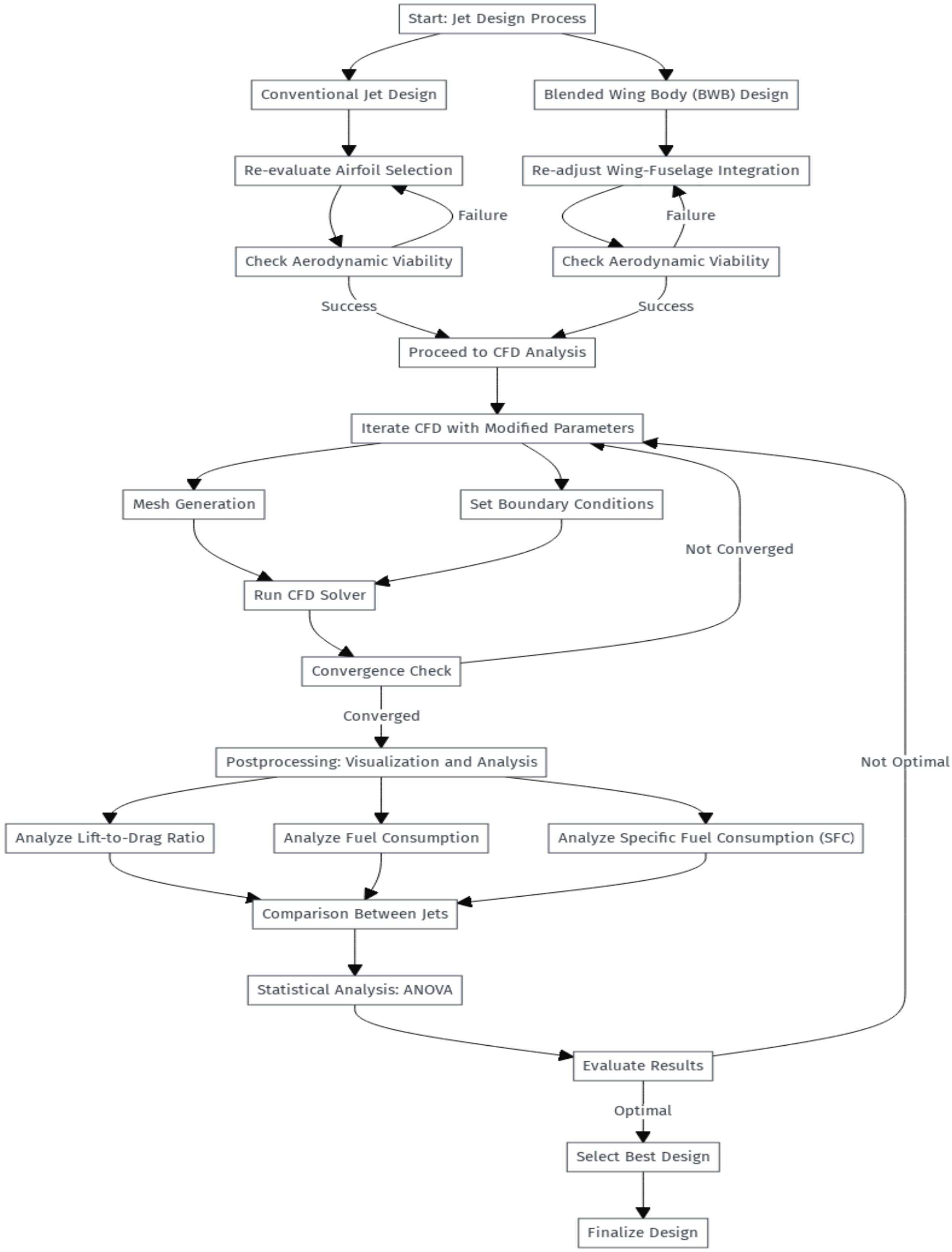
[19] Xu, X., Q. Li, D. Liu, K. Cheng, and D. Chen. 2020. "Geometric Effects Analysis and Verification of V-Shaped Support Interference on Blended Wing Body Aircraft." *Applied Sciences* 10, no. 5: 16–25

[20] Latif, M. Z. A. A., M. A. Ahmad, R. E. M. Nasir, W. Wisnoe, and M. R. Saad. 2017. "An Analysis on 45° Sweep Tail Angle for Blended Wing Body Aircraft to the Aerodynamics Coefficients by Wind Tunnel Experiment." *IOP Conference Series: Materials Science and Engineering*

[21] Lyu, Z., and J. R. R. A. Martins. 2014. "Aerodynamic Design Optimization Studies of a Blended-Wing-Body Aircraft." *Journal of Aircraft* 51, no. 5: 1604-1617

[22] Qin, N., A. Vavalle, A. Le Moigne, M. Laban, K. Hackett, and P. Weinerfelt. 2002. "Aerodynamic Studies for Blended Wing Body Aircraft." *AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*

Appendix A: Soft Code Flowcharts



Appendix D: List of Paper Presented and Published

"Innovative Aerodynamic Design of a Business Jet: A BWB vs Conventional Design's Comparative Analysis Study" Submitted to CFD Letters Journal –

https://semarakilmu.com.my/journals/index.php/CFD_Letters/index