An Analysis of the Developments in Blended Wing Body Aircraft for Sustainable Aviation

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Conventional air transport vehicles have over the years damaged our planet to a large extent. This led to the concept of making aircraft more environmental friendly. To achieve this, a great deal of research and development went into various methods that could reduce air and noise pollution caused by aircraft. The first and most obvious approach in this regard was to increase the fuel efficiency. Gradually, different designs and configurations were suggested. One of the most successful designs in this category is the Blended Wing Body. The wings of an aircraft of this design are blended with the fuselage to form an integrated structure. The body of a blended wing body aircraft is usually flattened and airfoil shaped. This maximizes the lift to drag ratio, improving the overall fuel efficiency of the aircraft. Blended wing body aircraft also produce less noise and can have a larger payload capacity with respect to the size of the aircraft. The main aim of this report is to cover the formulation, design, and recent studies and developments in Blended Wing Body aircraft and their feasibility.

Nomenclature

ACFA Active Control for flexible aircraft
ACT Active Control Technology
ANOPP Aircraft Noise Prediction Program
BWB Blended Wing Body
CFD Computational Fluid Dynamics
DEE Design and Engineering Engine
FMMG Flight Mechanics Model Generator
LFC Laminar Flow Control
PAA Propulsion Airframe Aeroacoustics
WingMOD Wing Multidisciplinary Optimization Design

I. Introduction

The design of aircraft has rapidly changed over the past several decades. Not only has there been a marked improvement in the structural configuration of the aircraft, but there has also a significant improvement in performance. With this increasing performance, the negative impact on the environment has been worsening due to an increase in the total anthropogenic carbon dioxide emissions. Aviation contributes around 2% of the total anthropogenic carbon dioxide emissions. However, carbon dioxide emissions alone are misleading as they do not represent the total radiative forcing from aviation, which is in fact closer to 5%

1. It is estimated that there will be an exponential growth in air travel over the coming years and a proportional increase in the negative environmental impact. This includes noise and pollution due to emissions. The conventional aircraft design needed improvement to meet the growing sustainability needs. This led to the design and development of alternate aircraft configurations. The blended wing body (BWB) aircraft is not a fully novel concept because it was considered by Horten, Northrop, and others from the mid 1930s to the mid 1950s, but was abandoned due to stability and control problems. The primary research in this area has been carried out by NASA Langley Research Center and McDonnell Douglas. The design they produced evolved over the years and is now known in literature as the BWB configuration.

As the name suggests, the fuselage of a BWB acts as a wing as well as a pitch control surface and it does not have a tail. With this simple modification, the aircraft reduces interference drag to a great degree. This is due to the smooth junction between the wing and the fuselage. The fuselage also plays an important role in the generation of lift by reducing the wing loading. This provides benefits in terms of aerodynamic performance

2. A BWB design approach is to maximize the overall efficiency by improving the propulsion system, the wings, and the body into an integrated

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lifting surface that offers great potential to substantially reducing the operating costs while improving performance. Studies have shown that the improvements of the BWB over conventional baseline aircraft include a 15% reduction in takeoff weight and a 27% reduction in fuel burn per seat mile. It has also been demonstrated that the BWB can cruise at mach numbers as high as 0.95. This report provides an analysis as to how this is achieved and discusses some of the recent research in BWB design.

In this report, the various research trends in BWB design are discussed. It is organized in the following manner. In Section II, the structural design of the BWB is dealt with. The aerodynamics and optimizations of the BWB design are covered in Section III. In Section IV, we talk about the controllability of BWB aircraft. In Section V, we discuss how the BWB design seeks to reduce the noise generated by aircraft. Then in Section VI, we deal with the environmental impact of this aircraft. Section VII concludes the report.

II. Blended Wing Body Aircraft Design

The design of the BWB can be traced back to the late 1920s. It was later re-introduced by Boeing Company in 1988. An example of a BWB aircraft is shown in Figure 1.

The BWB design made by Boeing has a fuselage which also serves as wing, an inlet for the engines, and additionally a pitch control surface. Directional stability and control was provided by verticals which also acted as winglets. This increased the effective aspect ratio. To provide visibility in the cockpit, a nose bullet was added. This provided additional effective wing chord to offset compressibility drag at the centerline due to unsweeping of the isobars at the plane of symmetry.

BWB aircraft have several unique constraints and requirements in different aspects of the design that they must satisfy, including the following: volume, cruise deck angle, trim, landing approach speed and attitude, buffet and stall, power for control surface actuation, and manufacturing. The tailless configurations associated with BWB designs have short moment arms for pitch and directional control. Thus, they require many large rapidly moving control surfaces. The scale of the control surfaces are related to the hinge moments. With increase in the area as the square of the scale, the moment increases with the cube of the scale. The hydraulic system is sized as to meet the maximum hinge moment. The power requirement for the hydraulic system is then a function of the rate at which the control surface is moved.

The Navier-Stokes computational fluid dynamics (CFD) methodology is used to define the final BWB geometry. Looking at the BWB design from an aerodynamics perspective, to minimize the drag by balancing the wetted area and shock strength, the outboard wing is loaded similar to a conventional configuration. The balance achieved is similar to that of the conventional configuration by movements of the wing along the centerbody.

The centerbody is unique to the BWB design. Being the passenger cabin, it carries the pressure load in bending. It must also carry the wing bending load. While the wing bending load rarely ever meets the design load, the passenger cabin experiences the design pressure load on every flight. The centerbody was based on two candidate concepts: a 5-inch thick sandwich and a skin plus 5-inch deep hat-section stringers. The outboard wing structure had just one design which was that of conventional aircraft.

The BWB design has many unique benefits but also has challenges, the biggest of which is the design of a cabin with windows and cabin walls. Initially, as there was no rotation symmetry in a BWB, it was challenging to design a pressurized cabin. This, however, was not the primary obstacle. Passenger acceptance was the main hurdle. This can be overcome by using multi-bubble pressure cabins. An interior configuration using multi-bubble pressure cabins...
is shown in Figure 2. This configuration reduces weight through the use of strength dominated structures instead of stiffness dominated structures. Segregation of the multi-bubble from the aerodynamic shell helps in making it strength dominated. The inner volume of the aerodynamic shell is significantly larger than that of the pressure vessel and this would sustain the pressure loads. There are two types of multi-bubble configurations that were suggested by Voet et al.: an open-cell multi-bubble and a multi-bubble with pillars. Although an open-cell multi-bubble offers better structural integrity, the multi-bubble with pillars gives more space and better interiors. The design of the multi-bubble uses the "Passenger Experience" approach. In this method, passengers were subjected to various questionnaires and their views were recorded. The questionnaires included important interior aspects such as visibility of exit routes, window placement, comfort, and privacy. The popular opinion about windows was that the installation of LCD screens which display window views would compensate for the lack of actual windows. Another option was that there would be a few windows that could be optimally shared among all passengers instead of the select few who would sit next to them. This window area would be separated from the regular seating areas and would serve as a socializing spot. The presence of interior pillars and separation in the cabin was not a major issue according to the study.

![Figure 2. Cross section of the multi-bubble concept](image)

Passengers revealed that they are influenced by the experience of the journey, beginning from their entry into the aircraft up to their arrival at the destination airport. In order to address this concern, an entry and exit sequence as shown in Figure 3 was developed. In this sequence, a bridge is created between the airport's glass facade and the foyer of the BWB with multi-bubble configuration. The large windows of the aircraft can be seen from the gate and, upon leaving the passenger bridge and entering the cabin, the gate's facade can be seen through the windows of the BWB. This enables the passengers to link the orientation of the front windows (which are curved and placed under an angle from the direction of flight) to the expected movement of the aircraft and the location and direction of their seat in space.

![Figure 3. Entry sequence and perceived spatial heights](image)

A wide oval cabin design as shown in Figure 4 is an alternative to the multi-bubble concept. The cross-section of the oval cabin is formed by four arcs of different radii. The tension and compression loads are carried by a box structure that is present at the interconnections of the nodes of the arch. This concept is both aerodynamically and structurally feasible since the member of the prismatic box structure forms the passenger floor. This oval design has several advantages: the emergency exits are easy to design and the problem of passenger comfort is solved with the ability to provide an uninterrupted view. This design is also structurally efficient. However, the design is hard to manufacture and it has a large weight penalty. It also compromises on the aerodynamic efficiency offered by BWB design due to its structural requirements. While this design has potential, it has several issues as stated and needs further investigation to achieve a better aerodynamic efficiency and to improve the overall performance of the aircraft.
The position of the doors and the emergency exits was also an important challenge since the BWB has less wall surface to escape through with respect to its volume and the number of passengers it transports. Thus, it is fairly difficult to create enough emergency exits. A study was carried out, assuming that the BWB had a capacity of 485 passengers. This is shown in Figure 5. Although, this design is very promising, it does not meet the FAA regulations for emergency egress and requires further research.

III. Aerodynamics and Structural Optimization of BWB Aircraft

For aerodynamic considerations, a CAD model is usually made of an aircraft and then it is subjected to various flow conditions. Ikeda and Bil performed an analysis on the aerodynamic features of BWB aircraft using CFD. This was based on the methods from NASA’s handbook on structural weight prediction. The BWB was designed using Catia v5 and the aerodynamic performance was calculated in FLUENT 6.2. The boundary conditions were as follows:

- 555 passengers can be accommodated while achieving flight comfort and meeting safety standards
- 66.4 tonnes payload
- 8,000 nautical miles (approximately 15,000 km) range
- Altitude 11,000m.
- Reynolds Number $5.12 \times 10^8$

The BWB model was analyzed according to the airflow impact on the surfaces. On the upper surface of spanwise extension, a large increase in drag and separations were identified by contour lines of turbulent kinetic energy as shown in Figure 6. The BWB design achieved about 1.4 times higher L/D ratio as compared to conventional aircraft, thus
proving that the BWB configuration has superior aerodynamic features. This configuration, although aerodynamically sound, is difficult to fabricate.

A better method is to simultaneously optimize the aerodynamics and structure by making use of Wing Multidisciplinary Optimization Design (WingMOD) code\(^8\). As the BWB aircraft cannot be decomposed into a wing and a fuselage for the design and analysis stages, trimming it tends to be more complex and time-consuming as compared to that of a conventional aircraft. WingMOD is used to optimize the wings and horizontal tails of the aircraft, keeping in mind the various practical constraints. The code uses intermediate fidelity analysis which can efficiently and rapidly analyze aircraft in twenty or more design conditions. These conditions reflect on the issues that the simulator is trying to address such as performance, aerodynamics, loads, weights, balance stability, and control. In WingMOD analysis, ten different optimizations were used to model, calibrate and optimize the configurations. Seven of these were used in progressively matching the different aspects of the design. Two more of these optimizations trimmed the aircraft without changing the planform. The last optimization involved 142 design variables and 930 contrasts. This optimization solved the balance issues by varying the planform.

Another similar study\(^9\) was conducted in which the BWB’s geometry is composed of a central body, an inner wing, and an outer wing to which the winglets are attached. These parts are “blended” to form the BWB geometry as shown in Figure 7. The purpose of the inner wings is to hold the fuel tanks whereas the winglets are attached to the outer wing. In order to make the design compatible with existing airport runways, the span of the BWB is limited to under 80 meters. The winglet surface is derived from a NACA 0012 aerofoil.

To evaluate the performance of the baseline design, first a theoretical assessment was carried out for ideal performance which included viscous flow simulations. Two different methods were used to study the effects of spanwise distribution on the BWB aircraft’s aerodynamic efficiency. The first is a low fidelity panel method and this was combined with a high fidelity Reynolds-averaged Navier-Stokes solution method. This solver was finally used for 3D aerodynamic surface optimization of the BWB on both continuous and discrete adjoint approaches. It was also shown that there is a progressive improvement of the aerodynamic performance for the given cruise condition and design.
A limitation of this study is that it is limited only to the given planform design. An important aspect that has not been addressed is the dependence of the aerodynamics of the aircraft on the structure itself. The emphasis of the co-dependence of aerodynamics and structure is important for multi-disciplinary optimization in regards to factors such as bending moment, aeroelasticity, flight stability, and controllability. These have not been considered.

These limitations can be overcome by using a software tool that can design and analyze a BWB configuration. It does this using simple estimation methods. The tool consists of four main modules to carry out the design and optimization of a BWB. A geometric model is formulated with 30 design variables. Using this model, four disciplinary models are obtained: an aerodynamic model, a model of the wingbox structure, a model of the cabin, and a model for the fuel tank. This constitutes the first two modules of the optimization tool. The next module is used to estimate the weight and calculate the center of gravity shift, the static margin, and the stability and control derivatives. The last module analyzes the results of the first three and compares them with 27 non-linear constraints. These four modules together are referred to as the design and engineering engine (DEE) as shown in Figure 8. A single iteration of DEE takes approximately six minutes on the test machine that was used. 20-60 iterations are required for the simulation to converge. However, the gradient based optimization procedure used does not guarantee that the local minimum found by the algorithm is the global minimum. The tool has several other areas where it can be improved such as refining optimization results by comparing the results to those of higher fidelity models. The optimization time can be further reduced by decreasing in the number of design variables, provided the number of designs that can be obtained is not violated.

![Figure 8. Structure of DEE for Conceptual Design of the BWB](image)

### IV. Control System for BWB Aircraft

A major technical challenge in the development of the BWB is its controllability. In contrast to common belief, flying wing aircraft can be made inherently stable. Originally, wing sweep was used in combination with outer wing sections. These outer wing sections have the same functionality as the horizontal tail of a conventional fixed wing aircraft configuration. This effectively makes the aerodynamic wing span smaller than the actual wing span and this has prevented flying wing aircraft from reaching its performance potential. The general method for achieving control is by placing several aerodynamic control surfaces on the trailing edge of the aircraft and, when present, on the trailing
edge of vertical aerodynamic surfaces\textsuperscript{11}. There are several problems with applying this method of control to BWB aircraft such as control power being low in pitch and yaw due to small moment arms and allocation of control surfaces being a critical issue.

ACFA 2020 (active control for flexible aircraft) is a collaborative research project funded by the European Commission under the seventh research framework program. This project involves innovations in the active control concepts for 2020 aircraft configurations like BWB aircraft. It covers all aspects of aerodynamic design, presents structural weight estimations, performance estimation and landing analysis. BWB aircraft have complex control algorithms and complex control system architecture. Instead of various single channel or single input single output controllers, a highly coupled multi-channel or MIMO controller is required\textsuperscript{12}. The ACFA aircraft design focuses on active control technology (ACT) as shown in Figure 9. ACT involves the use of controller technologies that enable improved flight performance, direct lift control, and flutter control. Multi-objective control surfaces are required for flight control and active gust and maneuver load alleviation due to high coupling of flap deflections and aircraft movements in all three axes of the BWB. ACT investigations are carried out for different flying velocities and weights ranging from maximum zero fuel weight to maximum takeoff weight. In order to facilitate the necessary yawing moment, crocodile flaps have been introduced in the very outer part of the wing. The Breguet/Leduc range equations were used to assess the fuel weight. It was assumed that the BWB transports a payload of 49.5 tons\textsuperscript{12}. This ACT aircraft configuration met all the stated requirements of the ACFA 2020 consortium.

A tool that automatically generates a non-linear flight mechanics model of a BWB aircraft within a multidisciplinary design optimization framework can be used to further assess the controllability of the aircraft in the conceptual design phase via desktop and piloted simulation\textsuperscript{11}. The flight mechanics model is developed in-house using the MATLAB/Simulink environment. The structure of the model is such that several people can work on the same model at the same time to ensure continuous development. The MATLAB/Simulink toolbox SimMechanics has been used to model the dynamic effects of fuel transfer and consumption. The model used for simulation has three levels of fidelity:

1. Vortex lattice method which is an extension from the classical Prandtl lifting line theory - instead of a lifting line, the vortex lattice method makes use of a lifting surface. The code used in this paper is Tornado. Tornado is used as a virtual wind tunnel to calculate the aerodynamic forces for a range of static and dynamic flight conditions.

2. First order panel method with viscous boundary layer integration - The analysis tool used is called VSAERO. It is also used as a virtual wind tunnel. An example of the pressure distribution over a BWB, calculated with VSAERO is shown in Figure 10.

3. Wind tunnel result

The aerodynamic data that is obtained from VSAERO is re-run after applying a finite difference in order to determine the control derivatives. The calculated aerodynamic forces, moments, and control derivatives are finally organized in a MATLAB data structure and fed to the Flight Mechanics Model Generator (FMMG) which is a code that automatically constructs a Simulink model. For example, if the aircraft in consideration has 15 control surfaces, then 15 actuator models are automatically connected to the aerodynamic model of the relative control surfaces. Although the FMMG tool is highly promising, it is limited to operate within a DEE.

Figure 9. ACT Aircraft Design Process\textsuperscript{12}
V. BWB Aircraft Noise

NASA has published the aircraft noise prediction program (ANOPP) that is used for noise assessment of the BWB. Using this as the baseline, several configurations were adjusted and studied. A silent aircraft experimental design known as the SAX-40 shown in Figure 11 was one such novel configuration. SAX-40 has an airframe design that incorporates a number of technologies that help in noise reduction. The smooth airframe that was designed for advanced low-speed capability not only reduces noise but also improves fuel efficiency. The airframe’s trailing edges are acoustically treated by deploying brushes to reduce the airfoil self-noise. This concept is similar to the quiet flight of the owl which uses its feathers to reduce the flow noise of the wing.

"It is important to note that the holistic approach and the integrated system design of the SAX-40 are crucial to achieve the noise goal and to improve fuel efficiency. In this, the all-lifting airframe incorporates a key design feature that distinguishes the conceptual aircraft design presented here from other BWB-type concepts. As depicted in Figure 11, the leading-edge region of the centerbody is aerodynamically shaped, and the all-lifting airframe is optimized to generate a lift distribution that can do the following":

1. The aerodynamic moments for pitch trim are balanced by the airframe. It provides a 5-10% static stability margin and also avoids the horizontal-tail lifting surface and reflexed airfoils.

2. It can also increase the induced drag during approach. This is achieved via elevon deflection and vectored thrust which is achieved by using rotating nozzles or vanes to deflect the exhaust stream. Although this results in significant weight penalty, it reduces the stall speed by 28% when compared to conventional aircraft.

The engine noise of the SAX-40 is reduced by placing the engines at the back and on top of the aircraft. This enables the main body of the BWB to have a shielding effect between the engines and the ground, thereby reducing the amount of noise generated. Although the SAX-40 provides considerable noise reductions, it also has some technical challenges. This includes achieving the desired structural integrity and other challenges in fabrication and manufacturing. The low-speed aerodynamics of the airframe needs to be assessed using 3D viscous flow computations. Another major challenge is the integration of the distributed propulsion system in the mainframe. Forced vibration issues due to non-uniform flow into the engine also need to be resolved.
Another concept was suggested by Thomas et al.\textsuperscript{15} in which a propulsion airframe aeroacoustics effect experiment was conducted for noise reduction in BWB. The authors stated that the best configuration for reduction of aircraft noise was by making use of state-of-the-art chevrons with a pylon above the engine in the crown position as shown in Figure 12. Elevon surfaces were also assessed to add shielding area. Incorporation of these technologies into a BWB aircraft was done in two parts. The first part was to move the engines two engine diameters forward on the body or to add an extension to the trailing edge in order to create shielding of the internal engine noise sources. The second part involved identifying Propulsion Airframe Aeroacoustic (PAA) technologies that could reduce noise levels and improve the shielding effectiveness by jet sources upstream. There are two main divisions in PAA. The first is associated with flow interaction whereas the second is associated with acoustic propagation.

Flow interaction effects are caused by the flow field of one component interacting with another, specifically because of the location or orientation of the installation. An example of this is the influence of the engine pylon on the jet exhaust flow. Acoustic propagation effects arise when noise generated from various components propagates and interacts with either structure or flow features created by flow over the airframe and propulsion device. For example, the acoustic propagation of fan noise along the exhaust duct is altered by the presence of bifurcator and pylon. Vertical surfaces were also added at the inboard location of the aircraft. They were considered because some low noise versions of the BWB concept were proposed in which the vertical control surfaces were moved from the tip to an inboard location. This was done based on the assumption that an additional increment of shielding might be obtained for aft-radiating engine sources, particularly at the side line angle. The configuration also rotates the conventional engine pylon from the keel position to the crown position so that this pylon with a known strong acoustic effect is located at the top of the engine as shown in Figure 13. A 3° flight path angle was kept fixed for all approach speeds. The minimum speed for the BWB (97 knots) was used for preliminary studies and then the speed was increased to 140 knots. The tests showed that there was a reduction of 42.4 dB cumulative below Stage 4 noise levels\textsuperscript{15}. 

![Figure 12. Chevron Nozzle with Pylon\textsuperscript{15}](image)

![Figure 13. Lowest Noise HWB configuration recommended based on the results of the study by Thomas et al\textsuperscript{15}](image)
VI. BWB Aircraft Emissions

BWB aircraft exhibit important reductions in fuel consumption as compared to conventional aircraft. The wing load alleviation effect of the BWB aircraft’s span loading and the passenger and cargo distribution leads to a more compact and cleaner aerodynamic configuration and a lighter airframe. Carbon dioxide (CO$_2$), carbon monoxide, and unburned hydrocarbons are the primary emissions that are formed when the fuel is burned during flight. The reduction of CO$_2$ emission using BWB design can be estimated globally, depending on the replacement fraction of conventional airliners by more efficient BWB, and in terms of passenger kilometers for those long haul routes that would be performed with the new aircraft type instead of the classical one. A BWB configuration is around 20% more efficient in terms of lift-to-drag ratio than conventional airplanes, which directly translates into an equal amount of fuel savings when they are of the same weight.

The architectural arrangement of the BWB aircraft allows an easier incorporation of laminar flow control (LFC) technologies over the wing. By applying laminar flow control over easily laminarized areas (around 30% of the upper and lower wetted surfaces), a fully loaded 300-seat class BWB could burn just 14.6 g/pax-km in a 10,000 km flight. This is equivalent to 46 g/pax-km of CO$_2$ which is around 40% lower than the equivalent conventional aircraft. However, joint discontinuities and improper surface finish are barriers to the optimal implementation of this technology.

VII. Conclusion

It has been predicted that there will be a dramatic rise in the demand for passenger aircraft travel and thus, sustainability is an important concept to keep in mind during aircraft design. The BWB design aircraft are fuel efficient and are significantly more environmentally-friendly than their conventional counterparts. They offer numerous advantages including being lighter in structure, offering better aerodynamics, better fuel efficiency, lower costs, lower noise emissions, and being more environmentally-friendly. However, there are several major limitations present in the BWB design aircraft. They are difficult to fabricate. During the manufacturing process, integration of the various systems is a difficult step. Owing to these difficulties, very few BWB models have actually been fabricated and wind tunnel tests and flight tests have been carried out. Two such BWBs are Boeing’s X-48B and X-48C. There is a lot of work and research that is to be done before the BWB design is ready for mainstream manufacturing. While BWB design aircraft have a few limitations at present, the design is well poised to become the standard for commercial aircraft in the coming generations.

References


