Performance Comparison of Next-Generation Blended Body Aircrafts for the Commercial Sector

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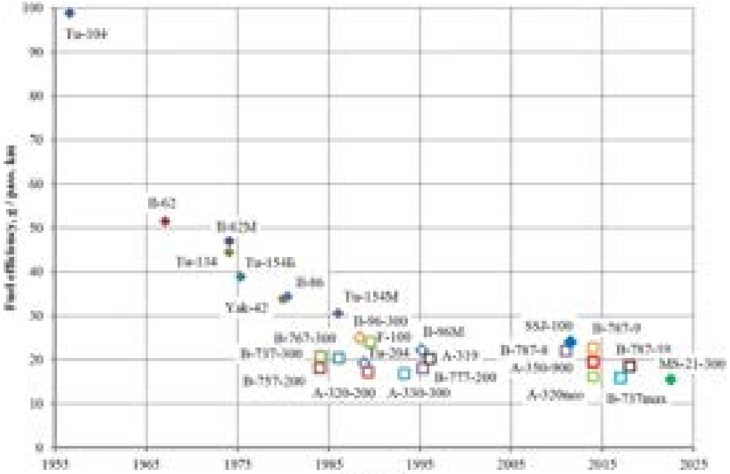
Abstract

Blended Wing Body (BWB) aircrafts are an important area of consideration and interest in regards to sustainability and more sustainable alternatives for consideration within the aerospace industry. The geometry of these aircrafts consist of a unified body where the fuselage transitions seamlessly into the wings of the aircraft. This geometry has already been applied in the existing military aircraft, the B2 Bomber and although has not yet been applied commercially, Airbus have developed prototypes such as the Airbus MAVERIC. This research paper provides an analysis and evaluation over aerodynamic properties, drawbacks and advantages to the applications of this technology within the aviation industry.

Introduction

The climate crisis has caused all industries to consider sustainable options with the task of improving fuel efficiency becoming increasingly urgent. However, development within the industry over the past 30 years shows little to no growth within the fuel efficiency department of existing aircrafts (Fig. 1) [1]. However, one of the reasons behind this lack of development is because of the lack of the importance placed on this issue. The focus for innovators has not been on increasing fuel efficiency as modern day aircrafts look to improve on comfort and the bottom line. Additionally, not much experimentation has been done in regards to the geometry of any given aircraft as such a drastic change has not been considered a worthwhile investment. However, due to more importance being placed on the climate crises, the industry must decide on a direction to take in order to reach more sustainable outcomes. [2]



[2]

(Fig 1. Fuel efficiency vs Year of launch/operation of narrow body commercial aircrafts designed for intercontinental use)

Considering this issue, one of the solutions currently in development are BWB (Blended Wing Body) Aircrafts which deviate from the traditional geometry of an aircraft and can be up to 20% more fuel efficient in comparison to existing aircrafts [3]. Instead of the tubular fuselage, BWB aircrafts have a lifting body which blends into the wings of an aircraft. This type of geometry for the aircraft decreases the drag generated on the plane thereby increasing the lift to drag coefficient.

Section 1

Lift-to-drag is a numerical value establishing a relationship between the lift and drag. This coefficient is especially important when evaluating the aerodynamics of a plane and its efficiency. Lift to drag is calculated using these following formulas in order to solve for C_D and C_L respectively [4].

$$C_L = \frac{L}{\frac{1}{2}\rho^2 A} \qquad (1.0)$$

$$C_D = \frac{D}{\frac{1}{2}\rho^2 A} \qquad (2.0)$$

These formulas individually calculate the values of Lift (C_L) and Drag (C_D) which can later be utilized in order to solve for the lift-to-drag coefficient. Within the equation, L and D are the aerodynamic Lift and Drag force (N) respectively . Furthermore, ρ refers to the ambient air density (Kg/m^2). The ambient air density is a value which is subjective to the temperature, humidity and atmospheric pressure. Ambient air pressure maintains an inverse proportionality with altitude as air density decreases as altitude increases, hence so does ambient air density. Finally, the variable A (m^2) refers to the frontal area of the object traveling through the fluid [5].

Lift is one of the four fundamental forces acting upon an aircraft (Lift, Weight, Drag, Thrust). Lift plays a crucial role on any aircraft as it opposes the weight of the aircraft thereby allowing it to fly in the first place. Additionally, lift is the factor which permits any given aircraft to reach the most suitable cruising altitude. At cruising altitude the lift is nullified due to several factors. Whenever altitude increases, air pressure and air density decreases. Consequently, at cruising altitudes the air density is not high enough in comparison to the density at ground level. Henceforth, lift decreases and aircrafts settle at a cruising altitude of anywhere between 30,000 and 40,000 feet which is the optimal height for the maximum thrust and least drag [5].

When considering the anatomy of a plane, the wings are responsible for generating lift. The cross sectional area of a wing follows the shape of an airfoil which creates a pressure difference due to its unique geometry. This pressure difference thereby creates lift. Additionally, the lift generated by the plane can also be manipulated via the wing. For example, increasing the size of the wing will also increase the lift generated. However, the drag will also increase due to the increased lift. Hence it is a trade off [6].

Drag, similar to lift, is another fundamental force acting upon the plane. Drag is classified as the resistance or opposition against the motion of an object through a fluid. In relation to airplanes, drag counteracts the thrust of the plane. For this reason, greater amounts of fuel needs to be used in order to counteract the drag generated from a plane. However, the geometry of an aircraft can be manipulated in order to minimize drag. The Coanda effect is applied thoroughly in aircrafts which is why they sport a curved and smooth shape as opposed to rigid one. The curved body of the object reduces drag by allowing any given fluid to stick to the surface of the object when it is in motion [6].

In relation to the previous example, wing sizes are often not increased despite this action having a positive effect on the lift since drag increases in tandem.

The geometry of BWB aircraft presents an opportunity to decrease drag and increase lift. The smooth transition between the fuselage of the aircraft and the wings of the plane reduces any existing interference drag as there are no sharp or steep angles for airflow to get caught on. Furthermore, skin friction drag across the aircraft is relatively lower in comparison to tubular fuselage aircrafts. In combination, the higher lift and lower drag present an opportunity to increase the plane's L/D ratio significantly [3].

Section 2

With greater importance being placed on the study and research of BWB aircrafts, the need and purpose for these aircrafts has extended and evolved since the turn of the millennium. Initially, BWB aircrafts were used mainly as military planes, especially bombers. Engineers found that the use of BWB aircrafts prompted multiple benefits as opposed to regular aircrafts. In the earlier paragraphs, it was established that BWB aircrafts showcase a higher L/D ratio in comparison to regular aircrafts. The higher L/D ratio translates to a lower required thrust in order to maintain cruising altitude. The lower required thrust further translates to less fuel being used when the aircraft is at cruising altitude which it would be in for the majority of its flight. Consequently, the aircraft can afford to maintain a higher payload [7]

Engineers capitalized on this discovery and began development of several blended body aircrafts which may not have been suitable for commercial use but were used widely in other fields. For instance, one of the most prominent real life examples of the implementation of BWB aircraft comes in the form of the B2 bomber commissioned in 1997. The BWB design of the aircraft not only posed several aerodynamic benefits but the innovative design also posed several stealth benefits. For example, the noise an aircraft produces can greatly affect whether or not it gets detected. However, due to the BWB shape, the craft is relatively softer in comparison to other aircrafts. Similarly, the increased L/D ratio allows greater fuel efficiency thereby increasing the maximum payload capacity as well. Furthermore, the large wingspan of the aircraft aids in generating lift and since the body is uniform, the drag induced due to this larger wingspan is relatively less than it would be in a regular bomber [8]. Additionally, the narrow width of the aircraft reduces the drag created and the seamless transition between the nose, wings and fuselage also aids in reducing both skin friction and interference drag. The unified body also makes it easier to coat the bottom of the aircraft with radar interfering technology which is especially helpful considering the purpose and requirement of this aircraft [7][8].

(Fig 2. Image of the Northrop Grumman B2 bomber during a low altitude test flight) [8]

Another BWB aircraft designed for military purposes is the Boeing X-45. The design incorporated the BWB idea by essentially joining the wings and the fuselage of the plane as one. However, this design deviates from the shape of the B2 bomber. The initial rendition of this model places the wings of the aircraft to the very end of the fuselage whilst the B2 bomber is essentially built as one entire unit where the wings and the fuselage are attached in all places. However, this design did change in the X-45C/X-46 and the X-47 where the aircraft increased in width whilst maintaining the BWB shape. However, in comparison to the B2 bomber, the shape of the aircraft is still significantly narrower mainly due to the difference in usage and purpose.

NASA began testing the concept of a commercial blended body in 2012 with the X-48c project. The project involved using biomimicry as means to try and enhance the fuselage of the aircraft in order to try and improve the L/D ratio. The design took inspiration from the Manta Ray's wing shape and implemented this concept into the design. However, due to budget cuts, the design was unable to make it past the testing phase.

The Airbus MAVERIC is the most recent aircraft designed which follows the BWB concept. In early 2020, the company began testing their BWB aircraft through a 2 meter by 3.3 meter aircraft with a surface area of approximately 2.25 meter^2. Testing revealed that the aircraft has the capability to be around 20% more fuel efficient than narrow-body aircrafts mainly due to the higher L/D ratio at cruising altitudes [3]. When analyzing the geometry of the aircraft, there are several factors which help in emphasizing the BWB shape of the aircraft. Firstly, the wings of the aircraft converge into the fuselage of the aircraft hence decreasing both skin friction drag and interference drag. Additionally, the curved surface of the aircraft allows air to flow seamlessly off the aircraft therefore reducing drag. Additionally, the geometry of the aircraft has a "lifting body". Lifting body aircrafts are aircrafts where the fuselage doubles as the wings of the aircraft hence producing a greater amount of lift across the cross sectional area of the aircraft. Considering these benefits, the Airbus MAVERIC can in theory act as a suitable and sustainable option for improving fuel efficiency in passenger aircrafts [3][9].

(Fig 3. Rendered image of the Airbus MAVERIC based on the current designs and prototype in testing) [10]

The novel prototype design follows the shape of the blended body aircraft closely but still deviates on certain factors in comparison to prototypes such as the Airbus MAVERIC and the projects released by NASA. The novel prototype takes inspiration from a manta ray (Similar to the X-48c), evident by the shape of the wings. The geometry of the wings will allow a more uniform distribution of both lift and drag across the wings of the aircraft. Additionally, the curved shape of the wings will also allow air to flow more easily in comparison to the wings present in narrow body aircrafts. Furthermore, the fuselage follows the shape of a NACA airfoil to a certain extent. Consequently, the fuselage of the aircraft doubles as a source of lift. Although the shape may create drag to some extent, the lift generated is considerably more in comparison to the lift generated by the fuselage in a narrow body aircraft. Despite this, the novel prototype may face some interference drag around the wings, the shape of the fuselage will compensate for this drag created [9].

However, despite this development and recent peak in interest over BWB aircrafts, the application of BWB aircrafts for commercial use within the aerospace industry is a difficult task. Firstly, the radically changed design must adhere to safety protocol especially in regards to the evacuation of the aircraft in case of emergencies. Within narrow body commercial aircrafts, the wings provide another emergency. This is not applicable within most BWB aircrafts as the wings are inaccessible from the cabin of the aircraft. Thus making it especially difficult to follow the 90 second mandate (a rule which states that passengers must be able to exit the cabin within 90 seconds and having at least half the exits of the plane blocked) [9][11].

In addition, for BWB aircrafts to be piloted, pilots must undergo rigorous training considering that the geometry of the aircraft is significantly different in comparison to narrow body commercial aircrafts. Furthermore, pilots are required to complete at least 250 hours of simulation training before gaining clearance for a commercial license. However, simulation hours for gaining a license will in all reason take longer as per the stark difference between the narrow body aircrafts and a BWB aircraft [8].

Moreover, companies are more likely to invest in the development of sustainable aviation fuel (SAF) in comparison to BWB aircrafts for the main reason that it is easier to research and implement hence making it more beneficial from a solely economical point of view as well. Although SAF is more beneficial in the short term, the plane's fuel efficiency would remain at the same threshold which is subjective to the model. Consequently, the plane would still release high amounts of carbon into the atmosphere. In an ideal world, the perfect solution would be a mix of both the blended body aircraft and SAF [12].

SimFlow is the CFD programme of choice for the simulations. SimFlow is software that uses the same numerics as the open-source programme and solver OpenFoam. SimFlow uses a cell-centered approach to the Finite Volume Method (FVM) as its numerical discretization scheme. In FVM, a grid of control volumes, or cells, often hexahedral or structured, divides the computing domain. In order to guarantee that the conservation equations are solved on these control volumes, SimFlow assigns the flow variables, such as pressure and velocity, to the cell centers [13]. This cell-centered methodology captures the flow behavior within each control volume and yields precise and consistent findings.

Simulation Parameters:

Solver Name	SIMPLE
Solver Type	Pressure Base
Governing equations	Navier-Stokes Equations
Discretization method	Finite volume method
Pressure- Velocity Coupling	Segregated Approach
Pressure Solver	Pressure Correction
Velocity Predictor	Implicit

Momentum Equation Solver	Implicit
Time Integration Scheme	Steady State
Flow Type	Incompressible
Turbulence Model	RANS (k-ω SST)
Transport Model	Newtonian
Base Mesh Type	Box
Cell Size	30.0m x 30.0m x 20.0m
Inlet Velocity	200 m/s
Absolute Tolerance	1e-06
Relative Tolerance	0.1

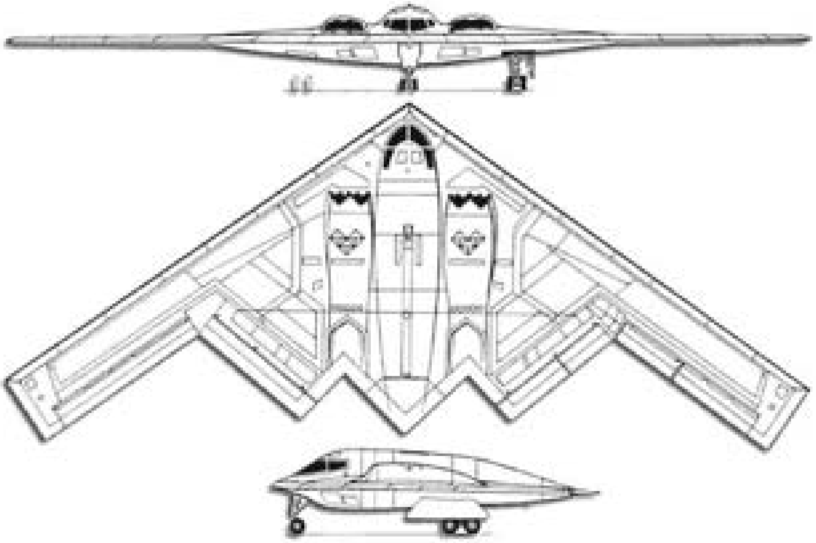
(Table 1. Parameters set for the simulation)

The parameters showcased above were implemented for the simulation in order to try and mimic real world scenarios as closely as possibly incorporating accurate and previously tested values used in SimFlow for simulations with a similar purpose. Using the RANS (k-ω SST) in the simulation provides more comprehensive and effective results as opposed to other models due to the better prediction when it comes to flow separation and behavior, in adverse pressure gradients [14]. Consequently, the inlet velocity used for the simulation was 200 m/s. Using this velocity is most accurate as it represents the speeds planes reach at cruising altitude [15]

The simulation run on the B2 bomber provided conclusive results as to the aircraft's aerodynamics at cruising altitude. The geometry of the aircraft highlights that it has a lifting body as a result of the wings and the fuselage being one in the same. Additionally, the uniform body of the aircraft reduces interference drag as underlined earlier. When looking at the results from the simulation, it can be stated that the aircraft's geometry aids in redirecting the airflow towards the engines of the plane or allow the air to easily flow off the back of the aircraft reducing the amount of drag produced due to a smaller net volume taken by the aircraft.

Additionally, if the side profile of the aircraft is further analyzed, it can be stated that the airfoil like shape aids in increasing lift from the fuselage of the aircraft. The shape aids in creating a low pressure environment towards the back of the aircraft as airflow is directed upwards and does not need to stick to the curved surface of the aircraft. Therefore, the velocity of the air within this low pressure zone is higher thus reducing the dependency on thrust ever so slightly. However, since the plane does not have a vertical stabilizer or any rudders, stability and steering will be an issue for the aircraft hence requiring overdependence on the split rudders positioned on the back ends of the wings.

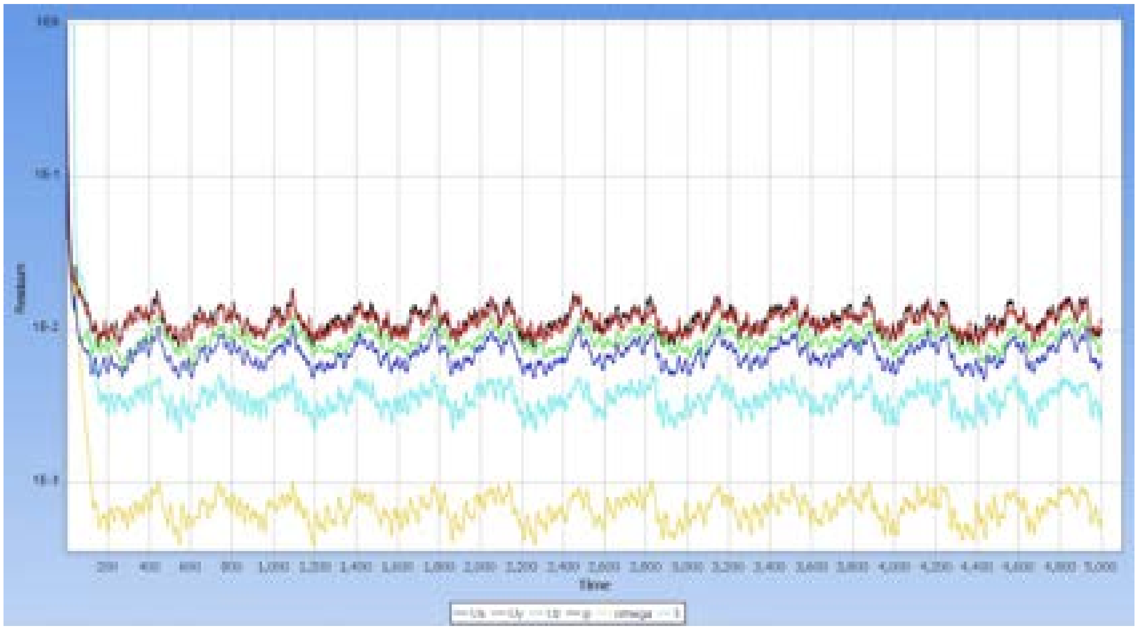
The simulation also aided in highlighting the attention paid to the nose of the aircraft. When analyzing the side view of the aircraft, it is visible that the nose has a slight camber which points downwards, similar to the beak of a pelican falcon which the aircraft takes inspiration from. Consequently, a greater volume of airflow is directed over the top of the aircraft at a higher velocity. The higher velocity in turn reduces the pressure on the top half of the aircraft.



(Fig 4. Orthographic diagrams of the Northrop Grumman B2 bomber) [16]

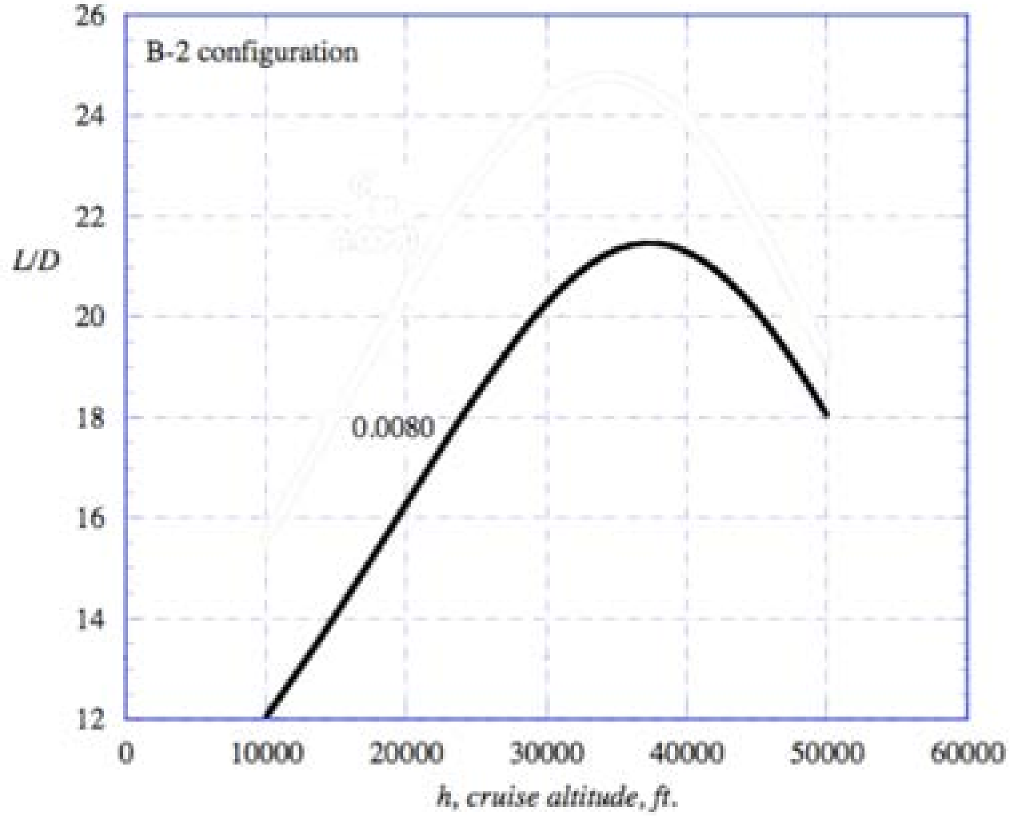
Despite the initial success of the simulation, data projected by the software did not seem to match predictions and the research conducted over the project. Originally, there were a total of three models to be tested as highlighted earlier in the paper. The B2 bomber, The Airbus MAVERIC and the Novel prototyped design. Running the simulation for each model would have provided concrete data which could be evaluated and analyzed. For instance, the L/D ratio of all three aircrafts was to be recorded and compared with existing narrow body fuselage aircrafts which are already being used in a commercial sense. Doing so would have assessed the effectiveness of the BWB's geometry and how it stands in accordance with narrow body fuselage aircrafts in this specific field.

By referring to research done throughout the project, it was hypothesized that the simulation would provide an insight on the L/D ratios of three aircrafts evaluating the geometries of different aircrafts which may qualify as BWB aircrafts. Furthermore, research pointed to the fact that the L/D ratios for all three of these aircrafts would be higher than the average L/D ratio for the narrow body aircrafts.

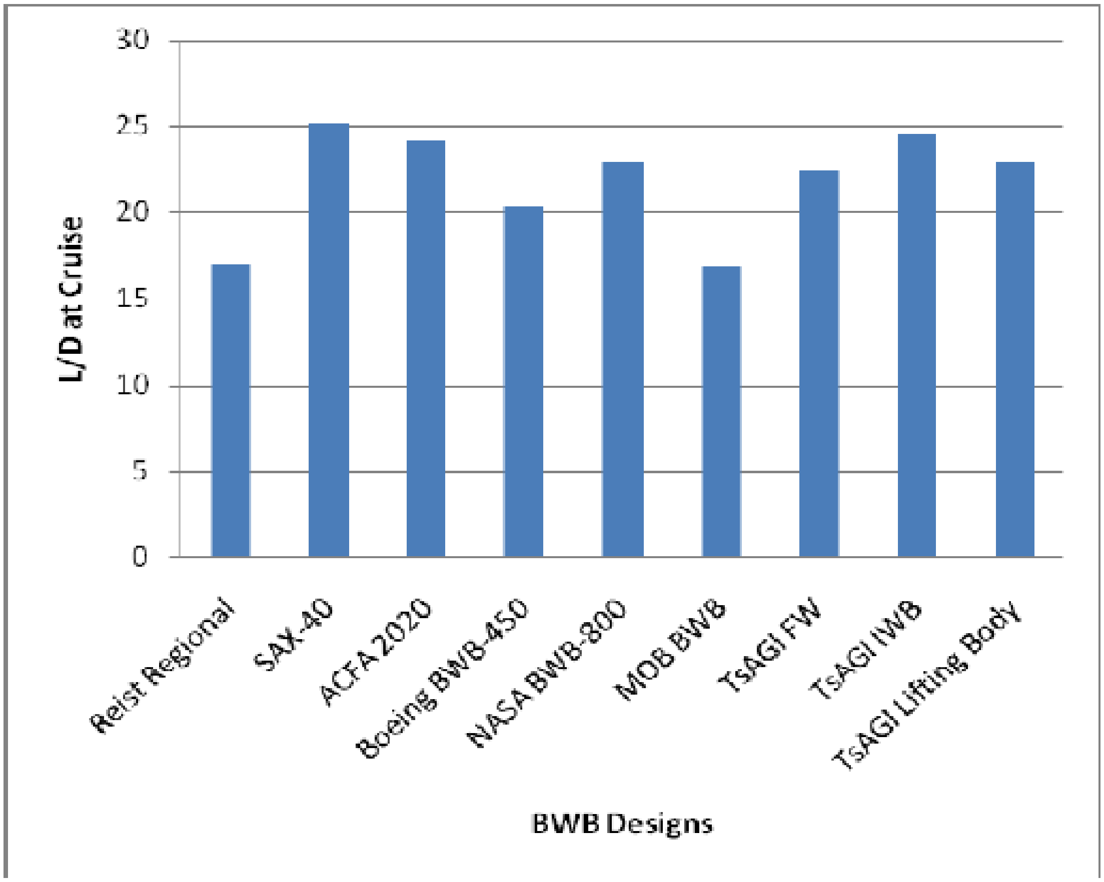


(Fig 5. Graph of the data received from the simulation presented in the form of Residuals vs Time)

Lift – to – Drag Ratio



(Fig 6. L/D Vs h,cruise,altitude,ft. for the B2 Bomber)



(Fig 7. L/D at Cruise vs BWB Designs) [17]

Despite this original hypothesis and concrete research supporting the hypothesis, the simulation did not provide promising results or data which seemed to match the research. For example, existing sources have calculated existing data of other BWB prototypes and models such as the NASA BWB-800 and the Boeing BWB-450 fall between 20 and 25 (as visible in Fig 7.)with the experimentation happening in almost identical conditions. However, simulation data was well below this number as the L/D ratio for both the Airbus MAVERIC and the B2 Bomber averaged to 0.1. In addition to this, the drag coefficient of the aircrafts was often a negative value which is not possible under steady flow pointing to there being a computational error. Although it is unclear what may have caused these massive deviations and errors, the assumption was that the software was unable to correctly recognise the mesh for the aircrafts causing an issue with the simulation and hence leading to poor results.

In an attempt to try and diagnose a problem, the meshing of the aircraft was examined and assessed both manually and by the software through the “mesh check” feature which SimFlow has. However, problems for the aircrafts did not seem to be with the meshing as the mesh check was not able to diagnose any error. Furthermore, initial meshing of the aircraft did also look fine as the geometry of the aircraft was closely matched by the software and the overall shape was accurate.

To try and improve the meshing characteristics, alternative geometries of the same models were explored. These models, like the first one, looked almost identical to the prototype and did seem as good fits for the simulation with all three models closely resembling the shape, design and features of the aircraft. However, despite this close resemblance, changing the model did not prove to be successful either as data projected by the simulation again failed to exceed a value of 1.

Another problem that arose while running the simulation was the software not being able to complete the required number of iterations. The goal of the simulation was to run a total of 5000 iterations in terms of time but the simulation would stop before reaching the 2000 mark and data post that point could never be recorded. Research was done on this issue to try and fix this problem where sources such as the official SimFlow forum were consulted. However, the forum did not provide any solution. In addition to trying this, the device on which the simulation was run also changed but the same problem arose again pointing to a possible computational error.

In a final attempt to try and solve this issue before switching gears was changing the plane's angle of attack. The angle of attack for any given aircraft lies between 0° and 8°. Consequently, more trials were done by changing the aircraft's angle of attack in intervals of 1°. The angle of attack for any given aircraft may vary depending on the chord of the airfoil relative to the wind. If the angle of attack is either too high or too low, it could lead to a loss of lift/stall. To eliminate this possibility, each angle was tested in order to ensure that this was not the case of the models. This again, did not cause any change in the data and did not lead to any improvements as the L/D ratio still averaged 0.1.

After many attempts, it was decided to try and focus on 2D airfoil analysis which would be similar to the side profile of the aircrafts in order to get data which could be used in order to get a partial understanding over the success and use of these aircrafts in specific. However, like the initial models, the simulation was unable to give any usable data off of these simulations as the same issues took place with the 2D airfoil analysis.

In conclusion, BWB aircrafts present the opportunity to incorporate sustainability into the aviation industry in a manner which is not dependent solely on sustainable aviation fuel. The unique and effective geometry of these aircrafts ensures a lower level of both turbulence and interference drag in comparison to narrow body aircrafts all in all leading to a higher L/D ratio and by extension leading to better fuel efficiency. Although the goal of the paper was to evaluate these aircrafts via simulation, the drawbacks of the software and technical difficulties prevented that from happening. If these issues were to be resolved, the simulations could be revisited in the future and lead to a more concrete and complete analysis over these aircrafts.

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