

COMPARING DIFFERENT SEMI-EMPIRICAL AERODYNAMIC TOOLS FOR ANALYSING NOVEL AIRCRAFT CONFIGURATIONS

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Abstract

In the conceptual design stage of aircraft design, it is common to use a low-fidelity or semi-empirical aerodynamic tool, including DATCOM, PANAIR, AVL, XFLR5 and VFP methods, to analyse the design in exchange for fast and robust calculations. However, all these tools apply different theories, assumptions, and limitations, which can lead to discrepancies in calculated results. Most of these tools are very mature and have been validated against existing aircraft designs. However, with the emergence of novel configurations, such as Blended Wing Body, the accuracy of these tools is put to the test again due to the pre-existing assumptions. For instance, DATCOM assumed a traditional tube-and-wing configuration, which the Blended Wing Body configuration does not reassemble. This study is intended to investigate and compare different semi-empirical aerodynamic tools' features, advantages and limitations. Further by comparing and validating the results of novel aircraft configurations to determine if existing semi-empirical aerodynamic tools can still provide accurate results for conceptual aircraft design.

In this research, it is expected to see how different theories and assumptions employed by these aerodynamic tools will lead to different limitations and divergence in results. The results will be validated and then analysed based on their accuracy, precision and computational time. A list of suitable aerodynamic tools for novel configurations will be suggested and supported by a case study.

Keywords: Conceptual aircraft design, Semi-empirical aerodynamic tools, Novel aircraft configuration, Blended Wing Body

1. Introduction

Conceptual design is the earliest stage in aircraft design. It is a stage where engineers have the highest flexibility to explore a wide range of designs, configurations and technologies.The design of modern, complex engineering products requires rapid development of a product definition that meets functional requirements while minimising cost to ensure successful market introduction. Experimental methods, although accurate, are largely unsuitable during the conceptual and preliminary design stages due to their high cost, long lead times, and limited flexibility for iterative design changes. Consequently, there is a strong reliance on computer-based aerodynamic analysis methods. At this stage of product development, the emphasis is not on using the most physically rigorous or state-of-the-art techniques, but rather on employing appropriate and efficient design methods that enable rapid evaluation. The need for quick data generation allows designers to explore a wide range of concepts and configurations through trade-off studies. This approach significantly reduces the time and cost associated with the conceptual design phase while still supporting informed decision-making. In order to achieve this, fast and robust calculations are needed. A lot of empirical methods are used during the conceptual design stage, especially in estimating aerodynamic performance and mass estimations.

Both, Denis Howe [1] and Daniel Raymer [2], have published books for conceptual aircraft designs, in which different approaches for conceptual aircraft design are suggested. Despite the difference in design approaches, both methods involved a significant number of empirical equations. These equations are good at providing a quick estimation yet there are a lot of limitations. The nature of empirical equations is derived from available data, which are only valid be applicable for designs with high similarity with existing aircraft. For novel configurations, such as Blended Wing Body (BWB) configuration, empirical equations will not be able to provide an accurate estimation. This is especially true for aerodynamic performance where BWB is known to have different aerodynamic behaviour compared to traditional Tube-and-Wing (TAW) designs. Empirical equations are also insensitive to geometry changes, which once more emphasis the limitation. Therefore, semi-empirical tools are used for more accurate results.

The main difference between empirical methods to semi-empirical or low fidelity tools is the correlation with the physical geometry. Aerodynamic tools such as PANAIR, AVL, VFP require some form of meshes, which allow a much more accurate calculation and are sensitive to changes of the geometry. However, in order to keep the computational cost down, assumptions and simplified theory is used as the basis of the aerodynamic tool. For instance, PANAIR uses panel methods, VFP uses full potential flow equations. These theories introduce limitations which can affect the accuracy of the results. All of these aerodynamic tools are very mature and have undergo different forms of validation against existing aircraft. Yet, these tools might not provide accurate aerodynamic predictions towards novel aircraft configurations due to the assumptions made based on existing aircraft. This paper aims to conduct an analysis and comparison between different semi-empirical aerodynamic tools and determine if they are suitable for novel configurations and identify any additional limitations and challenges when using semi-empirical aerodynamic tools for novel aircraft configurations.

2. Research aim

There is a growing interest in the research of novel aircraft configurations for new passenger aircraft. One of the most noticeable designs is BWB configuration. A significant difference between BWB and conventional TAW configuration is the geometry and aerodynamic properties, which directly reflect on the performance of the aircraft. It is important to have an accurate estimation in the early design stage to form a solid foundation for the design. However, empirical aerodynamic equations are not suitable in the absent of experimental results. It is also too expensive and time-consuming for high-fidelity aerodynamic analysis in the conceptual design stage, thus semi-empirical aerodynamic tools become an obvious choice. Yet there is still a lack of confidence in semi-empirical aerodynamic tools in analysing BWB configurations. The aim of this paper is to determine if existing semi-empirical aerodynamic tools are sufficient to provide accurate results for BWB configurations. Furthermore, a comparison between different aerodynamic tools will be conducted with regard to accuracy, limitations, computational times and so on, in order to determine which tool is currently the most suitable for analysing BWB configuration at the early design stage.

3. Existing semi-empirical aerodynamic tools

Semi-empirical and low-fidelity aerodynamic tools are commonly used in the early design stage because of their fast and robust calculations. Semi-empirical methods are a form of low-fidelity tool and it refers to computational tools that use both experimental data and physical based model. In general, a theoretical model is used to govern the calculations, such as panel method, the strip theory, the viscous full potential method and the vortex lattice methods. In Brandt's research[3], the importance of using semi-empirical in early stages of design and even preliminary design and how accurate estimation can lead a long way ahead in the design and optimisation. Therefore it is important to understand the theory behind each tool and what are the limitations are. Here is a list of low-fidelity tools representing different theories:

3.1 DATCOM

DATCOM, also known as the USAF Stability and Control Datcom (Data Compendium), was designed to provide a rapid estimation of aerodynamic stability and control characteristics through systematic summary of methods [4, 5]. DATCOM is designed to be self-contained and can calculate for any given flight condition and configuration. However, there is a fundamental limitation with DATCOM. These equations are empirical methods based on existing aircraft and experimental data, which are mostly wing-body-tail designs. Although there is a special configuration for the delta wing and a similar design, it cannot full represent a BWB configuration.

3.2 PANAIR

Panel Aerodynamic, commonly known as PANAIR, is a computer software developed by Boeing and NASA back in the late 1970s. The main purpose of PANAIR is to design and analyse configurations at subsonic and supersonic speeds. The fundamental theory used in PANAIR is a form of panel method. PANAIR uses higher-order panel methods, which uses a continuously varying source and doublet distributions to represent the flow instead of constant-strength panel methods. This allows a more accurate calculation, especially in supersonic flow, and a higher flexibility in the configuration [6].

3.3 AVL

Athena Vortex Lattice (AVL) is an aerodynamic and flight-dynamic analysis tool developed by Mark Drela and Harold Youngren since 1988. The code was based on previous NASA codes and VORLAX created by Lamar, E. Lan, L. Miranda and so forth [7]. As the name suggested, the fundamental theory of AVL is vortex lattice theory. It is most suitable for configurations with thin lifting surfaces at a small angle of attack and sideslip. In addition, AVL is cable of modelling fuselage and nacelles via slender body theory. Yet this does not takes into any consideration with any aerodynamic load generated by the fuselage [8].

AVL assumes a quasi-steady flow where unsteady vorticity shedding is neglected. This significantly limits the ability of AVL to analyse fast flight manoeuvrers and off-design points. AVL also uses the classical Prandtl-Glauert (PG) transformation to handle compressibility by converting PG equation to a Laplace equation and solved by basic incompressible method. Yet, this is not completely valid as free stream velocity become large, which leads to unreliable results in transonic flow beyond Mach 0.8 [8].

3.4 XFLR5

XFLR5 was created by Andre Deperros back in 2003. It is a free open-source software intended for aerofoils, wings and planes operating at low Reynolds numbers [9]. XFLR5 uses an approach to separate the Navier-Stokes equations into two parts, inviscid fluid and time-averaged turbulence, and tackle them separately. The inviscid fluid is assumed to be time-independent and incompressible flow. Different to other aerodynamic tools, XFLR5 provides different solvers for calculating the results. This includes lifting line theory (LLT), vortex lattice method and panel method. At the same time, first-order boundary layer integral equations and second-order boundary layer differential equations are used to estimate the viscous flow around the aerofoils [10].

With no doubt, there are a number of limitations as to the other aerodynamic tools. One of the limitations noted by the creator of the software is the lack of an interactive boundary layer loop. This is a coupling method between potential and viscous flow which is not implemented in XFLR5. In addition, XFLR5 also lack of the ability to analysis the flow interactions between body-wing [11].

3.5 VSPAero

VSPAero is an open source, parametric aircraft design tool. It has in-built integrated aerodynamic solver called VSPAero. VSPAero is a low-fidelity solver with the Vortex Lattice Method and Panel Method as the solver methods. Both VLM and PM is a numerical solvers with inviscid properties. Therefore, it cannot predict any flow with compressibility effects in it. VSPAero also can't predict flow separation, stall propagation, and shockwaves. Hence, if a transonic flow is detected, the solver will give a warning to the user that the data produced might not be accurate. In older VSP models, such as 3.44.0 below, there is a 2nd order Karman-Tsien Mach correction factor that could model soft shockwaves. In the newer version, the GUI hides the option to select that mode, even though it is still available in the code. The reasoning behind this is unknown as mentioned by the VSPAero developers himself[12].

3.5.1 SU2

SU2 (Stanford University Unstructured) [13] is an open-source CFD software suite widely used for aerodynamic analysis with unstructured meshes. It supports several flow models, including the Euler, Reynolds–Averaged Navier–Stokes (RANS), and Navier–Stokes (NS) equations, allowing the simulation of a wide range of aerodynamic flow conditions. Its flexibility in handling complex geometries and unstructured meshes makes it particularly suitable for aircraft aerodynamic analysis and multidisciplinary design studies [14, 15, 16].
The Euler equations are employed to capture nonlinear aerodynamic effects and wave drag phenomena. After the mesh generation process, aerodynamic simulations are carried out using SU2. Two main input files are required for the simulations: a mesh file and a configuration file. The mesh file defines the computational domain, while the configuration file specifies the flow conditions, numerical schemes, convergence criteria, and output variables. Once the simulation is completed, aerodynamic results such as pressure distributions and aerodynamic coefficients are post-processed and visualised using external analysis tools.

3.6 VFP

VFP (Viscous Full Potential) is a three-dimensional Computational Fluid Dynamics (CFD) method, implemented in FORTRAN, for predicting the flow field and aerodynamic forces of an isolated wing (wing-alone configuration) or a wing–body combination in a subsonic free-stream, including the presence of shock waves. The VFP equations are selected as an appropriate governing framework for modelling attached, compressible, viscous transonic flows, which are characteristic of transport aircraft wing design. Potential flow methods originate from the Navier–Stokes (NS) equations but are simplified through assumptions of inviscid, irrotational, and isentropic flow. While these assumptions significantly reduce computational complexity, they impose limitations on the applicability of the method. In particular, the assumptions of irrotationality and isentropy restrict validity to flow fields without shock waves, or where shocks are sufficiently weak such that the resulting deviations from isentropic behaviour introduce only minor errors in predicted pressure and velocity distributions. Although the assessment of stall behaviour is relevant for overall aerodynamic evaluation, the primary requirement at the conceptual design stage is to ensure that the configuration achieves maximum lift-to-drag performance at the design point, with adequate margins relative to boundary-layer separation and the associated onset of buffet, both in Mach number and angle of attack. Likewise, an efficiently designed transonic cruise aircraft would not be expected to operate in regimes where shock-induced separation becomes significant, as such conditions fall outside the intended performance envelope. VFP uses a relaxation process to solve finite-difference forms of the full non-linear velocity-potential equation for the flow around the three-dimensional geometry. It is coupled with a semi-inverse swept tapered integral Boundary Layer equation solver [17, 18]. Boundary Layer Equations directly solved in terms of the boundary layer integral quantities variables (δ, δ^*,θ, H) . ie: no costly and problematic post processing. With advances in computers, it has become possible to perform runs of VFP on a PC within a few minutes. The baseline VFP solver employed in this study was that developed by the UK Royal Aerospace Establishment (RAE) and Aircraft Research Association (ARA) for the UK aircraft industry during the 1980's, and is now available commercially from IHS ESDU [19, 20].

4. Methodology

For fair comparison, a BWB design with a pre-defined geometry is used, showing in Figure 1, and analysis by various aerodynamic tools. Each aerodynamic tool has to model the aircraft and generate the mesh if necessary. Then the design will be analysed based on the same set of flight conditions, including different Mach number, altitude and angle of attack. Coefficient of lift, drag and moment will be captured and compared.

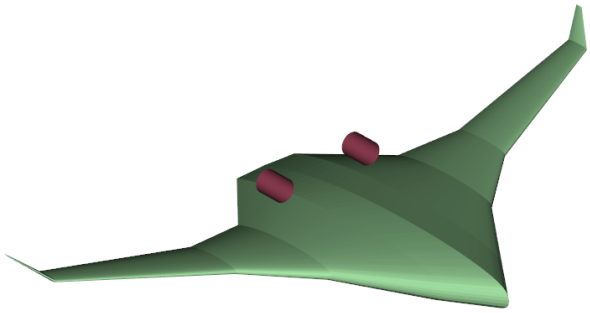


Figure 1 – Pre-defined BWB geometry

4.1 Geometry and mesh definition

A key factor to good aerodynamic estimation is the definition of geometry modelling and meshing. As previously stated, a pre-defined geometry is provided yet different aerodynamic tools require different meshing or discretisation prior to the analysis. Each method has its own assumptions and limitations, which at the same time change the model slightly. This can potentially lead to a significant discrepancy in the later calculation.

4.1.1 DATCOM geometry generation

Within DATCOM, configurations are categorised into different groups, including body, wing-horizontal tail, body-wing-tail, non-standard geometries and special configurations. For a BWB configuration, it is considered a special configuration and treated as a low aspect ratio wing. However, DATCOM does not fully model the geometry. Instead it takes certain inputs and generates a simplified version of it, as demonstrated in Figure 2 [5, 4]. Without a proper and accurate model, the accuracy of the calculation is significantly affected. This also means that the results are not sensitive to the geometry changes.

4.1.2 PANAIR discretisation

As mention in 3.2, PANAIR uses a higher-order panel method. So as to achieve that, the fidelity level of the model also has to improve accordingly. Different to traditional panel methods, where surfaces are discretising into quadrilaterals, curved panels are also used. By combining two different types of panels, it allows accurate modelling in both planar areas, such as fuselage and flat wing, and high curvature area such as leading edges.

There is an additional limitation with PANAIR where only half of the aircraft is modelled. In order to reduced computational time, there is a symmetry plane through the centre line of the aircraft. In most cases, this significantly helps to reduce the computational time, however this also forces the aircraft to be symmetric through the centre line. This creates a unique problem when it comes to designing such as the NASA AD-1 oblique wing aircraft and asymmetric aircraft like Blohm & Voss BV 141.

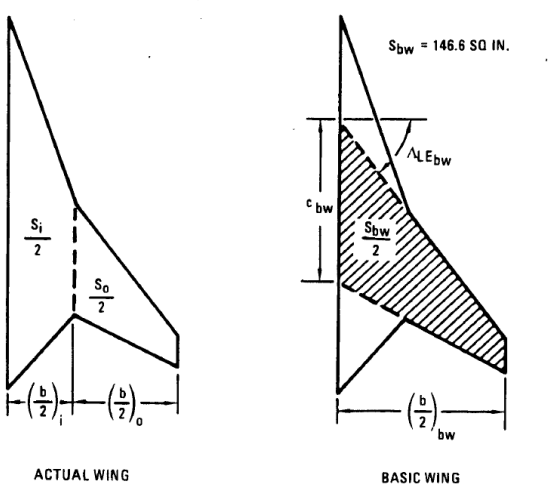


Figure 2 – DATCOM configuration modelling

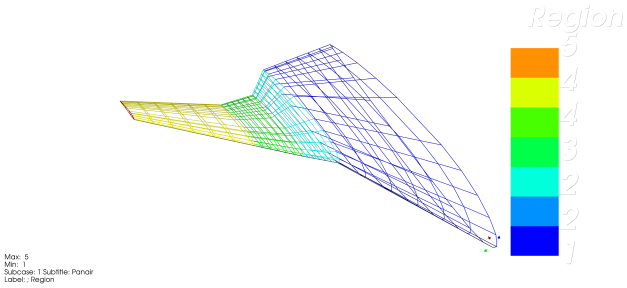


Figure 3 – PANAIR meshes

4.1.3 AVL discretisation

Similar to PANAIR, AVL discretise the main wing and other lifting surfaces into vortex lattice panels, which the geometry is controlled by NACA number, spanwise, and chordwise spacing parameters and scaling factors. Nevertheless, the panels are modelled as an infinitely thin sheet of vorticity along the mean camber line. In other words, the vortex lattice method is more suitable for thin aerofoils instead of thick aerofoils. On the other hand, as stated in 3.3, vortex lattice is designed for lifting surfaces, a non-lifting body is modelled based on its side-view and top-view profiles.

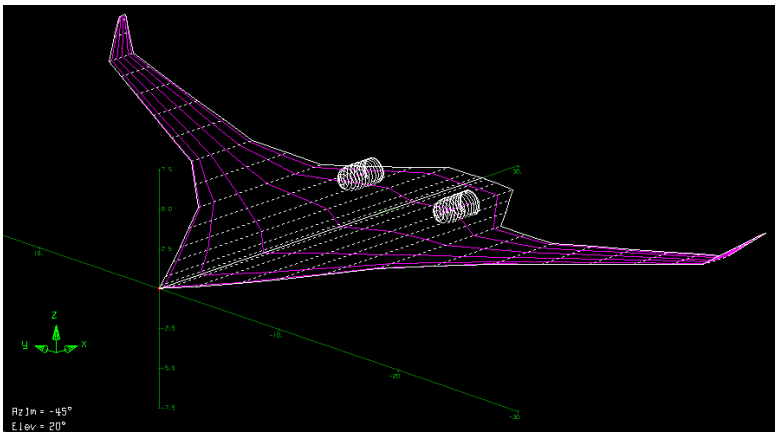


Figure 4 – AVL meshes

4.1.4 XFLR5 modelling

Similar to PANAIR, XFLR5 basically convert the surface of the designs into flat quad panels. As mentioned previously in 4.1.2, there is fundamental problem with this method, especially on surfaces with a massive curvature. However, unlike PANAIR or AVL, where the mesh is generated by discretising a pre-defined model, XFLR5 requires you to define the geometry within the program. The geometry is first started by defining aerofoil shape in 2D, then scale them by the chord length at each sections and connecting them together by setting the x & y offsets with addition information such as twists and dihedral. This applies to wings and all other lifting surfaces. It is also possible to model the fuselage of the aircraft within XFLR5 in a similar manner, where cross sections are defined.

This potentially creates some problems. This requires additional time for the user to recreate the model and the level of accuracy is heavily depends on the level of details by the users. In addition, the way the panels are joint together is linear, which means if is hard to represent any curved leading edge, which is sometimes spotted in novel designs such as BWB.

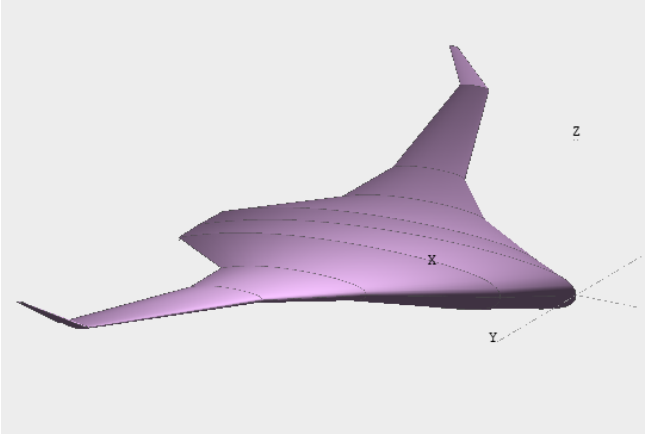


Figure 5 – XFLR5 meshes

4.1.5 VSPAero

To operate VSPAero, the model needs to have a proper mesh resolution to prevent misleading results. Since both methods use panel discretization, then the surface resolution will play a significant role in the aerodynamic coefficient accuracy. The mesh itself is divided into two different resolutions. Spanwise resolution (u) determines the pressure distribution across the wingspan, whereas chordwise resolution (w) affects the pitching moment accuracy and helps with pressure distribution along chordwise direction. In this simulation, the spanwise resolution is set at 60, with higher resolution concentrated around the kink and wing region. The chordwise resolution is set at 93 to properly capture the aerofoil curvature and ensure good convergence. The wake nodes value is set at 32 to increase accuracy of induced drag. Whereas the iteration value is set at 10 to ensure result stability since at higher alpha, the value tends to oscillate before converging. The minimum convergence criterion is set to be the induced drag and Oswald efficiency factor, in which both criterions need to have positive value to ensure Kutta condition was satisfied.

4.1.6 SU2 mesh

Parametric geometry information is first used to generate a solid aircraft model in BREP format. The BREP model is then imported into Gmsh [21] for mesh generation and CFD preprocessing. A computational domain is created around the aircraft to support aerodynamic simulations, showing in Figure 7. To improve mesh quality and aerodynamic prediction accuracy, local mesh refinement is applied in regions with strong flow gradients, particularly around the leading and trailing edges of the BWB configuration. This process enables the generation of high-quality surface and volume meshes suitable for high-fidelity aerodynamic analysis.

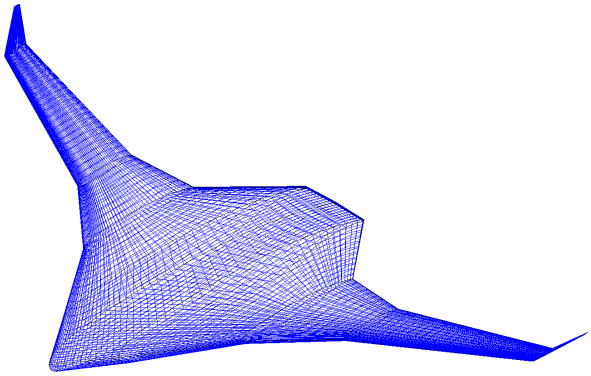


Figure 6 – VSPAero meshes

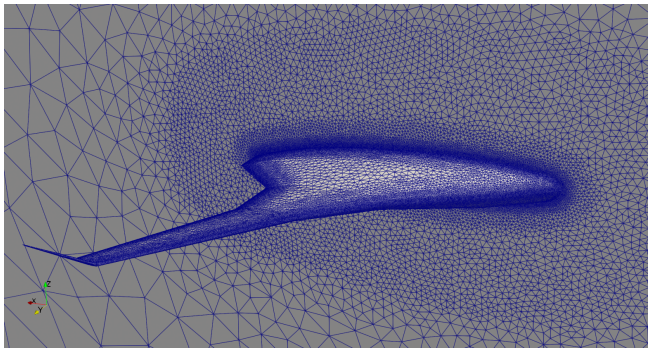
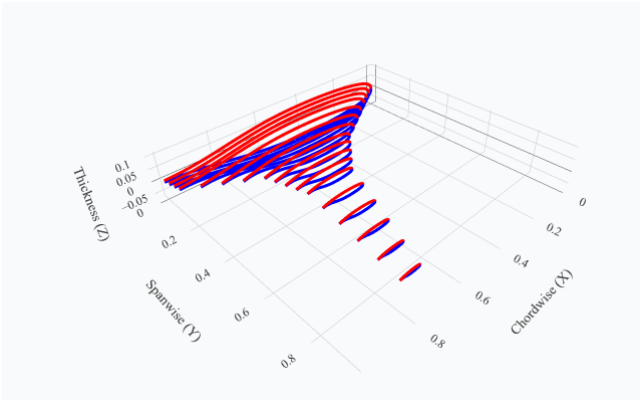


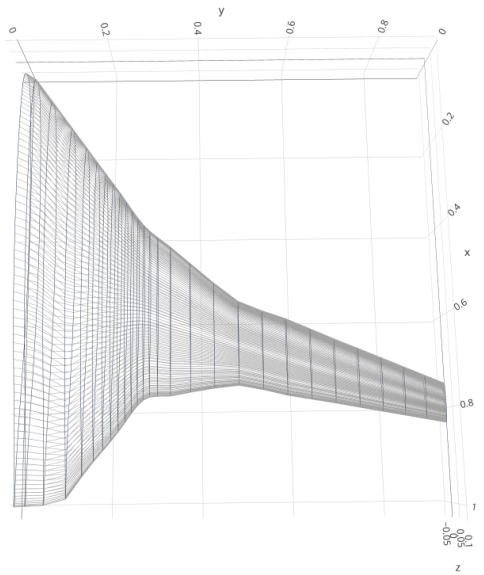
Figure 7 – SU2 meshes

4.1.7 VFP geometry and mesh

In order to run the VFP software, three input files, ascii format, are always required: The geometry file (.GEO) which provides information that specifies the parameters of the wing-alone or wing-body geometry of interest, namely the aerofoil shapes' coordinates along the span of the wing at the specified positions along with the chord lengths, twist and sweep angles, and dihedral. The wing geometry is defined by a number of control (aerofoil) sections, together with the types of interpolations to be employed between them, as shown in Figure 8a.



(a) VFP geometry



(b) VFP mesh

A control section corresponding to (the centre line) must be given even when a body is present. The section data must appear in order of increasing y. The winglet is not included because the limitation of the current version used in this work but its implementation is under development. The mesh file (.MAP) which provides information that specifies the mesh, or computational grid, on the geometry input. Mesh is shown in Figure 8b.
Finally, the flow file (.DAT) which specifies the flow conditions, as in the freestream Mach number and the angle of attack, parameters that control the iterative calculations and CFD simulation behaviour, or scheme, and parameters that control the output produced in terms of the extent at each grid refinement level. The iterative flow field calculation comprises a sequence of one or more steps, each step corresponding to a number of iterations on a grid of a particular refinement level. Once the grid calculation is complete, the flow calculation which follows has three levels of grid refinement: from coarse (level 3), to medium (level 2), to fine grid (level 1). The first viscous calculation of the initial run is always carried out after 50 inviscid iterations at coarse grid level, and this is then followed by a viscous calculation after every 10 inviscid iterations for the remaining flow calculations. During a VFP run, multiple output files are generated and stored in the working directory. The primary output file reports the convergence history, followed by the wing surface pressure distributions, flow-field information, and subsequently the boundary-layer data. It also provides the local and total force and moment coefficients derived from the integrated pressure fields. The boundary-layer section includes both local and overall viscous and skin-friction drag coefficients. The wave-drag component is evaluated using the approximate method originally developed by Lock [22] for aerofoils and later extended to three-dimensional wings.

4.2 Validation

It is very difficult to conduct validation without an existing flying BWB aircraft or expensive and time-consuming wind tunnel testing. However, the intension of these semi-empirical tools is to provide a quick estimation on the overall aerodynamic performance. Therefore the results are understandable and expected to be a little coarse, especially compared to high fidelity computational fluid dynamic calculations.

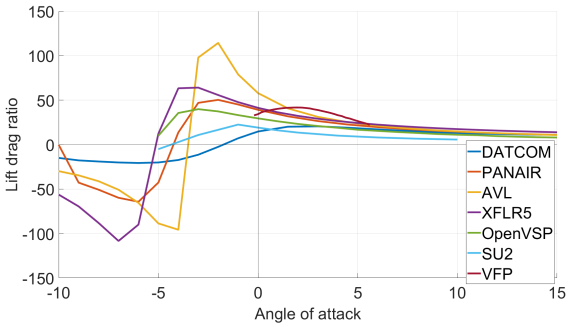
In Prince's paper [23], a validation case study was conducted using VFP, a high solution Navier-Stokes solver and wind tunnel testing results on a wing-body and a BWB. VFP shows a promising and matching results compared to both NS and wind tunnel results. Therefore in this study, VFP results will be used as the baseline for comparison.

4.3 Discussion and results

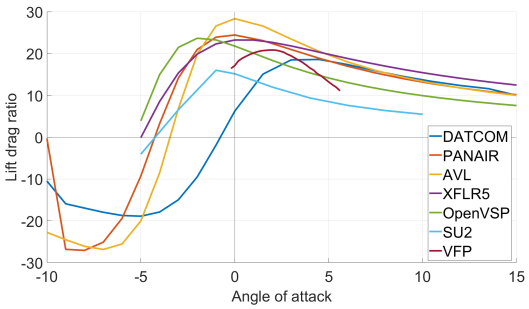
4.3.1 Lift drag ratio again angle of attack

From the results presented in Figure 9a, the results are fairly inconsistent and unrealistic. The results are showing an exceptionally high L/D ratio which is practically impossible to achieve. AVL is predicting a L/D over 100, where PANAIR and XFLR5 are predicting over 50 and 60, respectively. These are inviscid results generated by the aerodynamic tools directly. This means that no friction drag or form drag is taken into consideration. Software such as XFLR5 and VSPAero provide additional drag correction calculations for the viscid flow. Or else, separate drag correction factors need to be added externally.

It is possible to apply a correction drag component, D_{form}, back into the results, as presented in Figure 9b. The corrected L/D ratio prediction presents a much more accurate result. VSPAero and XLFR5 have their internal drag correction calculation. In the meantime, empirical form drag estimation is used as a correction for PANAIR and AVL provided by GENUS. Meanwhile, DATCOM has been the odd one compared to the others. Despite not having any drag corrected added, the method inherently calculate the viscid drag. This is because DATCOM are constructed based on existing data, which means viscid flow and boundary layer are already been taken into consideration.

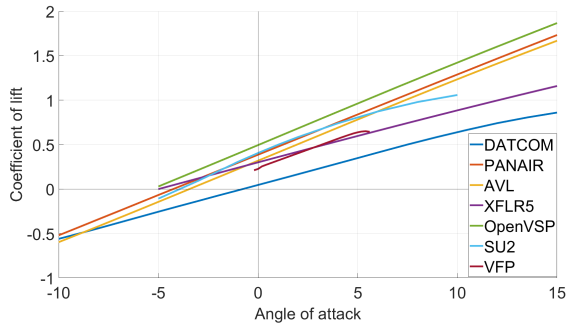


(a) L/D ratio against AOA

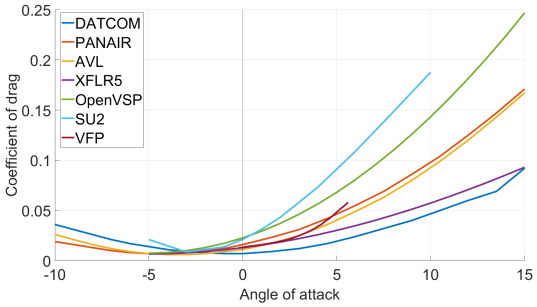


(b) L/D ratio against AOA with drag correction

From Figure 9b, most aerodynamic tools provide a very similar result for the BWB design. PANAIR and XFLR5 show heavily overlapping curve. This does not come as a surprised as both tools share a similar theory for the calculation. AVL presented a 31.7% higher maximum L/D ratio. While DATCOM and VFP peak at a higher AOA compared to most of the others. All the aerodynamic tools overestimate the L/D ratio from 6% to 31.7% compared to VFP result as baseline. These difference cause by a combination of little difference in C_L and C_D, showing in Figure 10a and 10b. In addition, DATCOM's calculation shifts the whole curve to the right where the peak L/D ratio happens at a higher angle of attack. The difference in the results are likely caused by the difference between the design and what is actually being modelled and analysed.



(a) C_L against AOA



(b) C_D against AOA

One of the other important things notice from Figure 10a is that there is no sign of stall. This is because of the flow is assumed to be inviscid and does not consider flow separation. In the other words, the results at high AOA are not reliable. In VFP calculations, the simulations crash when there is a flow separation, which in a way serves as a stall detection.

In a similar note, Figure 10b shows a more noticeable divergence between each tool as different theories and assumptions applied. VLM mainly estimates induced drag and poor in estimating pressure drag as aerofoil is assumed to be 0 thickness. On the other hand, the panel method estimates both induced drag and pressure drag. In addition, SU2 has the highest C_D prediction where it considers wave drag through Euler equations. This clear demonstrate a problem with semi-empirical aerodynamic tools. The drag estimation is only partial with missing components, such as friction drag and wave drag. This significantly underestimate the overall drag and overestimate the performance of the aircraft.

4.3.2 Coefficient of moment and neutral point

Apart from the lift and drag of the aircraft, the other important calculation is the coefficient of moment and neutral point estimation. These two are key indicators to determine the stability of the aircraft. Figure 11 shows the coefficient of moment against AOA, in which all of them show a similar gradient but with a different offset.

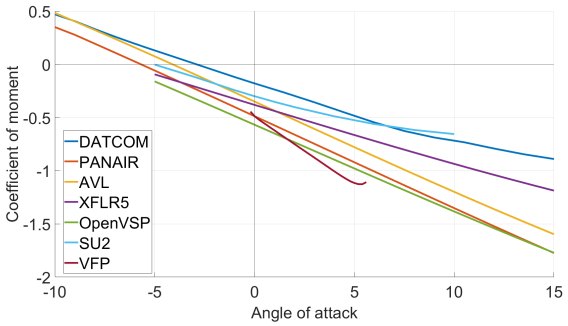


Figure 11 – Coefficient of moment vs AOA

As expected that, most of the calculations have a very similar results in both C_m and NP calculations. The result with the most noticeable difference is the results generated by DATCOM, which aligned with the previous results.

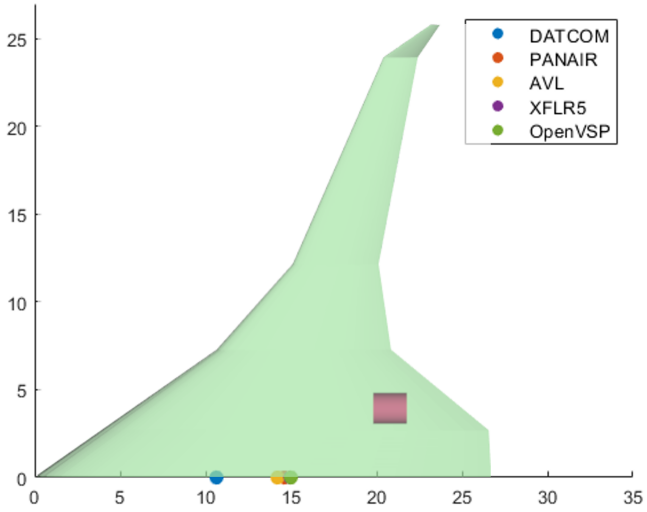


Figure 12 – Estimated neutral point

4.3.3 Application for BWB conceptual design

Table 1 summaries different aerodynamic tools and their features and in the previous sections, results of BWB calculations are presented and compared. Given majority of the tools are generating similar results, other criteria of the aerodynamic tools need to be taken into consideration. A key requirement for conceptual design tools is the robustness and short computational time. A lot of design explorations is needed during early design stage in which lots of iterations may be performed. If optimisation is involved, it can easily go up to thousand of calculations. The computational time becomes significant even the difference is between seconds and minutes. From all the mentioned aerodynamic tools, DATCOM, AVL and VFP have the fastest computational time, which make them suitable for design exploration. However, this does not mean that other tools are not suitable for BWB conceptual design. As the geometry get more converged and finalised, a higher fidelity tool is more recommended despite it requires a longer computational time.

One other important features of the design tool is sensitive to the changes to the design. During the design exploration, it is common to modify the aircraft geometry to find the optimum design. This including changing the wing span, chord length, swept angle and more. An aerodynamic tool which is sensitive to the changes will better capture the performance difference. Tools which mesh the model will be able to capture the changes quite easily. However, tools such as DATCOM will be lacking in this area as discussed in section 4.1.1. XFLR5 also suffers this problem as the model needs to be created separately.

Last but not least, the application of the tool itself is a significant contributor too. In section 4.1 discussed how different tools define and model the aircraft. Even though this does not directly affecting the computiational time, this still cost man-hour to model. Some of the tools such as VFP and XFLR5 require definiton of a set of cross-section aerofoils, which can be time consuming. The last factor about application of the tool is the reliability of the calculations. During the simulations, some design tools will not able to come up with a result or crash, such as XFLR5, AVL and VFP. This can cause by multiple reasons, such as bad and incomplete modelling, outside design range and flow separation. Yet, no matter what are the reasons behind, this will still affeft the optimisation and will potentially have to start again which increase the computational time.

5. Conclusion

This research has identified different theories used behind semi-empirical aerodynamic tools and evaluated them against the accuracy of analysing novel aircraft configuration such as BWB design. With different semi-empirical tools and different theories applied, results are diverged at times. Nearly all the aerodynamic tools are assuming inviscid flow to simply the calculations. This is shown that the drag is under estimated since friction drag is not considered. In addition, some tools are better at estimating certain drag compoents, for instance, AVL is better at induced drag estimation and lacking pressure drag estimation. This further underestimate overall drag and overestimate the performance of the aircraft.

The level of detail in modelling and computational time also have a strong influence in conceptual design. During the early design stage, it is common to explore different geometries. For example, changing the wing span, chord length, swept angle and more. This is even more crucial for novel configuration such as BWB. The aerodynamic tool has to be sensitive enough to capture the changes and calculate the performance differences. Among all the aerodynamic tools mentioned, DATCOM and AVL have the fastest computational time. Yet, their interpretation of the model might not be the most accurate. DATCOM fits the geometry into one of their preset configurations and AVL struggles to model thick aerofoils. PANAIR, VSPAero and SU2 discretise the model into mesh which provide a higher sensitivity to the changes of the geometry.

In addition, the tool also needs to provide a fast and robust calculations for a large amount of iterations, which also have a strong direct relation with the complexity of the mesh and accuracy. Tools with a simpler modelling methods, such as DATCOM, have a significantly faster computational time in the cost of accuracy. On the other end of the spectrum will be AeroVSP or SU2 which a much higher details of meshes and level of accuracy but with a longer computational time.

In conclusion, from the results it had demonstrated that most semi-empirical aerodynamic tools will provide similar results for BWB. This shifted the decision of choose which tools to use from accuracy to other features of the tool. This includes theory used, mesh generation to computational time. For design exploration, a faster tool such as AVL might be more suitable while SU2 is more suitable for a more detailed calculation for a frozen design.

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Criteria	Mesh	Computational time	Accuracy[a]	Limitations	Remarks
VFP	defined by inputting certain pre-decided parameters	minutes	baseline	Symmetrical aircraft; Lose accuracy at relatively high lift conditions	For cases with strong shocks and highly three dimensional flows VFP tends to match the trend but not the level.
DATCOM	defined by inputting certain pre-decided parameters	instant	8.8%	dose not fully model the geometry	
AVL	discretise lift surface both spanwise and chordwise	seconds	19%	slender body can also be modelled	more suitable for thin aerofoil
PANAIR	discretise the geometry into quadrilaterals and curved panels	minutes	31.7 %	only able to calculate of symmetric aircraft	
XFLR5	build your own geometry by joining aerofoil sections	seconds $\sim$ minutes	11.4%	only recommended to do calculation within low Reynolds number	
VSPAero	discretise the geometry surface into interconnected polygonal network	minutes $\sim$ hours	19.7 %		
SU2	volume mesh	hours	6.1%		

Table 1 – Aerodynamic tools comparison matrix

[a]Percentage difference of L/D_{max}