METHODOLOGY FOR A PRELIMINARY DESIGN STUDY OF A BOX-WING AIRLINER

I. Roy Salam, C. Bil
School of Aerospace, Mechanical and Manufacturing Engineering
RMIT University
PO Box 71, VIC 3083, Bundoora, Australia
ishan.roysalam@student.rmit.edu.au; c.bil@rmit.edu.au

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Abstract

The box-wing aircraft concept has recently been revived as a possible alternative design concept that offers key advantages to designers looking to maximize efficiency and minimize environmental impact and fuel burn of aircraft.

However the aerodynamic and structural characteristics of the planform are not well understood, even at a basic level, unlike for conventional configurations

In order to establish this baseline information, a parametric design study was conducted for a 150-seat short-range box-wing airliner. Low-fidelity design methods were used in order to explore a wider design space and the geometry that was unique to the box-wing was the focus of the study. The aerodynamic, structural and aero-structural outcomes were ascertained as function of the wing planform geometry.

The methods used to conduct this parametric study are the focus of this paper as they present an unique challenge compared to the well understood conventional wing planform. Brief results and their outcomes from the study are presented which show a combination of higher vertical separation, low horizontal separation and shorter wingspan was found to be optimal for of a box-wing configuration with respect to maximum specific range.

Nomenclature

b = Wing span
c_t = Thrust-specific fuel consumption
C_L = Coefficient of lift
C_D = Coefficient of drag
h = Vertical separation between wings
R = Range
S = Wing area
W_0 = Start cruise weight
W_1 = End cruise weight
ρ = Ambient density

1 Introduction

There are a number of significant challenges facing the civil aviation industry in the near future, including coping with increased demand, the need to reduce the environmental impact of air travel as well as the ever-present demand to reduce costs including fuel usage. In particular, ambitious goals regarding carbon-neutral growth and halving carbon dioxide emissions as proposed by the likes of Europe's Advisory Council on Aeronautics Research (ACARE) [1,2].

However in order to meet these ambitious goals, designers must look at breaking away from the evolution of current design paradigms and instead at revolutionary new concepts that may offer the only possible pathway to reaching the goals [3]. The box-wing concept (also known as the Prandtlplane, in honour of Ludwig Prandtl upon whose multiwing theory the concept is based) is one such concept that theoretically offers the kind of advantages necessary to meet these goals. The box-wing planform consists of two horizontal wings offset vertically and horizontally, joined at the tips by vertical winglets.

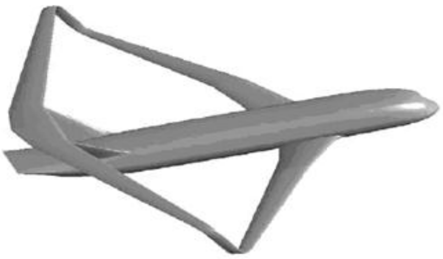

Fig. 1 Large box-wing concept [4]

Under certain conditions, such as equal lift distribution on both horizontal wings and a butterfly shaped lift distribution on the vertical winglet, it theoretically offers increased aerodynamic efficiency over conventional wing planforms. This arises from the vertical winglets, which form a closed wing system that inhibit the formation of wingtip vortices, which are the major cause of induced drag. Furthermore, the equivalent wing area is effectively split over two wings with each having a higher aspect ratio for the same wing span, improving aerodynamic efficiency.

The key design parameter for the box-wing configuration has been theorized to be the ratio of the height between the wingtips to the wingspan of the aircraft (*h/b*), and this must be maximized in order to gain maximum efficiency [4,5]. However the influence and interaction with regards to the other geometric parameters are largely unknown and there is little insight to their influence on the relationship between aerodynamic efficiency and wing weight.

Hence a preliminary study on the interaction between the geometry and the structural and aerodynamic characteristics of the box-wing concept is necessary. It focuses on the key geometric parameters such as the horizontal and vertical separation, the key aerodynamic qualities such as the lift and induced drag values and of course the wing weight. The results are then included in a simplified range equation to determine the impact on specific range as the figure of merit.

Due to the greater influence of induced drag, and hence a greater impact from its reduction, box-wing designs is most likely due to be more successful for commercial aircraft with a lower range and lower passenger capacity. Other design studies have focused on ultra-large box-wing aircraft [4] but economic feasibility is much more likely to come from smaller capacity aircraft hence this investigation concentrates on the possible design of a 150 seat passenger aircraft with a box-wing configuration. Efficiency variations for the box-wing design were compared to that of a modern short to medium haul transport aircraft, the Airbus A320. This aircraft type was used as the baseline aircraft throughout this study.

2 Theory

2.1 Aerodynamics

The initial basis for the Prandtlplane lies in the Prandtl-Munk Biplane Theorem [6,7] but successive studies [8] have found this to be inaccurate. Vortex lattice methods provide a quick and reasonably accurate low-fidelity pathway for analyzing aircraft aerodynamic characteristics. They can calculate the forces and coefficients for a given wing geometry and chosen flight condition, and hence can be used to explore a large design space without being overly complicated and computationally intensive to use.

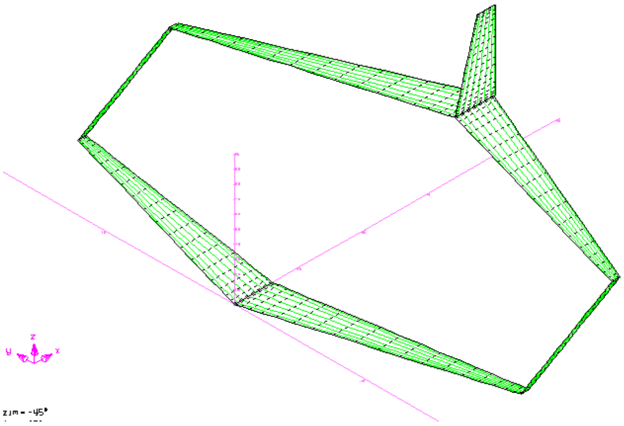

Fig. 2 Typical box-wing vortex lattice mesh geometry.

Athena Vortex Lattice (AVL) [9] was the vortex-lattice analysis code chosen as it has seen relatively widespread usage and found to be both reliable and satisfactory by other design studies. Its code allows for the modeling of the lifting surface and the wake and hence the impact of both wings on each other can be taken into account. However, it does have some disadvantages that need to be take into account when considering the accuracy of the results- namely, it cannot handle shocks, hence all Mach numbers used are subsonic (M < 0.6), and it cannot compute form drag, hence induced drag is the only component considered for the analysis. .

2.2 Structures

The wingspars, two for each of the horizontal wings, were analysed around a neutral axis through the middle of the box geometry, with the spars appropriately sized and the ribs and skin based on spar sizing. This is due to the fact that the box-wing structure provides a challenge in that the whole structure must be analysed together. A similar approach was used for joined-wing designs [10] which became useful for this study. The unique loading and the fact the box structure itself resists bending load, calls for an approach where the entire structure is analysed around a neutral axis.

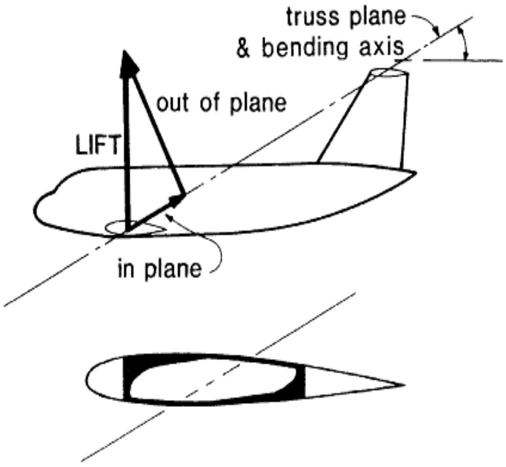

Fig. 3 The joined-wing structural behaviour [10]

Once the lift distribution is known from the vortex-lattice analysis, it can be used to estimate the wing weight with respect to the aerodynamic loads.

This coupled loading allows for the extra resistance to bending with the equivalent wing depth being the vertical distance between the two wings. This is important due to the fact it allows for some weight alleviation as in other cases a two-wing design is likely to be heavier than a conventional single wing structure.

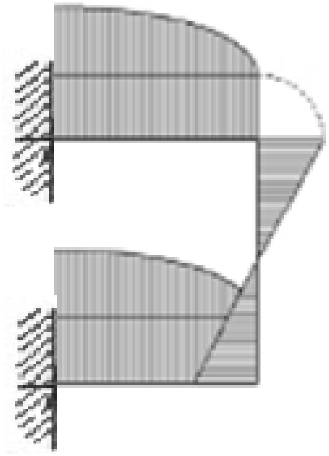

Fig. 4 Theoretical idealised lift distribution for a box-wing planform [4]

2.3 Aero-structural

Once the structural and aerodynamic investigations are complete, a deeper understanding and overview of the whole design space requires that both be incorporated into a single measure that can trace the influence of the various geometric parameters on the overall relative efficiency of the planform. A simplified version of the jet aircraft range equation was chosen to be this measurement as it included both life and drag coefficients as well as the weight.

3 Method

The geometric parameters investigated were those that were the most unique to the box-wing configuration - the vertical separation between the horizontal wings, the horizontal separation between the horizontal wings and how influential the span or the aspect ratio. The list of variables is shown in Table 1. While theory predicts some of them importance of these, it is not accurate and the understanding is definitely incomplete. So starting with a baseline design and keeping values such as the wing area the same, parameter variations were conducted that covered a fairly realistic range of values in order cover a relatively large design space. For simplicity and computational efficiency, a number of details such as the airfoils used were kept the same as for the baseline design. The span/AR comparison here is basically investigating what influence the actual box-wing planform has versus the effect of doubling the effect aspect ratio for each wing as a result of halving the wing area to spread over two wings. Most box-wing planforms simply take that approach without verifying its influence on the results.

Geometric Parameter	**Range**
Vertical wing separation	2 – 10 m
Horizontal wing separation	2 – 30 m
Span/AR	Span fixed or AR fixed

Table 1. Box-wing geometric parameters investigated

Finally, the box-wing design for maximum efficiency and a valid comparison requires equal elliptical lift distribution across both wings. With such a variety of geometric parameters varied, the only way this could be achieved was to use wing twist. Hence all the models were optimised using a MATLAB subroutine that tied in with AVL to ensure that an elliptical lift distribution was achieved. This ensured that the comparisons across different wing geometries were more consistent and more comparable to the baseline aircraft.

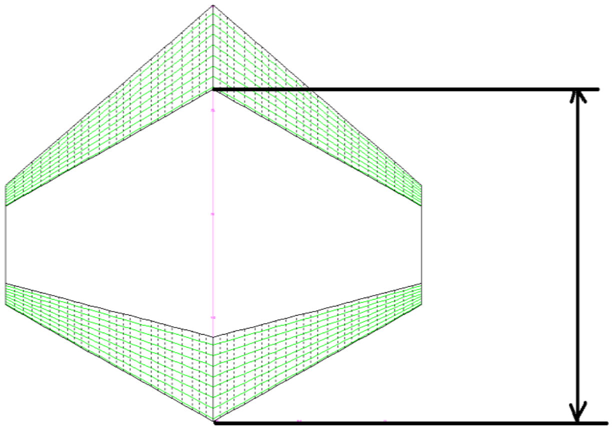

Fig. 5 Horizontal separation between wings

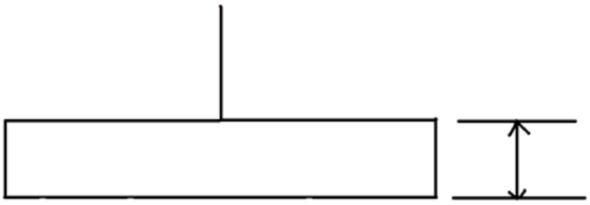

Fig. 6 Vertical separation between wings

3.1 Aerodynamics

Automation was incorporated to conduct parametric exploration. Furthermore, only the wing planform was investigation, the fuselage and other aircraft components were ignored. The AVL provided outputs including the lift coefficient, the induced drag coefficient and the lift distribution for specified conditions. This lift distribution was used for the structural analysis of both the horizontal wings and the vertical winglets, forming a key step in undertaking an aerostructural investigation of the box-wing design space.

The key here, as mentioned earlier, was ensuring as close to an elliptical lift distribution was achieved on each wing as possible while maintaining a quick computation time. This was done by dividing each wing into sections that were assigned their own individual angles of incidence that were subsequently tweaked in order to ensure the lift distribution was close to being elliptical.

AVL allowed for the output of strip forces at each section, meaning a comparatively detailed output was available for further analysis.

3.3 Structures

A 2-spar wingbox for each of the wings was assumed, with the first spar at 0.3 of the chord and the second at 0.7 of the chord along the length of the wing. The lift distribution from the aerodynamic analysis was turned into a bending moment, ignoring the weight of any fuel as that was assumed to be the same for all configurations and the baseline at this early stage of the analysis. The moments of inertia of the whole structure were found using the spar cap sizes, which was initially estimated and assumed to carry 0.7 of the overall moment.

The neutral axis and angle were found using these moments of inertia, and the bending moment was then applied along said neutral axis, which then allowed for the use of an iterative solver to refine the spar cap sizing using the stress at every spar cap. Then the skin and ribs were sized for the rest of the bending moment and the resulting shear values. The weights of the vertical wingtips are included but due to the low overall load on them, these weights were found to be negligible in comparison to weight of the horizontal wings.

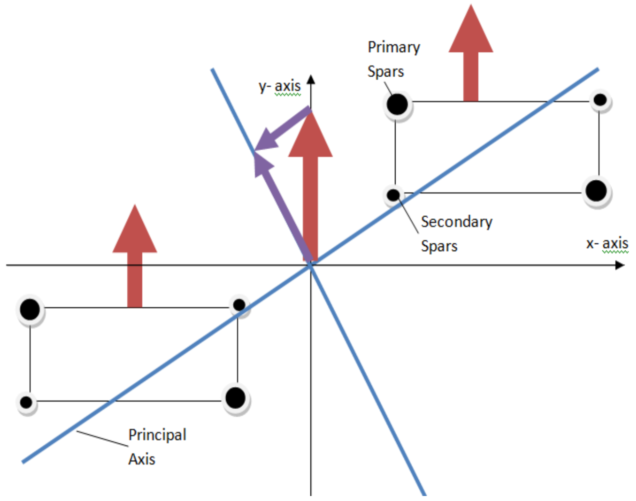

Fig. 7 The structural arrangement of the spars for the box-wing configuration

The spar areas were allowed to vary, but were linked. The moments of inertia and stresses were then reiterated and the spars re-sized till the area converged. Figure 7 illustrates the process as a flowchart

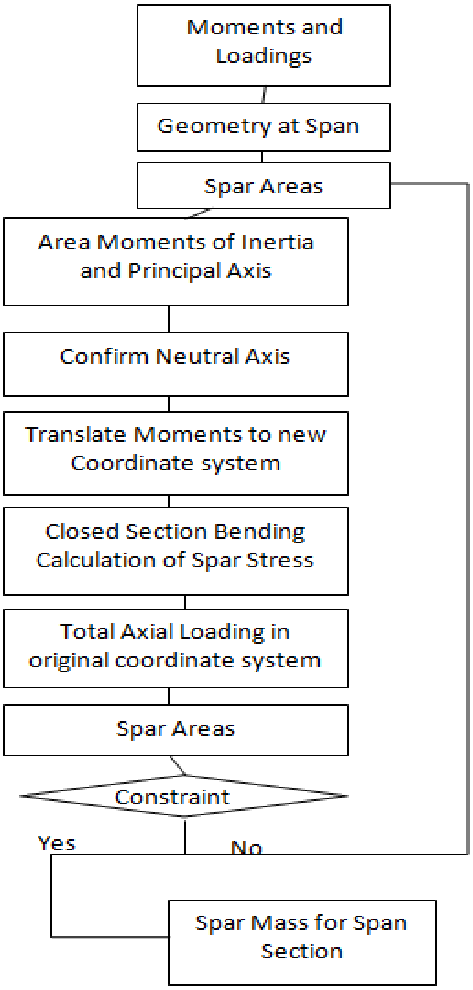

Fig. 8 The spar sizing process

It is acknowledged that this is a very coarse analytical process as the two wings themselves will not act in concert in reaction to an actual load but will instead bend and deform separately. Hence the intention here is not to rely on the actual values generated for the design process but to look at the trends that will hopefully become apparent in the weight and sizing of the wings and how they will affect the design space that is currently being mapped out.

3.3 Aero-Structural

The range equation used for this part of the analysis was:

$$R = 2\sqrt{\frac{2}{\rho S}}\,\frac{1}{c_t}\,\frac{C_L^{1/2}}{C_D}\left(W_0^{1/2} - W_1^{1/2}\right) \qquad (1)$$

This takes into account the various aerodynamic parameters that were the focus of the study, and factors in the wing weight by keeping the fuel weight constant. Assuming the same thrust-specific fuel consumption and the same fuel weight for the baseline A320 and the box-wing configurations analysed, as well as the same flight conditions obviously, this allows for the range to be used as an efficiency measure. Due to the limitations of AVL as discussed above, the drag coefficient for this analysis only consists of induced drag. The weights considered were only the wing weights, and a specified amount of fuel, as the other weights were held to be constant between the box-wing and the baseline wing.

4 Results

To make an assessment of the overall benefit of the box-wing concept, a figure of merit was introduced that reflects the amount of fuel required to fly a given range, i.e. the specific range.

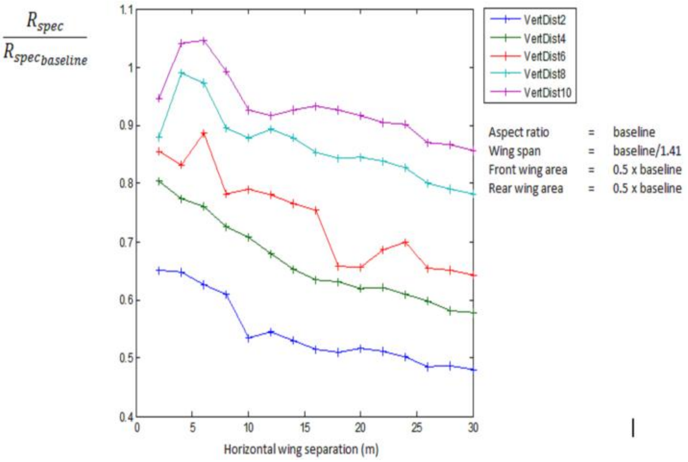

Fig. 9 Comparative Range Efficiency for a Box-Wing with baseline Aspect Ratio

Figure 9 shows the improvement in specific range compared to the baseline aircraft for the case of equal wing span with higher aspect ratio. A net improvement of 5% in specific range is found due to improved aerodynamic efficiency and keeping the wing increase moderate with high vertical and low horizontal wing separation.

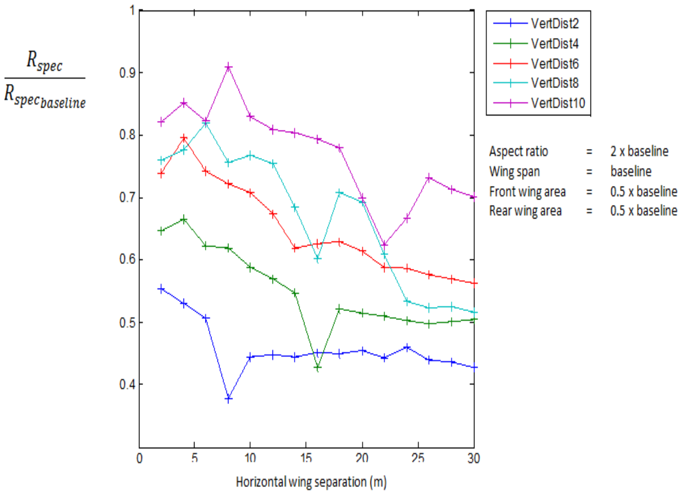

Fig. 10 Comparative Range Efficiency for a Box-Wing with baseline Wing Span

With the higher span configurations, it is apparent that the structural penalties imposed via the wing weight ensure that despite the higher aerodynamic efficiency means that overall this set of box-wing configurations cannot come even close to matching the conventional baseline aircraft in terms of the range, which serves as useful information for designers.

5 Discussion

It is really the method that is of primary import. A low-fidelity but reasonably quick way of considering the aerodynamic and structural design space of a box-wing planform will allow designers to more easily consider this planform when looking at potential new designs. As the results have shown, the box-wing planform is quite sensitive to minor geometry changes and hence this method to quickly narrow down the design space to the most viable areas is a significant help.

It must be noted that these preliminary results are yet to be verified by other methods, including high-fidelity tools such as finite element analysis or computational fluid dynamics. This work is currently being conducted at the moment, especially with regards to the very coarse structural model. An FEM code analysis of the same parameter sweep will allow for the verification and validations of the trends outlined and lead to a possible understanding as to how useful such a method is for future analysis and pre-design of this particular type of aircraft configuration.

The initial results lead to some interesting considerations for the future of the box-wing concept. Most of the design studies so far have been focused around large aircraft that have high horizontal separation between the two horizontal wings, a lower front wing and higher rear wing and relatively small vertical separation between the wings. These are all suboptimal choices for a box-wing planform, and instead designers going with the planform need to consider more radical designs that maximize the advantages provided by the planform.

Future research hence needs to look at ways the structural efficiency gained by the increased moment of inertia from the two wings can be improved without sacrificing the aerodynamic improvements. It also needs to consider the payoff between the increase in span which bring commensurate reduction in induced drag and increase in weight (as per conventional aircraft), and ways that this might be overcome.

Also the critical importance of stability and handling challenges with regards to special nature of the box-wing planform poses another question for the designer that needs to be considered at this stage. Incorporation of that discipline, at a very basic level, into the aerodynamic part of the methodology is an ongoing research problem that is currently being addressed as part of the overall research into the box-wing.

Finally, possible aircraft designs that can actually accommodate these design changes must be investigated, such as double-decker short range aircraft and so on. They form a possible pathway for the box-wing planform to come into use while keeping the aerodynamic efficiency benefits and using the structural efficiency on offer. Finally, the bending resistance effect from the box shape of the wing is also something that needs to be utilized further as it is something that has been left relatively untouched by other research in this area.

6 Conclusions

The box-wing offers a number of theoretical improvements that can used to meet some of the future challenges in the civil aviation industry, however it also has its own disadvantages. The design space for the planform needs to be thoroughly understood including how the structural and aerodynamic elements of the wing interact with each other, and how they can form the design drivers for the concept. The planform seems to be at its most effective with a high vertical separation, low horizontal separation and a shorter wingspan with a lower individual aspect ratio for each of the wings which give a promising window for future high-fidelity analysis of the box-wing. It further underlines the utility of using lower-fidelity design tools for the preliminary design of unconventional concepts like this.

7 Acknowledgments

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