BOX WING AIRCRAFT CONCEPTUAL DESIGN

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Keywords: *keywords list (Box Wing, Joined Wing, Optimization, Tip Fin Inclination, Wing/Tip Fin Joint Fixity)*

Abstract

This paper presents a conceptual design process for a medium range box wing aircraft is presented. The process begins with the initial estimates of components parameters followed by a constraint analysis to chose a design point. Structural considerations such as the appropriate wing mass estimation methods for box wing, wing/tip fin joint fixities and tip fin inclination are then presented. An investigation of longitudinal stability issues including trim and short period oscillation are also presented before description of the optimization routine developed for the study. Finally, a comparison is presented of how the box wing compares with a conventional cantilever wing aircraft designed for the same mission and payload.

Nomenclature

A	Aspect ratio
AoA	Angle of attack
b	Span
C_1	Mass coefficient
DOC	Direct operating cost
FD	Fuselage diameter
FEA	Finite element analysis
FL	Fuselage length
lbs	Pounds
LFL	Landing field length
m	Million
M_{TOM}	Maximum take-off mass
nm	Nautical mile
pax	Passenger
TFL	Takeoff field length
S	Wing area
USD	United States Dollars
$\wedge_{1/4}$	Quarter chord sweep angle

1 Introduction

As part of the search for the next future airliner configuration, and to mitigate the negative impact of airliners on the environment, there has been renewed interest in unconventional designs. An aircraft configuration of interest is the box/joined wing aircraft configuration, which in recent times has attracted the attention of researchers due to its claimed merits of reduced structural weight and low induced drag[1]. Box/joined wing aircraft potential of improved fuel efficiency and reduced direct operating costs have been other reasons to investigate the configuration.

Box/joined wing aircraft have different names, such as box wing, biplane and diamond wing. The essential difference is in the wing configuration and the principle of operation; see Figs 1 and 2. This study is about the joined wing aircraft that has tip fins linking the tips of the fore and aft wings together and appropriately called a box wing aircraft. The box wing of this study is based on Prandtl's[2] *'best wing system'* where a closed rectangular lifting system produces the smallest possible induced drag for a given span and height. Frediani[3] posits that Prandtl's[2] *'best wing system'*, if applied to current aircraft could offer induced drag reductions of up to 20-

30% based on a wing gap/span ratio of 10-15%. He states that, by the addition of Munk's[4] stagger theorem of biplanes, the induced drag is independent of sweep angles and so the Prandtl[2] wing system can be applied to high subsonic and transonic aircraft.

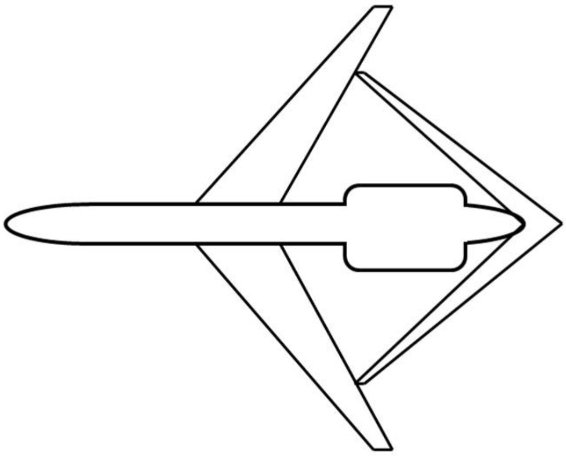

Fig. 1 Joined Wing Aircraft Schematic[6]

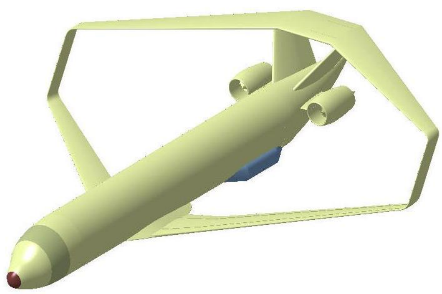

Fig. 2 Box Wing Aircraft Schematic

2 Aim of Study

The aim of the study was to design a 270 single class passenger capacity box wing aircraft with design range of 4000nm at Mach 0.8, cruise altitude of 36,000ft and maximum takeoff distance of 2500m[5]. By this specification the aircraft falls in the medium range transport category, similar to the Boeing 767-200. For comparison purposes a conventional cantilever wing aircraft was also designed alongside the box wing to the same specifications.

3 Methodology

Unlike conventional aircraft, there is a relative scarcity of information with regards to conceptual design procedures for box wing aircraft. Therefore, time-honed conventional aircraft design procedures outlined in Raymer[7] were modified and used for the design process, see Fig 3.

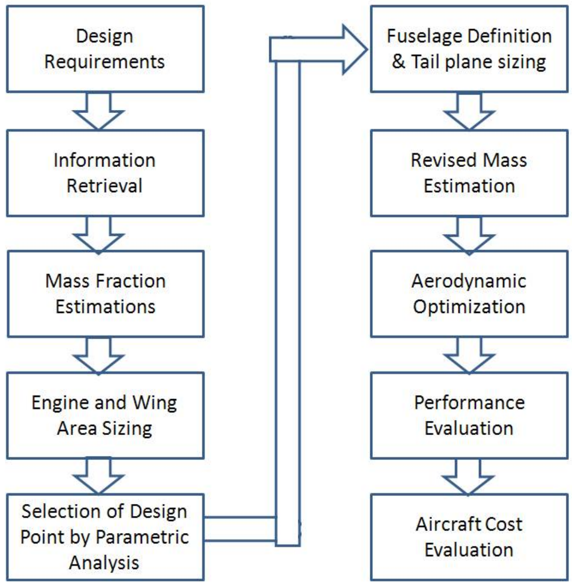

Fig. 3 Schematic of Design Process

Information of similar-sized conventional aircraft was retrieved and used to estimate the empty mass and fuel mass fractions and subsequently the initial mass statement. This was then used to estimate the engine size and wing areas. A parametric constraint analysis was then performed using methods given in Howe[8] to select an appropriate design point and thereafter the fuselage geometry defined. The tail fin was sized using methods in Jenkinson[9] and a more detailed mass evaluation subsequently performed. The wing geometry and assembly underwent an elementary parametric optimization process that included airfoil selection. Aerodynamic and performance estimation were then implemented using methods outlined in Jenkinson[9], Raymer[7] and Roskam[10]. Landing gear details were determined using Raymer[7] while position and loading were chosen consistent with Howe[8]. Field performance was evaluated using methods given in Raymer[7] and consistent with Ojha[11], Eshelby[12]. Cost issues were performed by taking an average of the outcomes of the methods in Raymer[7], Roskam[13] and Burns[14].

4 Structural and Aerodynamic Considerations

4.1 Modification of Mass Formula

One of the challenges in the conceptual design of a box wing airliner is estimating the wing mass. Several empirical formulae exist for estimating the mass of conventional cantilever wings but these would be misleading if applied directly to an unconventional configuration such as box wing aircraft. Therefore, a procedure for defining an empirical formula for the mass estimation of the fore and aft wings of a box wing aircraft shown in Fig 4, was performed.

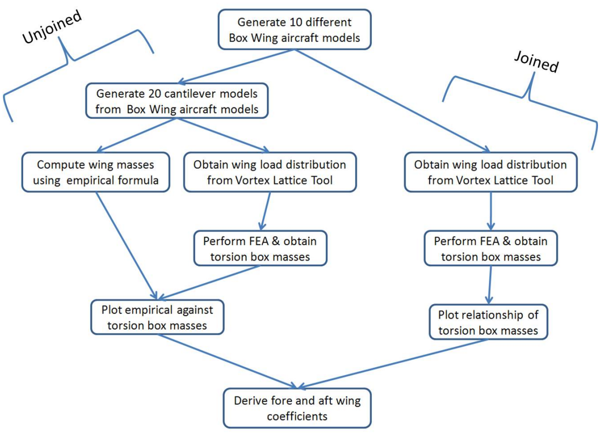

Fig. 4 Procedure Schematic

Ten different box wing aircraft models with appropriate medium range wing parameters were generated. The wing parameters of the ten box wing models were subsequently used to generate twenty cantilever winged (ten forward swept and ten aft swept but not joined at the tips) aircraft models. The masses of these wings were then estimated using Howe's[15] method. Howe's[15] method, Eqn 1, requires a coefficient, C_1 which depends on the type of aircraft. Typical C_1 values are shown in Table 1.

Table 1 Aircraft Type Mass Coefficients[15]

Aircraft Type	C_1
Long Range	0.028
Short Range	0.034
Braced Wing	0.021
Light aircraft	0.028 - 0.034

Next, to obtain the wing load distributions for an assumed flight condition each of the twenty cantilever winged aircraft was modelled in a vortex lattice tool called Athena Vortex Lattice[16](AVL). AVL is a program that utilizes vortex-lattice theory for aerodynamic and dynamic stability analysis of a given aircraft geometry. Fig 5 shows an AVL model of a box wing aircraft.

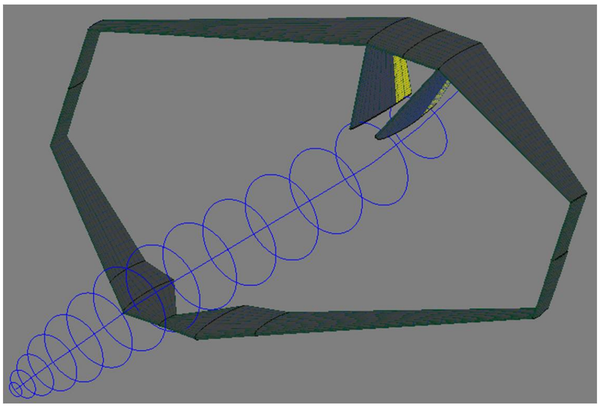

Fig. 5 Box Wing AVL Model

The wing loads were then used to perform finite element analysis (FEA) on the torsion box models of the entire cantilever winged aircraft from which the torsion box masses were obtained. A relationship was subsequently established between the empirical and torsion box masses of the twenty cantilever wing aircraft. In a similar manner the ten box wing models (joined at the tip)were modelled in AVL to obtain the wing loads and distribution for an assumed flight condition. The wing loads were then used to perform FEA on the torsion box models of the

$$M_W = C_1 \left[\frac{bS}{Cos\wedge_{1/4}} \left(\frac{1+2\lambda}{3+3\lambda} \right) \left(\frac{M_{TOM}N}{S} \right)^{0.3} \left(\frac{V_D}{\tau} \right)^{0.5} \right]^{0.9} \tag{1}$$

box wing aircraft from which their masses were obtained. A relationship was thereafter plotted with the equivalent cantilever torsion box model mass and that of the box wing. Using regression analysis the coefficients for the fore and aft wings were derived. By relating the torsion box masses of the box wing aircraft models to that of the conventional aircraft wing models and extending this relationship to their empirical masses, wing mass estimation coefficients, C_1 in Howe[15], were derived for the fore and aft wings of the medium range box wing aircraft; see results in Section 7.

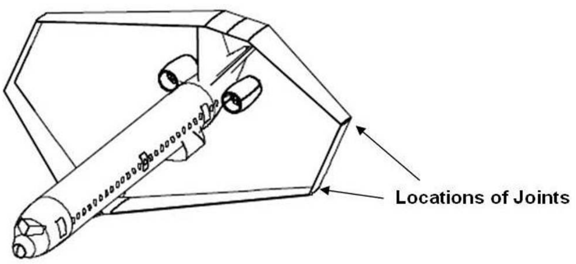

Fig. 6 Location of Joints

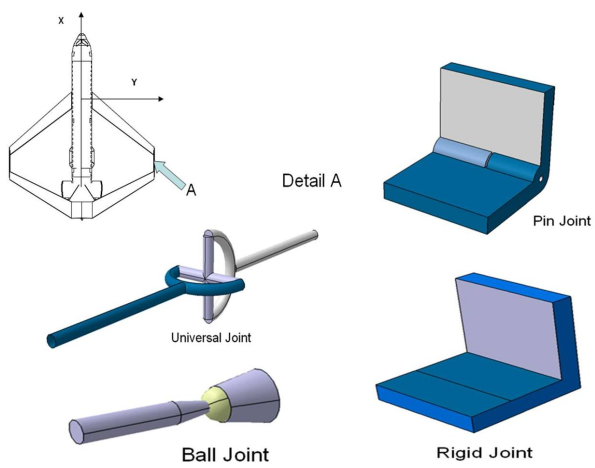

Fig. 7 Wing/Tip Fin Joint Fixities

4.2 Structural Consequences of Joint Fixity

A computational study was performed to compare the stress distributions in finite element torsion box models of a box wing structure that result from employing four different wing/tip fin joint fixities. The joint fixity types were the universal, ball, pin and rigid joints, see Figs 6 and 7, and they refer to the type of attachment that connects the tip of the fore and aft wings to the tip fin. The wing root to wing tip load distributions used for the analysis were obtained from AVL[16]. Studies by Wolkovitch[1] indicate that the optimum wing torsion box cross-sectional profile of the box wing configuration is one which accounts for the tilted bending axis of the wings by having the 'bending-resistant material' concentrated near the upper leading edges and lower trailing edges as illustrated in Fig 8.

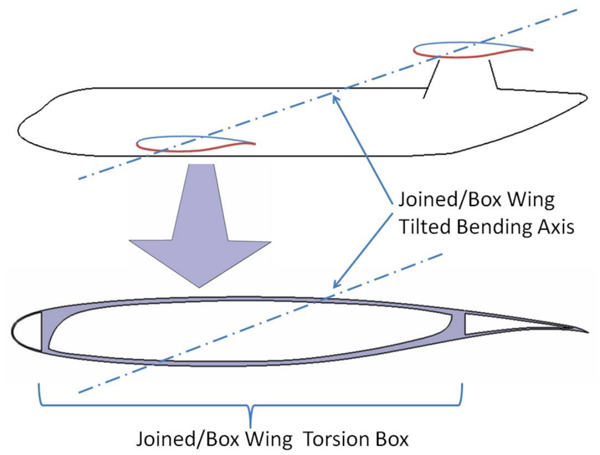

Fig. 8 Box Wing Tilted Bending Axis

However, for simplicity, an idealized wing torsion box cross-sectional geometry, sketched in Fig 9, was used in the study. The loads obtained from AVL were used to perform FEA of a statically loaded idealized box wing configuration. Due to the simplicity of the torque box and elastic axis beam type models used for the stress/strain analysis, only general stress trends

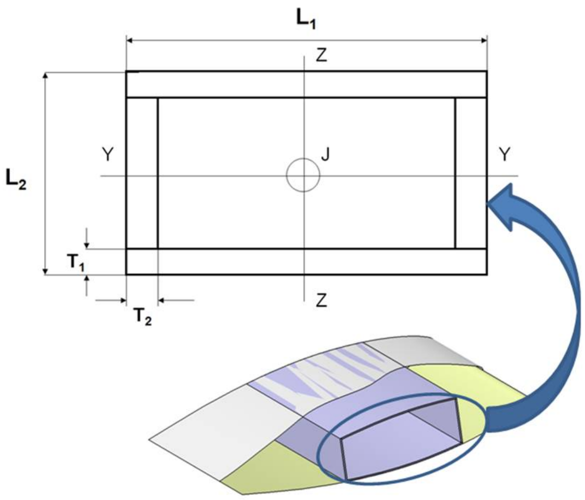

Fig. 9 Idealized Torsion Box Cross-Section Geometry[6]

were analyzed to determine the best wing-joint fixity in addition to other essential aerodynamic requirements.

4.3 Effects of Tip Fin Inclination

Computational studies were also performed to investigate the structural implications of changing only the tip fin inclinations of the box wing aircraft. Tip fin inclination refers to the angle the tip fin makes to the vertical body axis of the aircraft as shown in Figs 10 and 11. Flight loads for models with tip fin inclinations from 0^o to 40^o were generated using AVL[16]. Following the procedure outlined in the preceding paragraph, the flight loads were used to performed using FEA. The preliminary structural elements of the wings were sized as given by Howe [17]. Howe [17] states that out-of-plane bending moment and shear force are critical to estimating the mass of aircraft wings as they determine the effective end load material for spar web and distributed flanges respectively of the primary wing structural box. The results are in Section 7.

5 Longitudinal Stability and Control

A simplified neutral point equation was derived from first principles since there were no available

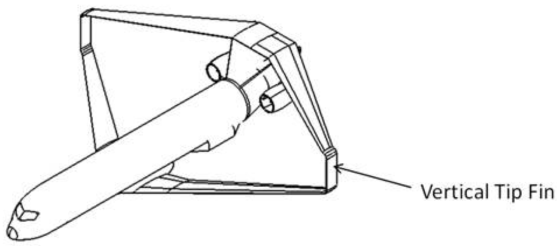

Fig. 10 Vertical Tip Fin[6]

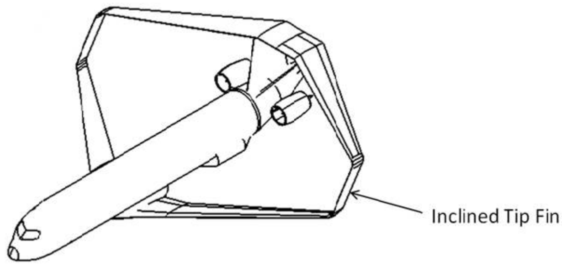

Fig. 11 Inclined Tip Fin[6]

specific neutral point determination method for box wing aircraft. This was then used to investigate longitudinal static stability issues of the configuration. In line with competing aircraft, a static margin of 2% was imposed to attain marginal intrinsic stability. This meant the fore wing had to generate 2% more lift and the aft wing 2% less lift. This in turn caused a fractional deviation from Prandtl's ideal configuration according to which the best wing system is the one where both wings generate the same lift. This accounts for a 0.01% increase in the overall induced drag of the vehicle which is close enough to the ideal not to defeat the purpose of the box wing aircraft. The increase in induced drag is the penalty to pay for intrinsic longitudinal stability.

Unlike the conventional aircraft, the box wing's cg range is quite limited and would require means such as fuel redistribution to ensure the cg stays within limits during operation. The box wing's cg range also demands that the nose gear bears loads of about 14% of the aircraft mass, which is high as given in

Howe[8]. Howe[8] states that the nose should bear loads ranging from 6% to 15% at operating empty mass (*OEM*) and maximum takeoff mass (M_{TOM}) respectively. However, for the box wing this load stays virtually constant throughout its limited cg range and so may not be very critical.

Using inertia statements of the box wing and conventional aircraft, along with aerodynamic data generated from Javafoil[18], trim analyses were performed in J2[19] for both aircraft at cruise to investigate trim stability. Thereafter, longitudinal dynamic analyses was performed to give insight into the short period oscillation of both aircraft. The results were then inputted on the longitudinal short period pilot opinion contours chart called the *'thumb print'* criterion. The *'thumb print'* criterion provides guidance to aircraft designers and evaluators concerning the best combinations of longitudinal short period mode damping and frequency to give good handling qualities. The chart is empirical and is based entirely on pilot opinion but adequate for conceptual design studies. The results are shown in Section 7.

6 Optimization Method

A design/optimization tool was developed to optimize the box wing and conventional cantilever aircraft designs. The design tool was implemented in Microsoft Excel and enhanced by Visual Basic for Application (VBA) algorithms. The tool was setup to solve multiobjective and multidisciplinary optimization problems using deterministic gradient search and stochastic non-gradient search algorithms. Furthermore, the results of the wing mass estimation coefficient, wing/tip fin joint fixity and tip fin inclination studies were implemented in the design/optimization tool. The architecture of the design tool is as shown in Fig 12 and it consists broadly of baseline design, geometry definition, wing structures, mass, aerodynamics, performance and cost modules. The arrows show the direction and paths of optimization routines of the tool.

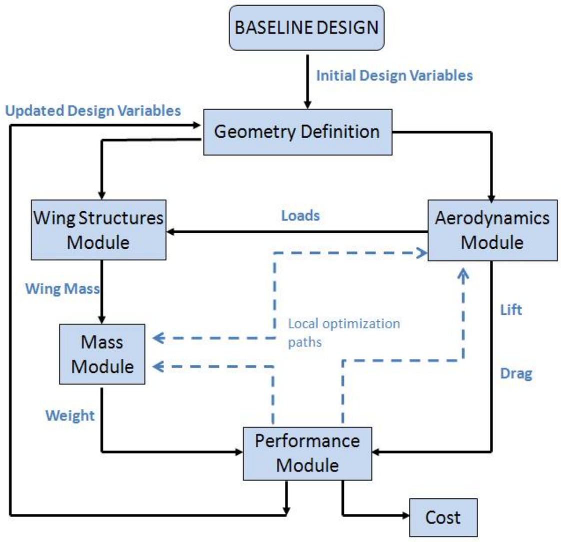

Fig. 12 Design Method Architecture

In the tool's multidisciplinary design optimization setup the constraints were takeoff distance, cruise speed and landing distance while the parameters were number of engines, fuselage diameter, aerofoils, wing span and wing gap for the box wing. The design variables were wing sweep, wing area and average thickness to chord ratio. The objective functions or measures of merit were minimization of all-up-mass, fuel per pax per nautical mile and DOC per nautical mile.

7 Results

The wing mass estimation coefficient of 0.28 derived for the fore wing proved to be the same as that derived for the aft wing. As the wings carry the same load and are connected by tip fins it was anticipated that their coefficient may be the same, because the wings are mutually bracing each other and the same set of constraints were applied to both. The significance of this is that the aft wing of a medium range box wing aircraft would be lighter than the fore wing. The reason for this is that for a medium range box wing aircraft the sweep angle of the aft wing would typically be less than that of the fore wing (wing area being the same), the resulting mass of the aft wing would thus be lower. This general result is of significance to the conceptual designer, for this difference in mass would be of consideration for center of gravity and static margin issues of the configuration. The mass difference would also be of influence in the positioning of other heavy items such as engines and landing gears.

Of the 4 joint types investigated, the rigid joint offered a lighter structure than any of the other three, with its significantly lower wing root out-of-plane bending moment. The rigid joint does not accentuate aero elastic problems because it transmits all stresses, it should also produce a heavier tip fin meaning greater inertia relief. However, this increase in the moment of inertia has a consequence of reduced roll responsiveness; an undesirable development for military aircraft but less critical for civil transports. The rigid joint also produces greater overall wing stiffness which could have ameliorating effects on the reduced roll responsiveness caused by a heavier tip fin. Finally, the rigid joint allows for the design of the wing tip/tip fin junction to take full advantage of the aerodynamic benefits of the configuration.

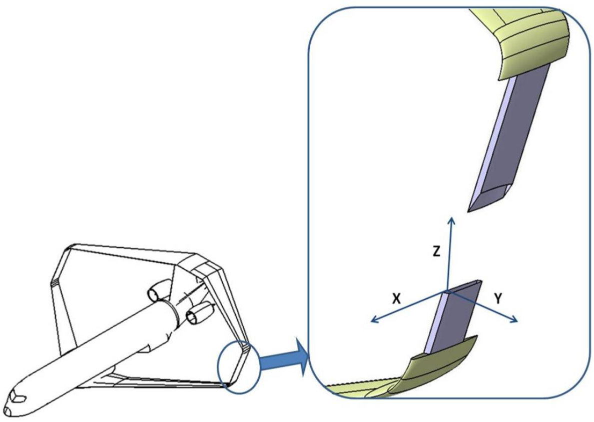

Fig. 13 Tip Fin Section[6]

Tip fin inclination significantly affects the torsional force, dragwise shear force and dragwise bending moment distributions in the wings of a box wing aircraft. However, there are only minor variations in out-of-plane bending moment and shear force distributions as a function of tip fin inclination. Minor variations were also observed in the cases for the tip fin torsion box masses, the overall wing torsion box masses and wing tip deflections. The changes in torsional force, dragwise shear force and dragwise bending moment with tip fin inclination did not affect the structural design of the tip fin as they are not design driving parameters.

The changes in torsion and dragwise shear force are not significant because the stiffness of the section is high enough along the fore and aft planes not to provoke an appreciable difference in deformation of the tip fin, see Fig 13. However, these torsion and dragwise shear force distributions would have significant influences on the wing/tip fin joint design and suggests heavy joints; an area not covered in this paper.

Furthermore, the minor variation in the out-of-plane bending moment, shear force distributions and torsion box masses suggests that tip fin inclination has a reduced effect on the structural design of a box wing aircraft. This deduction is valid from a structural viewpoint but tip fin inclination could have non negligible effects on the dynamic modes, flutter speed and frequency; areas not investigated.

The box wing and conventional aircraft trim were compared while cruising at 31,000ft at Mach 0.8 trimmed. From Table 2 both aircraft were cruising at about the same angle of attack but while the conventional aircraft's wing had a positive angle of attack the box wing's fore wing had a negative angle of attack. At the tailplane and aft wing both had positive angle of attack.

The fact that for the box wing aircraft the fore wing is at a *'low'* angle and the aft wing a *'high'* angle is in line with Bell's[20] highlight that the rear wing induces an upwash on the forward wing, which in turn induces a downwash on the rear wing. Thus, the fore wing's negative angle of attack is to compensate for the increased angle of attack caused by the upwash on it induced by the aft wing. Similarly, the aft wing's rather high angle of attack is to compensate for the reduced

Table 2 Aircraft Trim Parameters at Mach 0.8 31,000ft

Parameter (^{o})	Conventional	Box
AoA	1.70	1.68
Wing *AoA*	2.94	-1.32
Elevon		3.10
Tailplane/Aft wing *AoA*	1.12	2.10
Elevator	-0.22	-5.13

angle of attack induced on it by the downwash from the fore wing.

The trim drag of the conventional aircraft with an elevator angle of -0.22^o would be much lower than that of the box wing with elevon and elevator angles of 3.10^o and -5.13^o respectively. This suggests that further optimization is required for the box wing as the trim drag suggested by this simulation could reduce the advantage the box wing configuration has over the conventional aircraft.

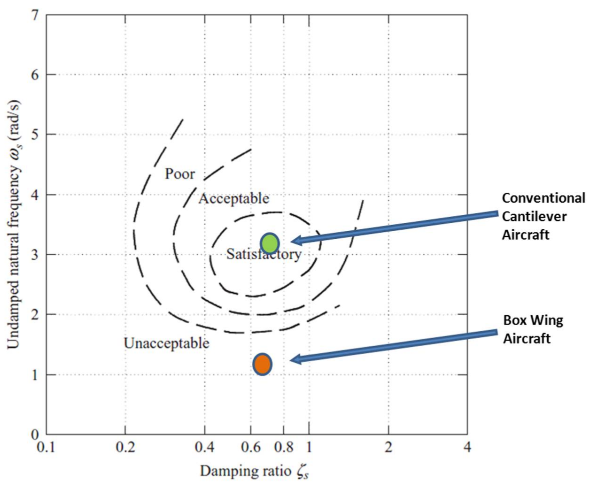

Fig. 14 Thumb Print Criterion[21]

The box wing aircraft model and the conventional cantilever wing aircraft model on the *'thumb print'* criterion is shown in Fig 14. This illustrates the significant difference between the conventional and the box wing aircraft. Whereas the conventional aircraft falls in the satisfactory area of the *'thumb print'* the box wing aircraft is in the unacceptable area. This is due to the principle of operation of the box wing and the fact that the static margin for the box wing at 2% makes for marginal longitudinal stability. Thus, to retain the aerodynamic advantages of the box wing configuration stability augmentation devices would be required; a technology which is well matured in the aviation industry.

Table 3 Design Outcomes

Aircraft Type	Conventional	Box Wing
	Dimensions	
b (m)	47.00	37.6
A - fore/aft	11.39	12.62/12.62
S - fore/aft (m^2)	194.00	112.00/112.00
$\wedge_{1/4}$ - fore/aft (^{o})	27	29/-24
FL (m)	46.00	46.00
FD (m)	5.60	5.60
	Masses	
OEM (kg)	53250.00	57605.00
Payload (kg)	31050.00	31050.00
M_{TOM} (kg)	114916.00	114240.00
Max fuel (kg)	46630.00	37692.00
Max pax	270	270
	Performance	
LFL (m)	1783	1615
TFL (m)	1640	1336
Range (nm)	4000	4000
Price (2007USD)	108.7m	121.9m
Fuel/pax/nm(lbs)	0.062	0.052
DOC/nm	20.88	20.34
DOC/nm/seat	0.077	0.075

The outcomes of the design/optimization of both aircraft types are shown in Table 3 and their sketches are shown in Figs 15 and 16. The box wing aircraft MTOM came out being about 95% of that of the conventional aircraft and shows better field performance. Also significant is the DOC/nautical mile in which the box wing is 97% of that of the conventional aircraft. The cost performance values could be even lower but for the new programme difficulty factor inputted into the aircraft cost algorithm to account for the novel box wing configuration. This, amongst

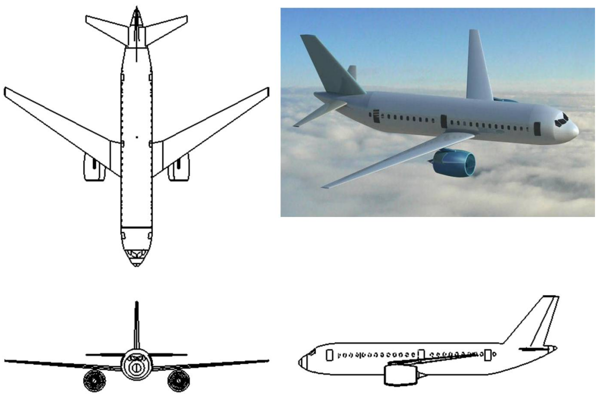

Fig. 15 Optimized Conventional Aircraft

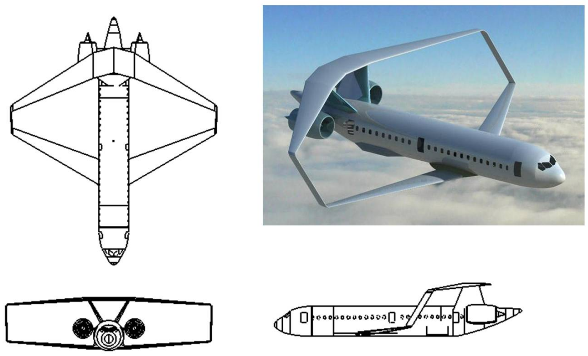

Fig. 16 Optimized Box Wing Aircraft

others, accounts for the relatively high aircraft market price shown in Table 3. However, the DOC/nautical mile advantage of the box wing increases with increase in the fuel price.

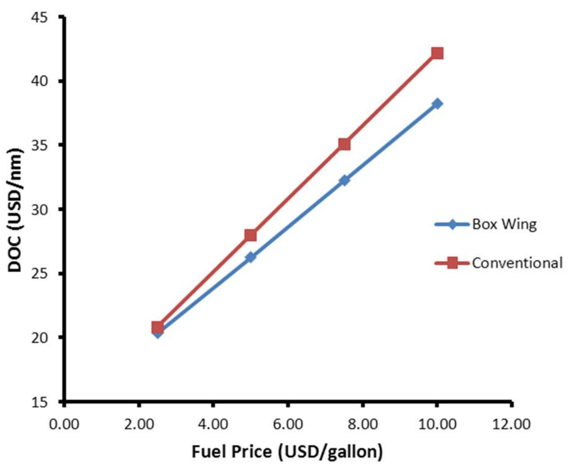

Fig. 17 DOC/nm Trend with Fuel Price Increase

Fig 17 shows how the box wing aircraft's DOC/nautical mile benefit improves from 97% of the conventional cantilever wing aircraft at 2.5 USD per gallon to 90% at 10 USD per gallon. Thus, with the likelihood of fuel prices continuously increasing and the carbon tax already introduced in Europe, the box wing has a clear advantage over conventional designs. Furthermore, the reduced wing span of the box wing makes it suitable for large long range designs that would easily fit into the 80m box at airports. Thus, the box wing aircraft has the potential of being a viable replacement to the conventional cantilever aircraft.

8 Recommendations for Future Work

The analytic models used for this study were relatively simple, to reduce the data preparation and the turn-around time of data processing. Also, the weights estimated obtained from the finite element tool in this study were limited to the structural torsion box of the wing; trailing and leading edges, control surfaces and auxiliary component weights were excluded. Thus, for more detailed analysis further studies would be required which should include torsion box cross-sections that account for the aforementioned omissions and the tilted bending axis of the box wing configuration.

A non-linear analysis is recommended for future work in identifying post buckling behaviour of the box wing aircraft wing system. It is also recommended that flutter and divergence analysis of the box wing configuration be performed for a more complete investigation into the effects of the joint fixity. It is further recommended that a separate investigation on the effects of different tip fin inclinations be performed from a purely aerodynamic perspective. A comprehensive CFD analysis is also recommended.

Acknowledgments

The authors acknowledges the support of the Department of Aerospace Engineering, Cranfield University and the Nigerian Air Force.

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