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Research paper

Wing area optimization for box wing aircraft

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Abstract

The optimization of the wing area of a medium range box wing aircraft was carried out in this study using a multidisciplinary conceptual design/optimization approach based on gradient search algorithm and regression analysis. The methodology was also applied to a similar sized conventional cantilever wing aircraft and the result generated an optimal wing area similar to the real wing area of the cantilever aircraft considered, thereby validating the methodology.

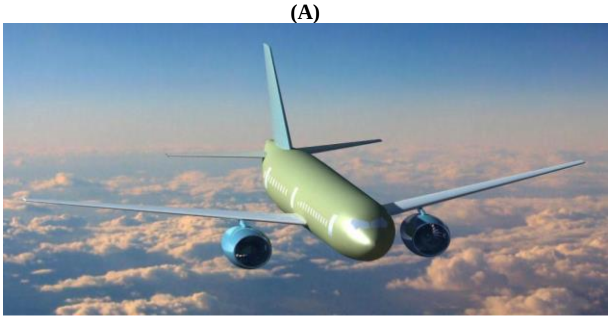
Nomenclature
AUM: All up Mass
DOC: Direct Operating Cost
CDo: Zero Lift Drag Coefficient
Λ: Wing Sweep Angle
τ: Wing Average Thickness to Chord Ratio
Subscript
A: Aft Wing
F: Fore Wing

Keywords:*Algorithm; Box wing; Optimization; Regression analysis; Wing area.*

1. Introduction

The negative impact of air travel on the environment has generated renewed interests in unconventional aircraft configurations. The Box wing and Joined wing aircrafts (see Fig. 1) studied by Wolkovitch [1] Kroo [2], Nangia [3] and Henderson [4] are examples of such unconventional aircraft configurations. These studies have shown the lower induced drag, improved fuel efficiency as well as reduced direct operating costs associated with these unconventional configurations. Similarly, Prandtl [5], Munk [6] and Frediani [7] studies have highlighted the superior aerodynamic efficiency of the Box wing configuration, derived from biplane configurations over conventional configurations.

(A)



(B)

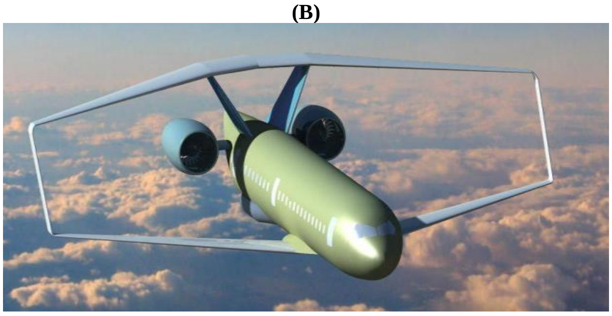


Fig. 1: Box Wing Aircraft (A), Conventional Aircraft (B) [1].

An aircraft's wing area affects so many of its parameters. For instance, wing area determines the wing loading and lift coefficient, which both influences the aircraft performance as well as economic parameters such as direct operating cost (DOC) and fuel per pax per nautical mile. Optimizing wing area is therefore imperative in aircraft conceptual design. While methodologies for optimizing wing area of conventional aircraft abound the same cannot be said for Box wing aircraft. It is therefore instructive to develop a methodology for evaluating the optimum wing area for a medium range box wing aircraft. To fill this gap, this paper therefore proposes an optimization techniques based on gradient search algorithm, for the optimization of wing area of a medium range box wing aircraft.

2. Materials and methods

2.1. Materials

This study adopted the conceptual design of a medium range box wing aircraft studied in Cranfield University as outlined in ref [8], [9] (a description of the reference aircraft is provided in section 2.2.1)as well as Visual Basic and Microsoft Excel software for the wing area optimization problem studied. The detailed description of the aircraft used in this study is as follows [9]:

Aircraft type	Box wing aircraft
Range	4000 nautical miles
Maximum takeoff mass	127,760kg
Wing span	37.6m.
Fore and aft wing gross areas	118:32m^2 each.
The wing gap, measured at the wing tips:	8.0m
Fore and aft wing sweep angles:	40 and -25 degrees respectively
Fuselage length:	46 meters
Fuselage maximum diameter:	5.6m.

2.2. Box wing aircraft wing area optimization

In this work, the wing area optimization was carried out using a combined approach based on deterministic as well as stochastic gradient search algorithm, implemented using Visual Basic. The study objective functions were All Up Mass (AUM), Direct Operating Cost (DOC) and Zero Lift Drag Coefficient $(\mathrm{C_{DO}})$, subject to aft and fore wing sweep angles for all wing area considered as depicted in Eqn. (1).

$$\text{minimize } \mathrm{AUM}(\Lambda_F, \Lambda_A, \tau), \mathrm{C_{Do}}(\Lambda_F, \Lambda_A, \tau), \mathrm{DOC}(\Lambda_F, \Lambda_A, \tau)$$

Subject to

$$-22 \le \Lambda_A \le -36, 20^o \le \Lambda_F \le 42^o$$
$$\text{for } s = (180, 190, 200, 216, 224, 230, 235, 240) \quad (1)$$

Eight wing areas; 240m^2, 235m^2, 230m^2, 224m^2, 216m^2, 200m^2, 190m^2 and 180m^2 were arbitrarily selected and their models built the in the optimization tool. The established minimum wing area (S) was validated using a plot of a function beta (β_S), against S, where the β_S was computed using Eqn. (2). The computation was performed simultaneously hence no duplication or layering of the process.

$$\beta_S = \frac{\frac{L}{D}}{\left(\frac{L}{D}\right)_{min}} + \frac{M_{TOM}}{(M_{TOM})_{min}} + \frac{DOC}{(DOC)_{min}} + \frac{\mathrm{Fuel/pax/nm}}{(\mathrm{Fuel/pax/nm})_{min}} + \frac{TO_{Dist}}{(TO_{Dist})_{min}} \quad (2)$$

Where

$M_{TOM} = M_{TOM}(S)$, $L/D = L/D(S)$, $DOC = DOC(S)$,

$\mathrm{Fuel/pax/nm} = \mathrm{Fuel/pax/nm}(S)$, $TO_{Dist} = TO_{Dist}(S)$

All factors in Eqn. (2) affect each other directly and indirectly as is usual with aircraft design. The benefit of Eqn. (2) is that the best of all the variables as a function of wing area can be represented by one function and enables the decision making process with regards to the optimum wing area. Furthermore, in agreement with Jemitola [9], fore and aft wing sweep angles of 30 and 22 degrees were chosen as the sweep angles that satisfy the minimization of M_{TOM}, prevention of the effects of drag divergence machnumber, mitigating aero-elastic issues for the model and minimizing D_{OC} and lower the value of the more optimum the model. The useful load represented using Eqn. (3) was evaluated, as a fraction of their maximum payloads and presenting the same parameter alongside similar in-service aircraft (the B767-200 and A310-300), a practical sense of what represents the optimum becomes clear [8].

$$\text{Useful Load} = 0.008S - 1.3823 \quad (3)$$

2.3. Comparative analysis

A similar optimization procedure described in section 2.2 was performed to determine the optimum wing area for the conventional cantilever aircraft using the baseline aircraft parameters described in [9]. Ten wing areas; 240m^2, 235m^2, 230m^2, 224m^2, 216m^2, 200m^2, 190m^2, 180m^2, 170m^2 and 160m^2 were considered in this study. Similarly, the useful load for the cantilever was computed using Eqn. (4) and the result was compared to those two in-service aircraft specifically, B767-200 and A310-300, so as to validate the proposed methodology [9].

$$\text{UsefulLoad} = 0.0143S\ 2.3589 \quad (4)$$

3. Results and discussion

3.1. Box wing aircraft wing area optimization

The optimized values of M_{TOM}, L/D, FR, DOC/nm, Fuel/pax/nm and TO_{Dist} for the varied wing areas considered in the study is shown in Table 1, while a plot of M_{TOM}, L/D, FR, DOC/nm, Fuel/pax/nm and TO_{Dist} against wing area is shown in Fig. 2.Worthy of note is the high L/D values of the obtained for box wing aircraft. Although the box wing configuration is more efficient than the conventional configuration, in the real conditions of aircraft operations this high L/D values could be reduce to about 85% to 90%. Generally, the models with wings areas of 190m^2 and 180m^2 could not fly the design range of 4000nm because of an inadequate wing fuel tank capacity as evidenced by their fuel ratios (FR) in column 4 of Table 1.

Table 1: Box Wing Models Optimization Results

S (m2)	M_{TOM} (kg)	L/D	FR	DOC/nm	Fuel/pax/nm	TODist (m)
240	115979.49	23.55	1.45	21.85	0.0535	1271.04
235	115498.12	23.63	1.39	21.78	0.0531	1291.14
230	114912.59	23.73	1.34	21.70	0.0526	1310.99
224	114135.97	23.84	1.30	21.58	0.0520	1335.15
216	113331.37	23.98	1.21	21.47	0.0514	1372.14
200	111424.70	24.30	1.08	21.19	0.0500	1451.34
190	110172.94	24.50	0.99	21.01	0.0490	1506.90
180	109076.21	24.71	0.90	20.84	0.0482	1570.84

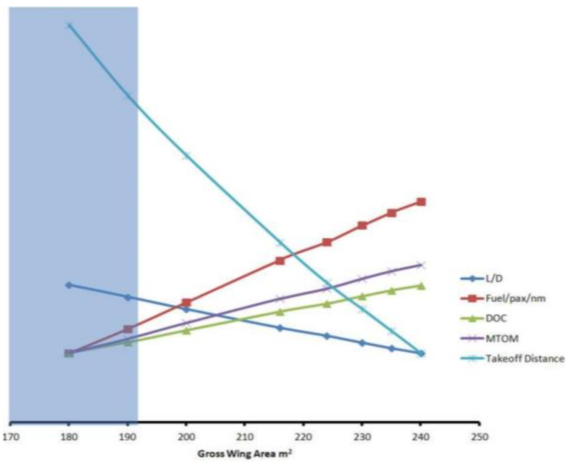


Fig. 2: Optimization Parameters against S - Box Wing Aircraft.

From Fig. 2, it would seem that the model with S = 200m^2 is the optimum wing area because it offers the highest L/D, lowest fuel per pax per nautical mile, lowest M_{TOM} and DOC in comparison to S values of 216, 224, 230, 235, 240. This was substantiated by Fig. 3, which is a plot of a function betaβ_S , against S, where the lower the value of the more optimum the model.

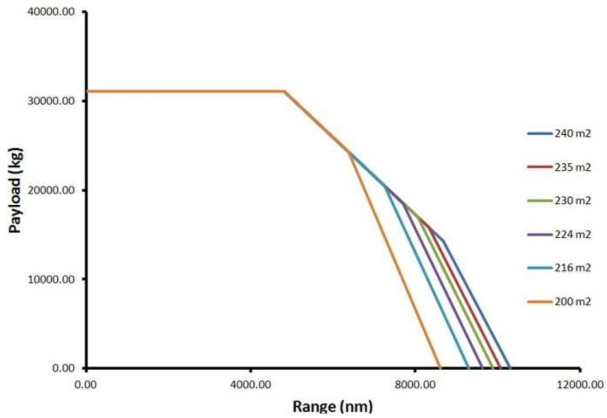


Fig. 3: Optimization Function against S - Box Wing Aircraft.

However, plotting the payload against range (see Fig. 4) as well as the useful load against wing area (see Fig. 5) for the box wing aircraft considered in comparison with in-service aircraft (B767-200 and A310-300), it becomes clear that the optimum wing area is 224m^2. Also the regression analysis shows an R^2 value of 0.999, which indicates accuracy data fitting and a validation of the method.

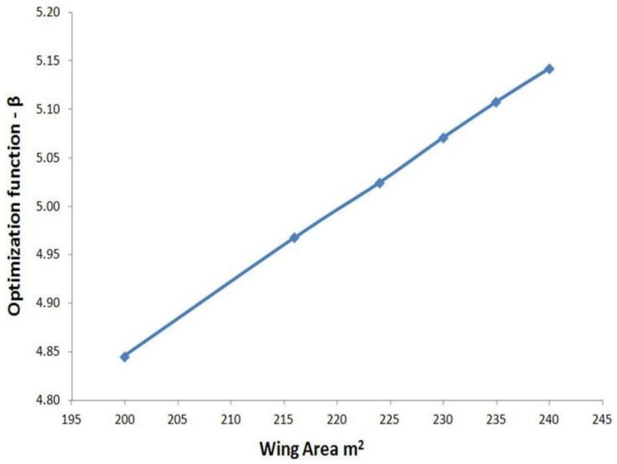


Fig. 4: Payload Range Plots for Wing Area Models.

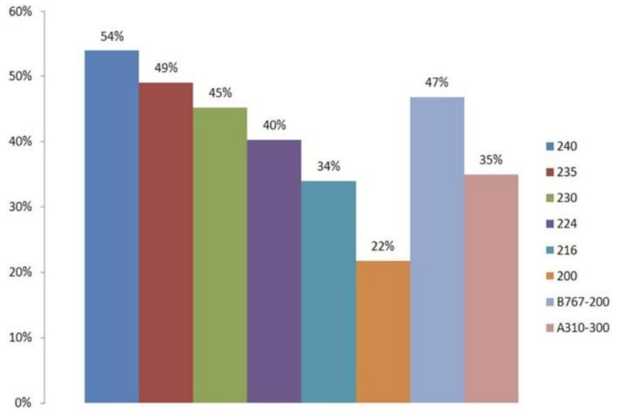


Fig. 5: Useful Load for Wing Area Models.

3.2. Comparative analysis

Using the optimization tool described in section 2.3, the results shown in Table 2 was reached. A combined graph of L/D, fuel per pax per nautical mile, takeoff distance, DOC and against wing area is shown in Fig 6. Similarly, the model with wing area of 160m^2 could not fly the design range of 4000nm because of an inadequate wing tank fuel capacity and are highlighted by the shaded portion as depicted in Fig. 6. It seems that the model with S = 170m^2 is the optimum wing area because it offers the highest L/D, lowest fuel per pax per nautical mile, lowest M_{TOM} and DOC. Considering the plot of a function beta, against S (see Fig. 7), it further appears as if the wing area with 170m^2 is the optimum.

Table 2: Conventional Aircraft Models Optimization Results

S (m2)	MTOM (kg)	L/D	FR	DOC	Fuel/pax/nm	TODist (m)
240	125942.70	17.46	1.93	23.01	0.0750	1485.98
235	125355.08	17.54	1.84	22.92	0.0744	1510.60
230	124830.74	17.63	1.79	22.82	0.0738	1535.43
224	124058.91	17.72	1.73	22.70	0.0730	1565.54
216	123182.65	17.86	1.60	22.55	0.0720	1610.89
200	121263.74	18.13	1.42	22.23	0.0700	1710.22
190	120026.97	18.32	1.31	22.03	0.0687	1780.14
180	118853.07	18.51	1.20	21.83	0.0674	1859.20
170	117610.92	18.70	1.09	21.63	0.0661	1947.38
160	116424.95	18.91	0.98	21.43	0.0649	2048.10

However, plotting a graph of payload against range as well as a chart of useful loads against wing area as shown inFig. 8 and Fig. 9 respectively, it becomes evident that the optimum wing area (S) , becomes 216m^2 which is similar to the wing area of the compared A310-300 and coefficient of determination (R^2) of 0.9959 was also reached, thereby validating the method.

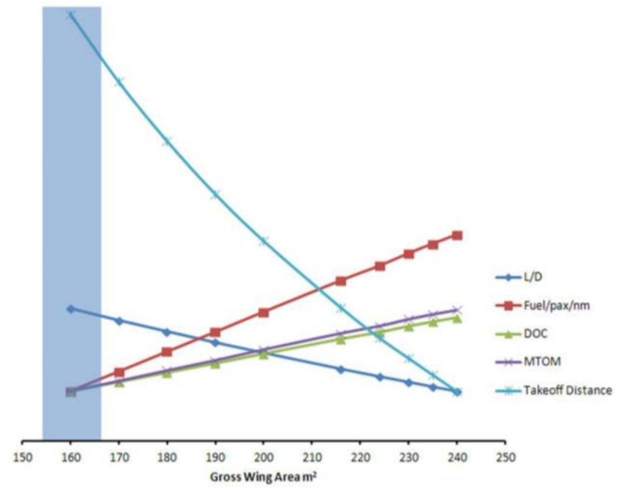


Fig. 6: Optimization Parameters B against S - Conventional Configuration.

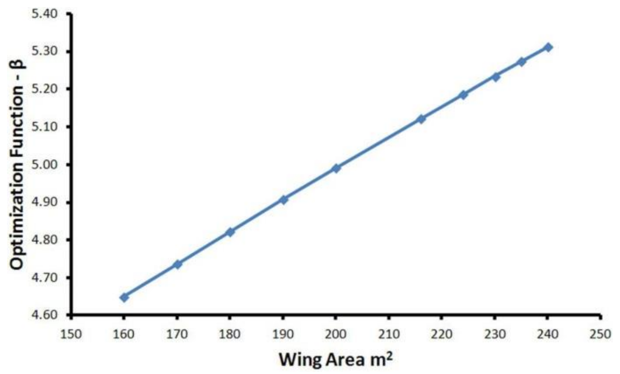


Fig. 7: Optimization Function B against S - Conventional Configuration.

Although the results shown in Table 3 are optimistic, the improved aspect ratio of 11.39 is rather high for aircraft of this category. What is typical are values below 10. The implications of this over-optimized wing include a rather heavy wing. Furthermore, for a medium range transport aircraft the high aspect ratio of 11.39 also means that there would be aeroelastic problems to contend with. This issue can be mitigated by adjusting the wing area and geometry but for the purpose of this optimization study this aspect was left for future investigations.

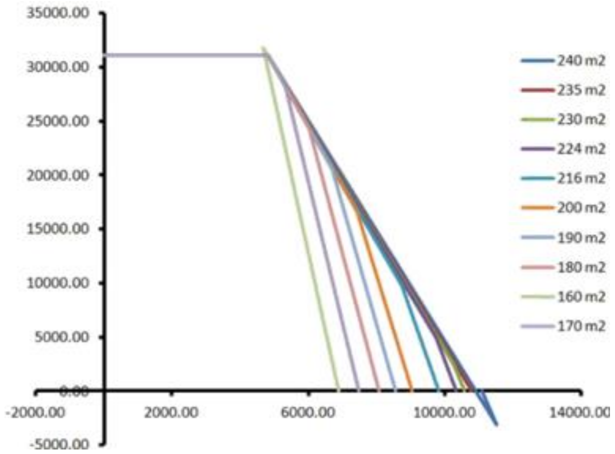


Fig. 8: Payload Range Plots for Wing Area Models.

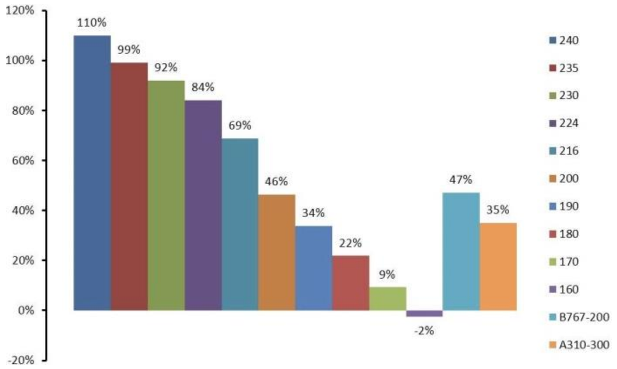


Fig. 9: Useful Load for Wing Area Models.

4. Conclusion

This study shows that the optimum wing area for a medium range box wing aircraft is 224m^2. As for the conventional cantilever wing aircraft the results show good approximation with in-service aircraft. However, the results would need to be subjected to aero-structural analysis such as computational fluid dynamics, aeroelasticity and finite element analysis for a holistic consolidation of the methodology.

Acknowledgments

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