OPTIMISING TRANSPORT FLYING WINGS

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Abstract

The research work reported in this paper aims at optimising the planform of a pure flying wing, i.e. with straight leading and trailing edges, conceived as an airliner of the 300 seat class, respecting the 80m wingspan limit. First, the relevant criteria used for design and sizing are discussed, as well as some suitable design constraints. The paper concentrates later into aspect ratio, tapper ratio and Mach number effects. The figures of merit chosen for optimisation are direct operating cost and maximum take-off weight per passenger, for a specified constant range of 10000 km. The optimum aircraft fulfilling all constraints has an aspect ratio of 6.2, carries 277 passengers in three class seating and is near 40 percent more fuel efficient than conventional wide bodies of similar size. By relaxing a secondary constraint the optimum moves to an airplane with 342 seats, aspect ratio of 5.8 and about 11 percent more efficient than the full constrained case.

1 Introduction

In the initial stages of a new airplane design the process is driven by four major driving forces:

- The market, that fuzzily poses the initial specifications;
- The airworthiness requirements, which constitutes a crucial check list of key issues to be considered and respected;
- The existing experience or, in other words, the solutions provided in the past to similar problems; and
- The available and emerging technologies that can be incorporated in the project.

Although all four must be taken into account to create a feasible concept, i.e. an alternative solution among the many possible, it is the market by far which leads the way. In this sense, it must recalled that all world air traffic studies forecast a remarkable increase, higher than 5 percent per annum, in passenger-kilometers and around 6.5 percent in cargo [1-4]. The downturns caused by the terrorist attack of September 11 2001, the avian flue, or other regional or global crisis, hardly affect the positive trend or imply some delay on it, as shown in Fig. 1.

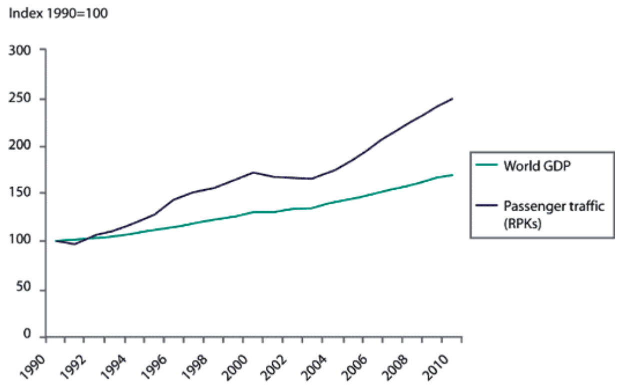

Fig. 1. Historic and forecast evolution of world economic product and passenger air traffic.

Needless to say the predicted traffic growth varies from region to region, with USA at the bottom and Asia-Pacific Rim on top. The details of such forecasts differ among and within airplane manufacturers and air transport institutions, but the essentials hold: more than 20000 new airliners will be needed along the next 20 years, apart from more than 4000 in the regional jet category.

According to such studies, this high demand for new airplanes will occur in conjunction with a continued pressure to achieve significant reductions in direct operating cost and environmental impact. It is then easy to understand that noise, emissions and ease of maintenance are gaining upper positions among the airplane selection criteria of airlines [5]. So any new airplane will be scrutinised against new decisions schemes.

On the other hand, the aeronautical engineers have been rather conservative with respect to the configurations of transport airplanes, although the advances have been tremendous in aerodynamics, propulsion, materials, structures and on board systems [6]. A slow, albeit continuous, evolution has been the leitmotiv of more than 80 years of commercial aviation; particularly of the last 50, which correspond to the universalisation of air transport [7]. The so-called conventional layout, with a slender fuselage mated to a high aspect ratio wing, aft-tail planes and pod mounted engines, has been kept frozen over decades [6].

But, as declared by many researchers using a varied number of indicators, the capability of the conventional configuration is approaching an asymptote, around the size of an enlarged A380.

Therefore, aeronautical engineers have started to consider unconventional aircraft in order to overcome the limits, and to achieve performance or operational improvements, including drag reduction, increased useful load, diminishing environmental impact, etc. [8, 9].

Among these novel arrangements the flying wing seems to be one of the most promising in terms of weight efficiency, fuel consumption per passenger, payload carrying capacity or noise reduction [10-12].

The present paper discusses the relevant criteria used for designing and sizing one of such flying wings, as well as some suitable design constraints, before concentrating into aspect ratio, tapper ratio and Mach number effects. The figures of merit chosen for optimisation are direct operating cost and maximum take-off weight per passenger for a specified constant range of 10000 km.

2 Flying wings and blended wing bodies

The flying wing concept is not new. It was used by Lippisch and Horten in Germany in the 30s and by Northrop on prototypes flown in the 40s [13]. Some British firms performed interesting conceptual design work during the 50s on potential airliners with this configuration [14].

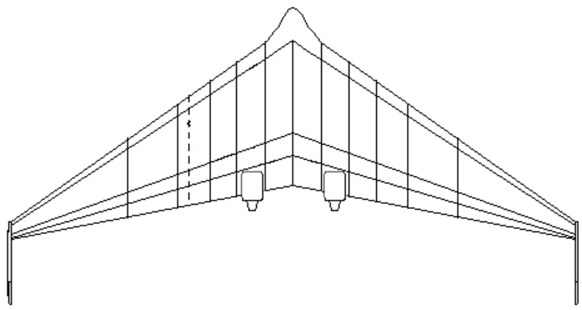

Fig. 2. Plan view of a transport flying wing.

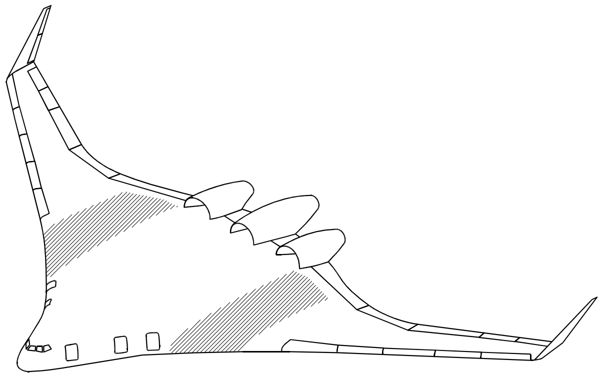

Fig. 3. The blended-wing-body aircraft.

Currently, researchers and designers are working on two main configurations: a rather pure flying wing, with straight leading and trailing edges (depicted in Fig. 2); and a blended wing-body arrangement, BWB, in which the body adopts the shape of a much flattened fuselage mated to an outer wing (see Fig. 3).

The studies published cover most existing segments of commercial aviation, from a one hundred seat delta wing [15] to gigantic 1500 seat aircraft [8]. By far the large majority of papers deal with the BWB layout [10, 11, 16-18], mainly for its growing capability which easily results in a family [19, 20]. It exhibits improved characteristics in aerodynamics, for its relatively reduced wetted area, and structural weight, for its spanloading effect, with respect to conventional layouts.

However, the bulky inner body counter-balances, at least in part, those beneficial effects. The lift coefficient is still relatively high [21] and the lift alleviation by payload and main structure is only partial [11]. Pure flying wings behave much better in these two key aspects. But to allow an efficient use of the inner space they need to be larger than a minimum size and incorporating thick airfoils. Moreover, they can hardly form families in a similar sense to what is common with conventional airliners.

The research reported here is one of a series devoted to analyse main features and performances of a pure flying wing, of the 300 seat class [12, 22-24]. Previous papers have shown that this concept is feasible, can beat conventional airliners of similar size, and can exploit emerging technologies like laminar flow control or thrust vectoring, among others. The core of the present work is the optimisation of aspect and tapper ratios, as well as getting some light on Mach number effects in performances and economics.

3 Optimisation process

Optimising the wing planform, for a pure flying wing with straight leading and trailing edges, means finding the values of aspect ratio, A, tapper ratio, λ, and swept angle, Λ, which provide an optimum for some specified figure of merit. Since the methods used to perform the process are rather simple, as corresponds to a conceptual design where very little information is available [25-27], it is desirable to take two different figures of merit to increase the robustness of the whole procedure. In the present research the figures of merit are direct operating cost, DOC, and maximum take-off weight per passenger in three class seating, Wto/Npax; both are representative of efficient performance and good design.

The process chain is presented in Fig. 4. It includes six modules devoted to wing and cabin geometries, aircraft main weights, aero-dynamics, thrust, performances, and economics. The process ends with an assessment of constraints and the presentation of results.

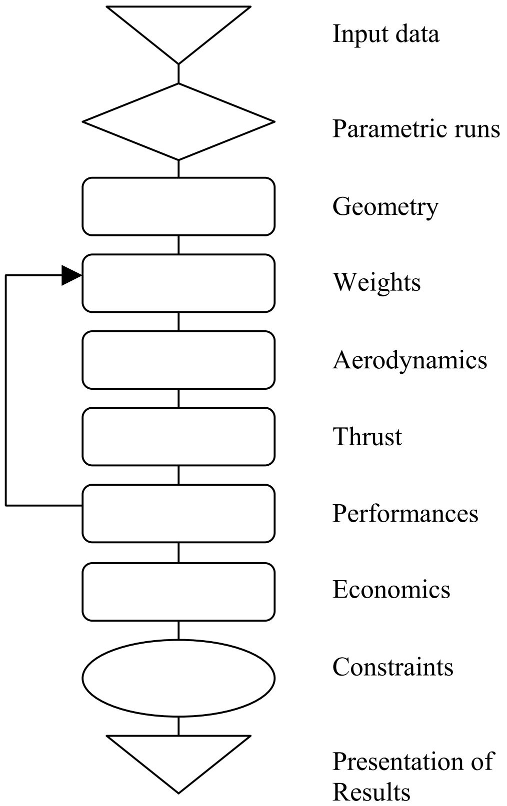

Fig. 4. Process chain used for optimisation.

Four constraints were identified as meaningful for this configuration: cabin width (to limit vertical accelerations in bank movements); cruise lift coefficient (related to cabin attitude in cruise and buffet onset in manoeuvres); wing tip chord (for structural reasons); and number of passengers (for evacuation requirements).

The presentation of results for each M_{nom} (the design value), A and λ combination includes DOC and Wto/Npax and a code for the constraints surpassed (0 if none). In this way it is possible to check the impact of the various constraints in the final results.

Some input data are assumed to be constant for consistency and to provide a common base for comparison with results obtained by other researchers: range, wingspan, and airfoil type and relative thickness. The range is established at 10000 km (5400 NM), a rounded figure typically used in long range conceptual design studies. Moreover it is representative of dense routes between Europe and US West Coast, between Europe and Asia-Pacific Rim, or between US West Coast and Asia-Pacific Rim [28]. The overall wingspan is limited to 80 m as for code letter F ICAO's new standards [29]. Taking into account that the aircraft incorporates winglet-like vertical tails (see Fig. 2), the available wingspan, b, is reduced to 78 m, which is the value used in computations.

Last, the airfoil chosen in the flying wing design is one of slightly aft-loaded type with 17 percent relative thickness. However, for trimming purposes, an inverted aft curvature of reflexed type is used in the central part [18, 21], approximately corresponding to the passenger cabin. The transition between both types of airfoils occurs along the freighthold. Nonetheless, the airfoil relative thickness is kept constant at 17 percent over all wingspan, and the spars always run at 11 and 67 percent of the chord for structural compatibility. The airfoil thickness in the outer wing looks a bit too high but it is required for structural reasons since the chord is actually very short but must withstand the loads of ailerons and vertical tails.

The whole process is repeated for M_{nom}=0.8, 0.82 and 0.85. These values are considered representative of high subsonic long range flights [8, 30]. From results obtained in former stages of the research, the aspect ratio is analysed only within the range 5 to 7 and the tapper ratio between 0.06 and 0.28. As stated earlier, the expressions used to compute the variables are fairly simple. For example, the swept angle is computed as [27]

$$\Lambda = arc\cos\left(\frac{0.7}{M_{nom}-0.04}\right)^2 \tag{1}$$

Where M_{nom} is the design Mach number (constant for a design case) and is not the actual flying one (that is allowed to vary). On its side, the cabin area, S_{cab}, is

$$S_{cab} = 0.14A\left(\frac{1+\lambda}{1-\lambda}\right)\left[\frac{4b^2}{A^2(1+\lambda)^2} - c_{\min}^2\right] \tag{2}$$

Where C_{min}= 15m, is imposed for habitability by airfoil geometry and spar location. By definition the wing area is $S=b^2/A$. The number of passengers in three class seating is obtained as

$$N_{pax} = 0.96\,S_{cab} \tag{3}$$

With S_{cab} in square meters. The density is about 10 percent lower than that of conventional airliners, for its different internal geometry (with more side walls, acting as wing ribs), and aisles and corridors needed for evacuation (see Fig. 5).

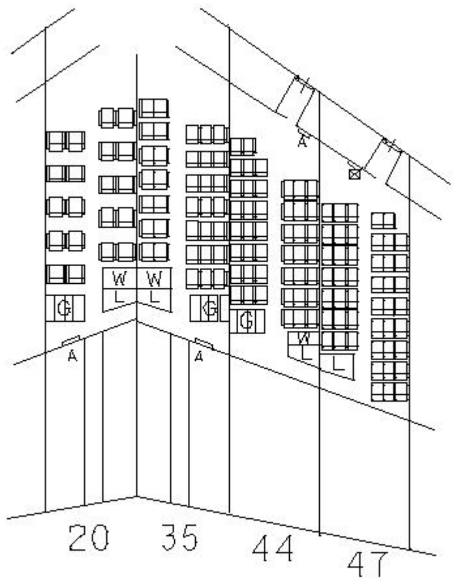

Fig. 5. Possible solution on three class seating in a flying wing. The outer bays are symmetrical.

The drag polar is assumed to be parabolic [25-27]. The non-lift dependent part is estimated as [31]

$$C_{D0} = 4.06\,c_{fw}\cos^{0.5}\Lambda\left[1+\frac{0.085}{(1+\lambda)}\right] + C_{D0w} \tag{4}$$

Where c_{fw} is an averaged friction coefficient over the wetted area (about 80 percent of the area in the passenger cabin and freighthold sections is assumed to be laminar). The last term corresponds to the wave drag, at high subsonic speed, which can be estimated as [27]

$$C_{D0w} = 3.578\left(M - \frac{0.71}{\cos^{0.5}\Lambda}\right)^{2.5} \tag{5}$$

In the performance module, the take-off field length is limited to about 2000 m from previous studies, although it does not really intervene, and there is no need for high lift devices neither in take-off nor in landing manoeuvres.

Direct operating cost is estimated in relative terms with respect to a base design established in previous analysis. As usual, it represents the contributions of aircraft price, crew, fuel, airport and navigation taxes, and maintenance. For example, the price dependent contribution (i.e. depreciation and insurance) is obtained as [32]

$$C_{price} = \left(0.18\frac{W_{to}}{W_{toref}} + 0.05\frac{T_{to}}{T_{toref}}\right)\left(\frac{9.42}{M} + 0.5\right)\frac{24.45}{N_{pax}} \tag{6}$$

Where Wto is maximum take-off weight, Tto maximum static thrust at take-off, M stands for average flight Mach number and Npax for number of passengers. The constants appearing in the equation are matched to the reference case: 300 passengers and M=0.8.

4 Parametric results

For each design case, i.e. the constant initial input data plus a given set of A, λ and M_{nom}, the procedure provides values for a large number of variables: wing area, cabin surface, swept angle, number of passengers, maximum take-off weight, operating empty weight, payload, trip and reserve fuel, mid cruise lift over drag ratio… and direct operating cost. It must be noticed that this last is a relative DOC and not an absolute value. With the former variables the second figure of merit, i.e. maximum take-off weight per passenger, is computed.

Along the process many intermediate variables are also computed, some of which of very high interest to understand the peculiarities of the flying wing, like the specific range (i.e. the range flown with a unit of mass of fuel). In this sense it is important to perceive that this aircraft must fly higher than conventional airliners for its different drag polar parameters and low wing loading. In effect, the cruise lift coefficient for optimum cruise has to be [33]

$$C_{Lcr} = \sqrt{\beta C_{D0}\,\pi A \varphi} \tag{7}$$

Where β is a parameter related to the Mach number dependence of the specific fuel consumption, about 0.6 for current high bypass ratio turbofans.

The vertical balance of forces, lift equal to weight, yields

$$\frac{W_{cr}/S}{\gamma/2\; p M^2} = \sqrt{\beta C_{D0}\,\pi A \varphi} \tag{8}$$

Where γ is 1.4, and p and M are pressure and Mach number at cruise conditions, respectively.

As indicated earlier, the specific range is one of the key intermediate variables. Following the definition of specific fuel consumption, the range travelled by unit of fuel mass burnt becomes

$$\frac{dR}{dW} = -\frac{M\,a}{c_j}\frac{L}{D}\frac{1}{W} \tag{9}$$

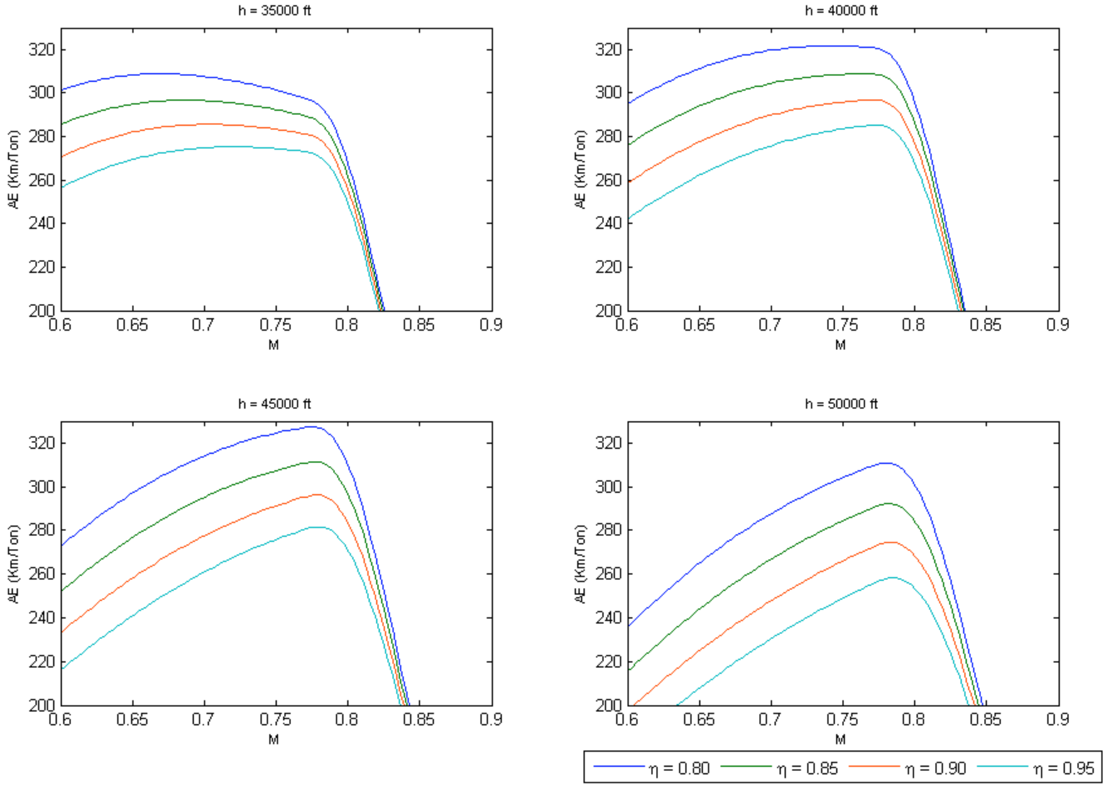

Fig. 6. Specific range for the design case M_{nom}=0.8, A=6.3, λ=0.2, at various η=W/Wto.

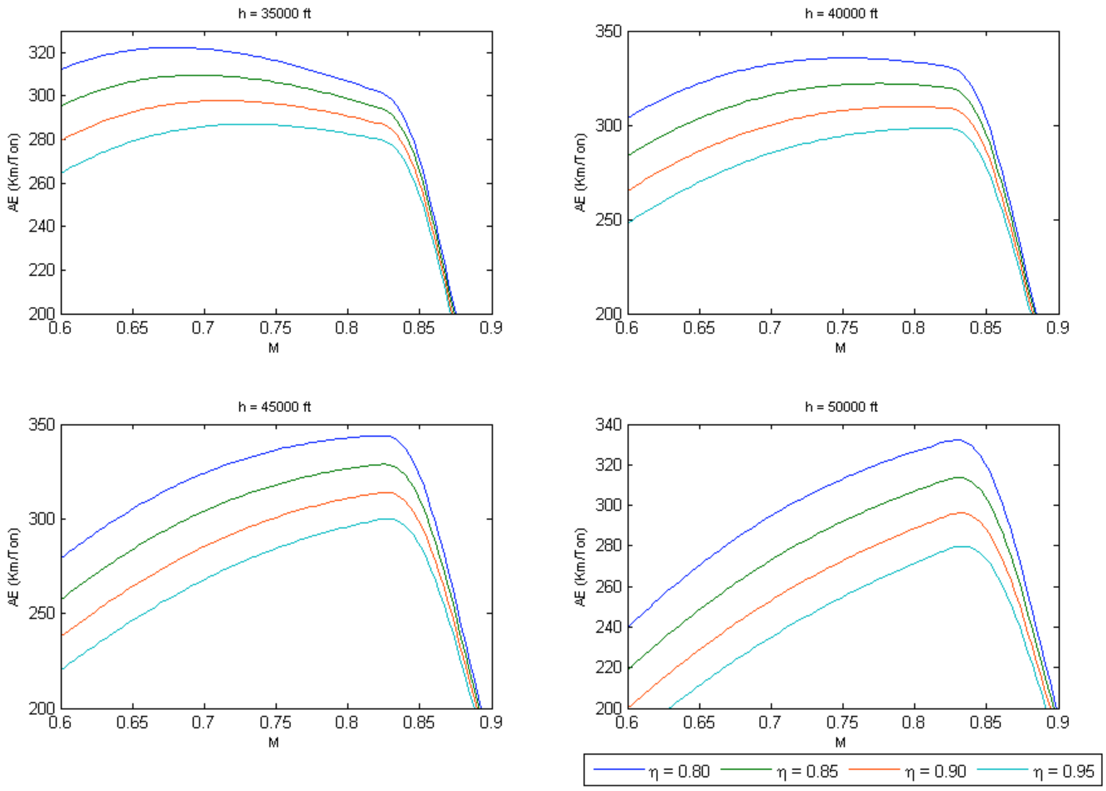

Fig. 7. Specific range for the design case M_{nom}=0.85, A=6.3, λ=0.2 at various η=W/Wto.

The results show that the optimum altitude for the flying wing is always around 45000 ft, the exact location depending upon the weight fraction with respect to the maximum take-off weight and the nominal or design Mach number. This maximum, as a function of altitude, is rather flat; which means that the loss of range is almost negligible provided the flight remains around between 41000 and 47000 ft. The sharp decline in specific range due to drag rise is easily seen in all curves.

Also visible in the curves, although less easy to interpret, is the dependence of the optimum with the actual flying Mach number. Fig. 8 helps in understanding that.

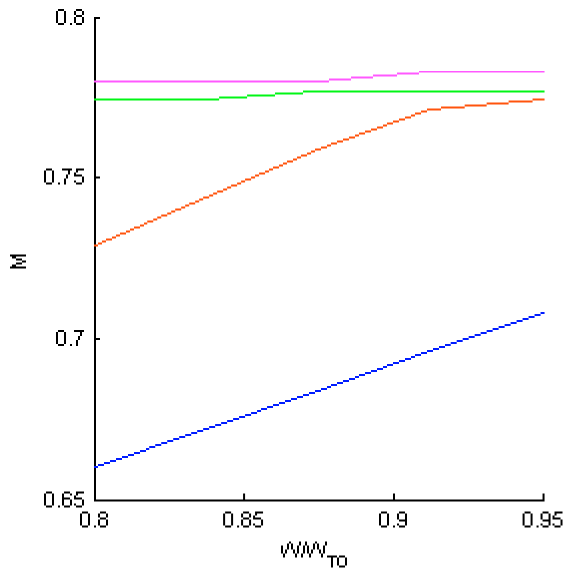

Fig. 8. Flying Mach number for optimum range in terms of airplane weight and flight altitude for the case M_{nom}=0.8, A=6.3 and λ=0.2.
— 35000 ft — 40000 ft — 45000 ft — 50000 ft

Because of the low wing loading, flying at 35000 ft is very inefficient, apart from being too much slow for a long range. From the very beginning of its long cruise, at W/Wto=0.95, the aircraft has to fly at 40000 ft to benefit from the outstanding features of this configuration. Flying higher than conventional implies that in spite of having a much better aerodynamics, the thrust over weight ratio at take-off needs to be about the same that in a common airliner, i.e. around 0.25, to allow this efficient cruise. As the flight progresses and the weight diminishes, say to about W/Wto=0.9, the aircraft climbs up to some 43000 ft and beyond.

Flying conditions for maximum range always occur at 0.02 below M_{nom}. The best economic cruise, the one with minimum DOC, occurs at M_{nom} since the increase in fuel burnt is more than compensated by the decrease in depreciation, insurance, crew and maintenance contributions.

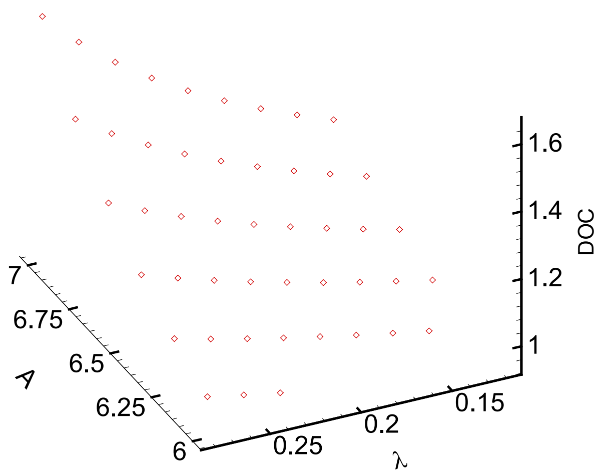

Fig. 9. Constrained results of direct operating cost in terms of aspect ratio and tapper ratio for M_{nom}=0.8.

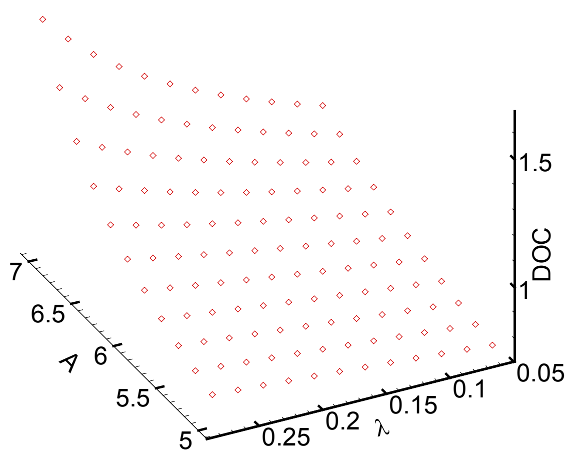

Fig. 10. Unconstrained results of direct operating cost in terms of aspect ratio and tapper ratio for M_{nom}=0.8.

The main results, however, are those corresponding to the figures of merit: direct operating cost and maximum take-off weight per passenger.

Figs. 9 and 10 show DOC in terms of aspect ratio and tapper ratio for M_{nom}=0.8 for the constrained and unconstrained cases, respectively. The constrained optimum for DOC corresponds to A=6.2 and λ=0.14, which are values quite apart from those of conventional airliners, typically in the 7-10 and 0.2-0.3 ranges, respectively. The optimum found is only a relative minimum within the state-space of acceptable values of A, λ pairs, given M_{nom}; i.e. it does not correspond to a mathematical minimum with second derivatives equal to zero. This mathematical minimum falls much outer than the envelope of A, λ values studied.

The values of A and λ for optimum DOC do not change with M_{nom} for the three cases considered: 0.8, 0.82 and 0.85; although the actual value of minimum DOC decreases a bit, 1.7 percent, from low to high M_{nom}.

It must be realised that DOC is more dependent on the aspect ratio than on tapper ratio. This is clearly seen in the curves and can be quantified by computing the non-dimensional sensitivity derivatives

$$\frac{\partial\, DOC}{\partial\, A}\,\frac{A}{DOC} \; and \; \frac{\partial\, DOC}{\partial\, \lambda}\,\frac{\lambda}{DOC} \qquad (10)$$

Around the optimum DOC, such non-dimensional derivatives are 1.41 on A and 0.142 on λ.

If all constraints are relaxed, the parametric range widens to include A values below 6, and λ below 0.12, that were ineligible in the constrained case for they overpass one or more constraints. For example if A diminishes the cabin gets larger and there are too many passengers to be evacuated safely, according to cabin size and potential exits [34].

One of the constraints is somehow more arbitrary than the others: the cabin width, to limit vertical accelerations in bank manoeuvres. If this specific constraint is relaxed, the optimum moves to A=5.8 and λ=0.1, which produces a reduction of 10 percent in DOC. Again, this new, partially unconstrained optimum does not change with M_{nom} for the three cases studied, and the minimum DOC reduces by about 2 percent on passing from M_{nom}=0.8 to 0.85.

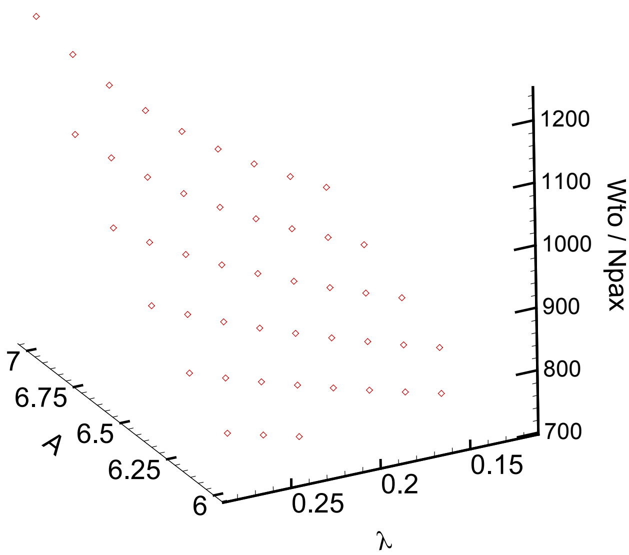

Fig. 11. Constrained results of maximum take-off weight per passenger in terms of aspect ratio and tapper ratio for M_{nom}=0.8.

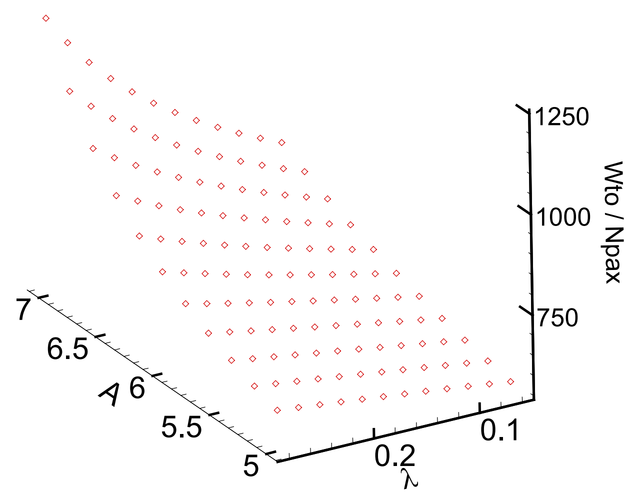

Fig. 12. Unconstrained results of maximum take-off weight per passenger in terms of aspect ratio and tapper ratio for M_{nom}=0.8.

Figs. 11 and 12 depict Wto/Npax in terms of aspect ratio and tapper ratio for M_{nom}=0.8 for the constrained and unconstrained cases, respectively. The results are pretty much the same as those for DOC, with a constrained optimum for Wto/Npax at A=6.2 and λ=0.14, independent from M_{nom} in the three cases considered. However, there is an important difference between DOC and Wto/Npax. As indicated earlier, DOC diminishes very little with M_{nom}, less than 2 percent from M_{nom}=0.8 to M_{nom}=0.85; meanwhile Wto/Npax increases around 3.3 percent with M_{nom}: 722.6 kg/pax at 0.8 to 748.7 kg/pax at 0.85. The same behaviour holds for the partly unconstrained case described before.

To learn more on parametric dependence the non-dimensional sensitivity derivatives are computed

$$\frac{\partial\, Wto/Npax}{\partial\, A}\,\frac{A}{Wto/Npax} \quad and$$

$$\frac{\partial\, Wto/Npax}{\partial\, \lambda}\,\frac{\lambda}{Wto/Npax} \qquad (11)$$

The derivatives are 1.35 and 0.142, respectively, which means that here too the aspect ratio is more impacting as design variable than the tapper ratio, although this last plays a role in some of the constraints. The sensitivity derivatives with respect to Mach number do not only change sign between DOC and Wto/Npax but becomes larger in this last: -0.273 in DOC against +0.548 in Wto/Npax.

5 Final considerations

The optimum planform found for the medium size flying wing studied here corresponds to A=6.2, λ=0.14, according to the two figures of merit employed: DOC and Wto/Npax. Regarding the design Mach number, the results vary for the DOC-based optimum suggests M_{nom}=0.85 meanwhile Wto/Npax indicates M_{nom}=0.80. In both cases the savings in fuel consumption are enormous, around 35-40 percent with respect to medium size wide bodies, achieving an outstanding figure of 14.6 g/pax.km.

Any optimisation process depends largely on the chain of modules and constraints, but also, more importantly, on the figures of merit used; their reliability and relevance. In this sense both DOC and Wto/Npax are highly relevant but, perhaps, the second one is more reliable than DOC for being based upon equations and expressions that require a smaller number of parameters to be adjusted and unknowns to be guessed.

The conflict in optimum M_{nom} requires further studies, including more accurate expressions for DOC or the intervention of new figures of merit.

In any case the results confirm previous findings and throw new light on the role of various design parameters.

The flying wing is a sound and feasible concept which, in spite of the many problems to be addressed and solved before becoming a reality, might pave the way for future developments of civil aviation in a more restricted environmental scenario.

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