FLYING WING VERSUS CONVENTIONAL TRANSPORT AIRPLANE: THE 300 SEAT CASE

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Abstract

Unconventional aircraft are being studied by the aeronautical engineering community with accelerated interest and effort to improve economic efficiency and to overcome operational and infrastructure-related problems associated to the increasing size of transport airplanes.

The objective of the research reported here is to assess the technical feasibility and operational efficiency of a medium size, wingspan-limited flying wing in C layout; a configuration which has many advantages at easily achievable technology levels.

To this end, the conceptual design process of a 300 seat C-wing has been done, completed with a comparison of performance and operational issues with last generation twins. The results are greatly encouraging and predict 10-20 percent increase in transport productivity efficiency, without the burden of new or aggravated safety or operational problems.

1 Introduction

Commercial aviation started as an organised activity after the end of World War I and became a mature industry in the 30s. But it was after World War II when it experienced an incredible boom with unprecedented growth rates [1]. The demand of new aircraft, adequate to quite different market segments, allowed airplane manufacturers to test many ideas and technologies in a wide variety of disciplines: aerodynamics, materials, structures, control, avionics, etc.

Interestingly, an aircraft configuration of military origin was found to be the best compromise for the entangled set of safety and operational requirements which had to be fulfilled by transport airplanes. Thus, the Boeing B47 layout is recognised today as the first step of aircraft design evolution [2,3]. The configuration is characterised by a slender fuselage mated to a high aspect ratio wing, with aft-mounted empennage and pod-mounted engines under the wing. A minor variation with engines attached at the rear fuselage was also developed during the 50s.

The continous improvement over the last 50 years can be well represented by a 30% increase in M (L/D) [2], an increase of more than 100% in range parameter, including the effect of specific fuel consumption, or a decrease of 80% in cost per ton-mile [4]. Size effects have played a major role in this evolution since the average number of passengers per aircraft has grown from about 70 in early 60s to well over 200 at the end of the 90s [3,5].

Currently, the major problems of commercial aviation are the need for further improvements in economic efficiency and attenuation of environmental impact, together with the simultaneous challenge of air transport growth and air traffic congestion. And it seems that the conventional configuration is approaching an asymptote for its problems of infrastructure compatibility and safety issues [3,6,7,8].

Aeronautical engineers and scholars have been studying, with accelerated interest and effort, several unconventional configurations to solve operational and infrastructure-related problems associated to size effects of the already classic layout. These novel arrangements include spanloader aircraft, multiple body concepts, PAR/WIG vehicles, blended-wing-body airplanes, flying wings, etc [2,3,4,9]. Claimed advantages of these configurations are drag reduction, increased useful load, short airfield capability, noise reduction, cuts in direct operating cost, and other appealing improvements.

However, paradoxically, most of these unorthodox configurations pose airport compatibility problems of similar or worse level as those of the very large conventional aircraft to which they are suposed to substitute. For example, wing span and landing gear track, loads on runways, inadequate matching with airport terminal geometry and facilities, passenger and cargo loading and unloading, etc. And they also pose new or aggravated issues on stability and control of the aircraft, decay of intense wing tip vortices, emergency evacuation, psychological acceptance of uncommon layouts, etc [7,10,11].

In spite of the former list of drawbacks, the ideal configuration for long range flights is the flying wing in C layout, which solves in a great extent the aforementioned stability and control, and wing tip vortex problems [3].

The objective of the research reported here is to assess the technical feasibility and operational efficiency of a wingspan-limited, C-wing aircraft.

It is widely recognised that when a proposed new concept fits within a 80x80 m box, most of the runway and taxiway-related compatibility problems are solved. The largest pure flying wing which fulfills the above specification is a 300 seater, and the present paper will show that such an aircraft is viable and can beat conventional airplanes of similar size. The aircraft is shown in Fig.1.

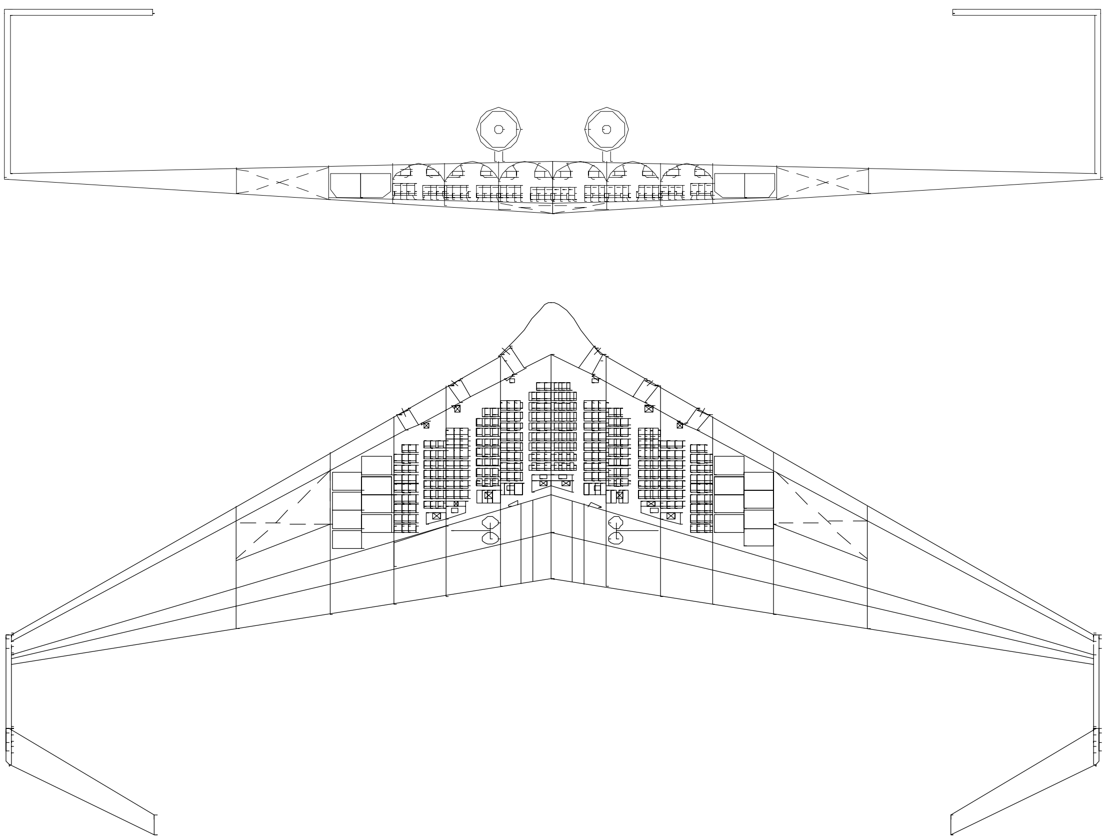

Fig. 1. Two view sketch of the flying wing, showing the inner arrangement.

To carry out a fair comparison, mid 90s technology level in aerodynamics, materials and propulsion is used in the estimation of the various design variables. Consequently, LFC, composites in primary structure or ultra high bypass turbofans are not considered. Moreover, to emphasize the intrinsic features of the configuration-size combination, the layout is conceived with maximum simplicity, both internally and externally; and common design methods and operational procedures are used in the design process.

2 Initial Sizing

The starting point for the conceptual design of the aircraft is a common long range mission: 10000 km (5500 NM) with full passenger load (28500 kg for 300 pax) at M=0.8. No initial cruise altitude is specified, although it is expected to be well over 30000 ft. The speed is slightly slower than that considered by other researchers [2,3,7,9] but it has two advantages: first, it does not require highly sophisticated or unconventional airfoils; and, second, together with a low wing loading it allows a moderate sweep without drag rise nor other adverse effects.

A key step in any airplane design process is the selection of the airfoil. In the present study it had to be chosen since the very beginning for its direct implication in the sizing of the cabin and the wing area. The main selection criteria were [2,3,10]: good transonic behaviour, high C_{lmax}, moderate pitching moment and adequate C_{l0}. A moderately aft-loaded airfoil, with 17 percent relative thickness, was selected.

To keep the design as simple as possible, including a fairly conventional primary architecture, the payload is situated between the front and rear spars, which are located at 11 and 67 percent of the chord. These figures are appropriate to arrange cabins of reasonable length while providing suficient bending rigidity; which is otherwise less important than in conventional designs for its low wing loading and spanwise distribution of payload and other weights.

Once the location of the cabin is defined, its area depends only upon wing aspect ratio, taper ratio and span. Three criteria are used to select suitable values for the design variables: maximum area per passenger (see Fig. 2), for comfort and emergency evacuation reasons [2,8]; cabin height taller than 1.9 m [10]; and minimum MTOW [2]. It goes without saying that the 80 m wing span limit has to be respected. Since the roof is curved, all aisles and most of the cabin have height well over 2.1 meters, similar to the figures used in other

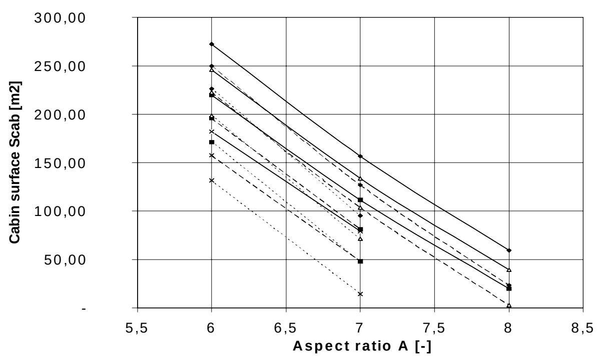

Fig.2. Cabin area versus wing aspect ratio for taper ratio λ=0.12 (solid lines) and λ=0.18 (dashed lines) for wing span 70, 73, 75 and 77 m (this last in the upper most position).

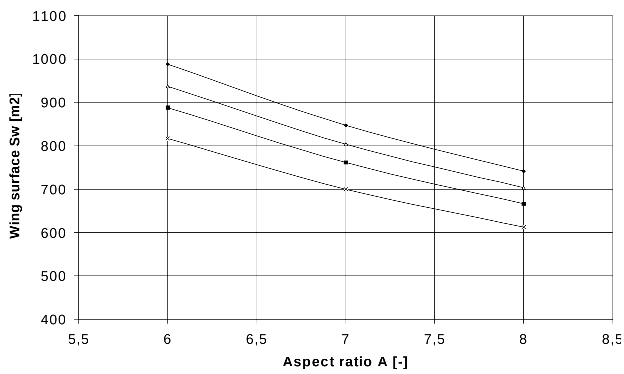

Fig. 3. Wing area versus wing aspect ratio for wing span 70, 73, 75 and 77 m (this last in the uppermost porition).

studies [2,10]. The sweep angle has no direct influence on the cabin area, but decreases the usable space and might have a negative psychological impact on the passengers.

Table 1. Main features of the flying wing

VARIABLE	VALUE
Maximum length	45.9 m
Maximum width	77.1 m
Maximum height	16.3 m
Maximum take-off weight	205200 kg
Operating empty weight	108600 kg
Maximum payload	35000 kg
Maximum fuel weight	75600 kg
Thrust to weight ratio	0.283
Cabin area	230.4 m^2
High density capacity	330 pas
All tourist capacity	312 pas
Three class capacity	237 pas
Cargo hold volume	72 m^3
Wing area	892.9 m^2
Wing span	75 m
Aspect ratio	6.3
Taper ratio	0.11
Mean aerodynamic chord	14.46 m
Relative thickness	0.17
C/4 sweep angle	30º
Wing loading	2254 Pa
Max. width of landing gear	14.00 m

On its side, as it is obvious, the wing area depends only on wing span and aspect ratio, as presented in Fig. 3. The final values of wing geometry and other relevant data are presented in Table 1.

The first estimate of the maximum take-off weight, MTOW, is done with a simple method [12], using a mission profile which includes diversion to alternate airport and loiter. The operating empty weight, OEW, has been taken is this first guess as 0.53 MTOW [6,11]. A more detailed account on the main weights will be presented later.

As indicated earlier, the wing is arranged as a dual entity: a fully unconventional inner wing with passenger cabins and freightholds in both sides between the spars, plus engines, landing gear, and many equipments in the non-pressurized part; and an outer wing with fairly conventional architecture, including fuel tanks outboard of the freightholds. A third spar, not part of the torque box, is located behind the rear spar to create adequate spaces for landing gear, APU and other equipment, and to attatch elevons which run over most of the trailing edge (the exception are the four innermost segments).

The passenger cabin is arranged as a set of six parallel bays, each one with the traverse dimensions of A320, connected in spanwise direction at the front with a wide aisle (~1.2 m) and at the rear with a narrower aisle (~0.8 m), for passenger loading and unloading, evacuation and servicing. The bays are separated by wing ribs. The minimum 1.9 m height occurs at the front and rear outermost corners. Overhead luggage compartments are provided with 20-30 more space than in A320. Longitudinal inclination of the cabin floor in cruise is kept below 1 degree, thanks to an appropriate matching between C_{l0} of the selected airfoil and the wing loading. Analogously, traverse floor inclination is kept below 2 degrees for an adequate compatibility among inner arrangement, airfoil shape and dihedral.

All galleys, toilets and wardrobes are located at the rear of the cabin for aesthetic and operational reasons. The grouped location of galleys and lavatories allows a very efficient servicing of the airplane.

A type A door is located at the front of each bay with its frame attached to the spar web. The exit, equipped with inflatable slides, rafts, and all suitable emergency provisions, is then through a wide corridor in the leading edge. Two type B doors [13], located at the rear of the central bays, permit servicing of the aircraft without disturbing the normal passenger flux and providing additional emergency escape routes through the rear spar web and vertically split tail cones equipped with slides and rafts.

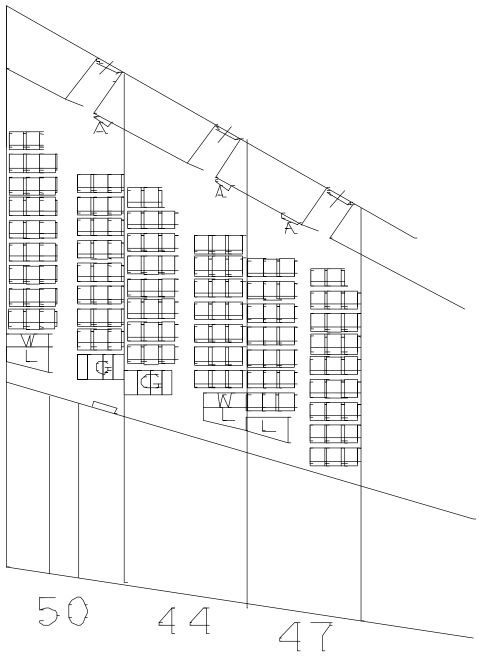

Fig. 4. Cabin arrangement for all-tourist layout at 86 cm pitch. The figures indicate passengers per bay.

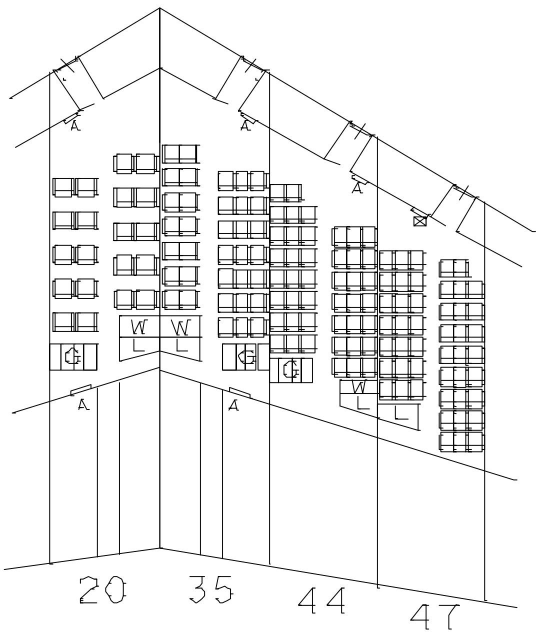

Fig. 5. Three-class seating layout, with first class in left-centre bay and business class in right-centre bay.

Although the maximum foreseen capacity, with suitable and proper use of space, is 330 passengers at 76-79 cm pitch, Fig. 4 shows a typical all-tourist arrangement, at 86 cm pitch, with 282 passengers and Fig. 5 depicts a three-class seating layout with 237 passengers, including 20 first class and 35 business travellers. These passengers occupy the central bays and benefit from adequate comfort levels.
Since passengers have no window, a specific provision has been done in seat pitch and detailed weight to include individual screens or monitors through which it could be possible to see the actual outer view or a variety of entertainment programs, as a means of counterbalancing the negative psychological impact of the absence of windows.

The cargo compartments are sized to carry two rows of LD3 containers. Only between 30 and 40 percent of the available volume is occupied by passenger luggage, thus offering additional capacity for commercial cargo. The design process performed did not include a more accurate sizing of the cargo compartment, but the volume defined in Fig. 1 and the MPL obtained are considered adequate for this preliminary analysis. Loading and unloading of the containers takes place through cargo doors in the leading edge, similarly as the main doors of the passenger cabin.

To assure that there is no fuel limitation in ordinary operation, the maximum fuel weight is chosen as the one corresponding to carry the typical three-class payload; i.e. 237 passengers, or about 0.6 MPL. It results in 94500 liters or 75600 kg. Three tanks are considered: a small volume with 8800 liters, located under the front part of the two central passenger bays, around the nose landing gear, which is also useful for trimming the aircraft; and two main tanks with 42800 liters each, close to the front spar, and outboard of the cargo compartments. Obviously there is enough additional volume to enlarge the main tanks for increased take-off weight versions or to improve range in low density routes.

The way of selecting the wing loading and thrust over weight ratio is somehow different from conventional cases. Here, the definition in

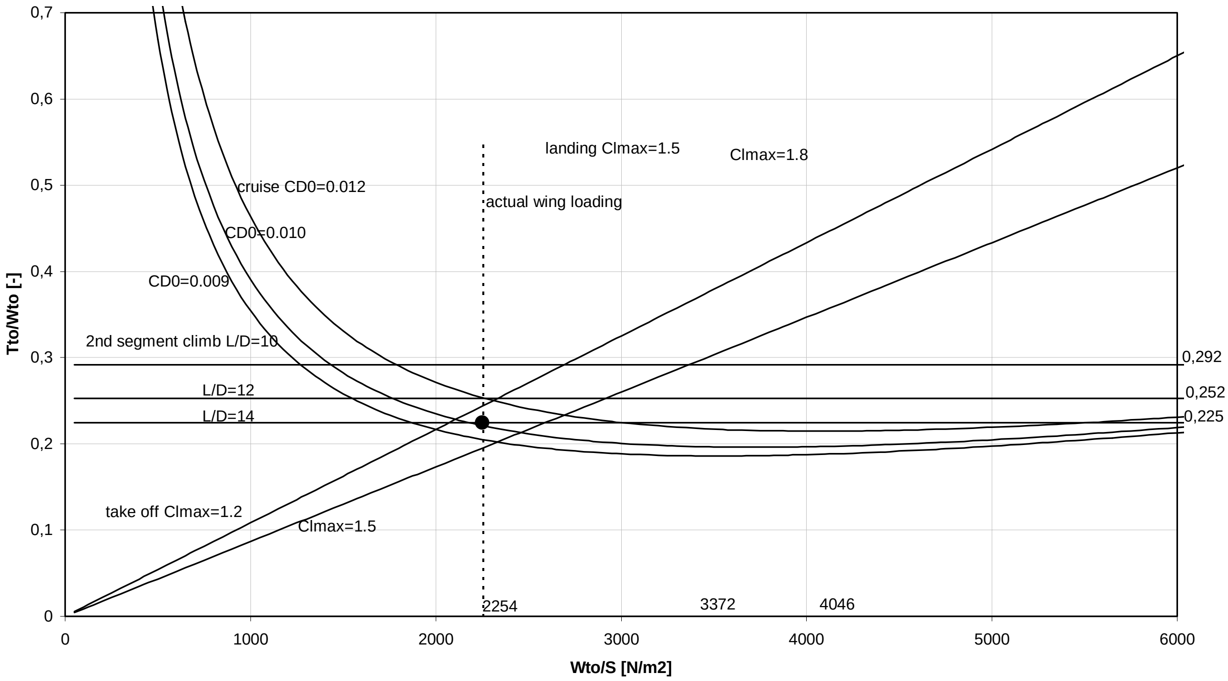

Fig. 6. Cruise, take-off, second segment climb and landing requirements in the wing loading versus thrust over weight ratio plot.

some detail of the wing architecture, an accurate estimation of the wing area, and a first guess of MTOW have been done since the very beginning.

So, this step of the design pocess has been mainly carried out to confirm whether high lift devices are required or not. Figure 6 shows the common T_{to}/W_{to} versus W_{to}/S plot with four performance requirements: take-off, second segment climb, cruise and landing [12,14]. With a take-off field length of 2000 m and adequate values for C_{Lmaxto} [2,11], the manoeuvre is represented by straight lines from the origin. The second segment climb requirement [15,16] is depicted in terms of the lift over drag ratio, which has to be consistent with the selected C_{Lmaxto} value. On its side, the cruise curves correspond to a cruise mid-point defined at 0.85 MTOW, M=0.8 and 45000 ft, for various drag polar parameters. Finally, the landing field length is set at 1500 m, which approximately correspond to an approach speed of 119 knots, far less than the common 150 kts specification [2]. The suitable design point is W_{to}/S=2250 Pa and T_{to}/W_{to}=0.225. Later in the design process it was known that the thrust lapse from take-off to some desired economic cruise (with altitude around 45000 ft) was much more demanding and the thrust over weight ratio had to be increased up to 0.28. It is clear that, unlike the blended-wing-body and other heavily loaded vehicles, the C-wing does not require slats, leading edge suction, nor any other high lift device for its low wing loading, both in take-off and in landing.

Once the wing and the engine are properly sized, other aircraft components are designed and positioned. The main landing gear, with four wheel boggies, is placed between the rear and the third spars, just behind the intermediate passenger bays. This solution allows 8.5 degree banks at touch down and landing gear maximum width within the 14 m limit. A slightly diagonal retraction will be needed to accommodate the boggies. Both the main as well as the nose landing gear wells require minor modifications of the airfoil to offer adequate volume in retracted position.

Vertical tailplane sizing is performed with the help of tail volume coefficient. Due to the specific features of the unconventional configuration a value of 0.02 is chosen. The figure is equal to that reported in [11] but is much smaller than that of conventional airplanes [14]. The spars of the vertical tail are fitted to the wing spars and since its torque box

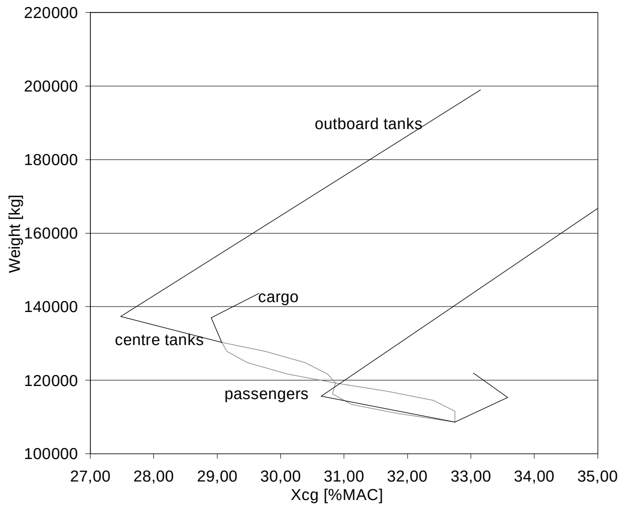

Fig. 7. Effect of passengers, cargo and fuel on the location of the centre of gravity.

is much shorter in relative terms than that of the wing, the chord is 40 percent larger, thus reducing the aspect ratio and the structural problems of the vertical tails. On the other hand, most blended-wing-body and flying wing designs have no horizontal tail, but it is considered here an important advantage, both in terms of trimming the nose down effect of the aft-loaded airfoil and of improving stability and control. Therefore half-span horizontal estab-ilizers are fitted at the extreme of each vertical tail. Again a small tail volume coefficient, 0.1, is chosen for this purpose.

A detailed estimation of all important weights has been done to obtain the location of the centre of gravity of the aircraft in many flying conditions. The wing structure weight has been computed in two steps: first with the help of an accurate method [17] to which a reduction of 30 percent for bending relief has been applied; second, the weight of the pressurization shell, computed as proportional fractions of A320 fuselage weight, is added. Very likely the procedure is conservative [18]. Engines, equipment, furniture, etc, have been either estimated [14,19] or directly taken from known sources. The centre of gravity of the operating empty weight is at 32.5 percent of the mean aerodynamic chord. Most conditions fall within a 28.5-34 percent range (see Fig. 7), much shorter than that of conventional aircraft [2,14], and consistent with the location of the aerodynamic centre, estimated to be at 33 percent in cruise. The cg range can be shortened even more with an appropriate policy of tank usage.

3 Aerodynamics and Flight Mechanics

A Mach number dependent parabolic drag polar is assumed in all aerodynamic and performance calculations. The corresponding terms are estimated with the method described in [14]. An alternate estimation with a different method [20] produced very similar results. Winglet effects are evaluated as a multiplying term on the Oswald factor [3,21]. The flying wing aerodynamics benefits from the very high Reynolds number and the relatively low wetted area, leading to $(L/D)_{max}$=23.4 in cruise, in good agreement with the values reported in other studies [2,9,11]. The drag divergence, i.e. ΔC_D=0.002 [14], occurs at M=0.85.

The engine, selected after the performance requirements plot of Fig. 6, is one of PW4000 family, ruberized up to T_{to}=285 KN.

Climb performances have been calculated as a function of weight, Mach number and altitude, from the aerodynamic properties of the airplane and the engine characteristics [14,20,22]. Just after take-off the maximum vertical speed is 18.7 m/s (3680 ft/min). The service ceiling at 0.97 MTOW is 41500 ft at M=0.65, but decreases to about 37000 at the cruise Mach number of 0.8. The aircraft needs almost 25 minutes to climb up to an initial cruise altitude of 35000 ft, travelling 235 km on the ground, and burning fuel as much as 0.016 MTOW.

FAR/JAR field performance are estimated with methods described in [14,22]. The take-off field length is as short as 1860 m without requiring high lift devices, while the landing field length is 1320 m at C_{Lmaxl}=1.5, thus requiring a very minimum deployment, if any, of trailing edge high lift elements.

As an example of cruise performance studied, Fig. 8 shows the specific range (distance covered per unit mass of fuel burnt) for three different values of weight and three cruise altitudes as a function of Mach number

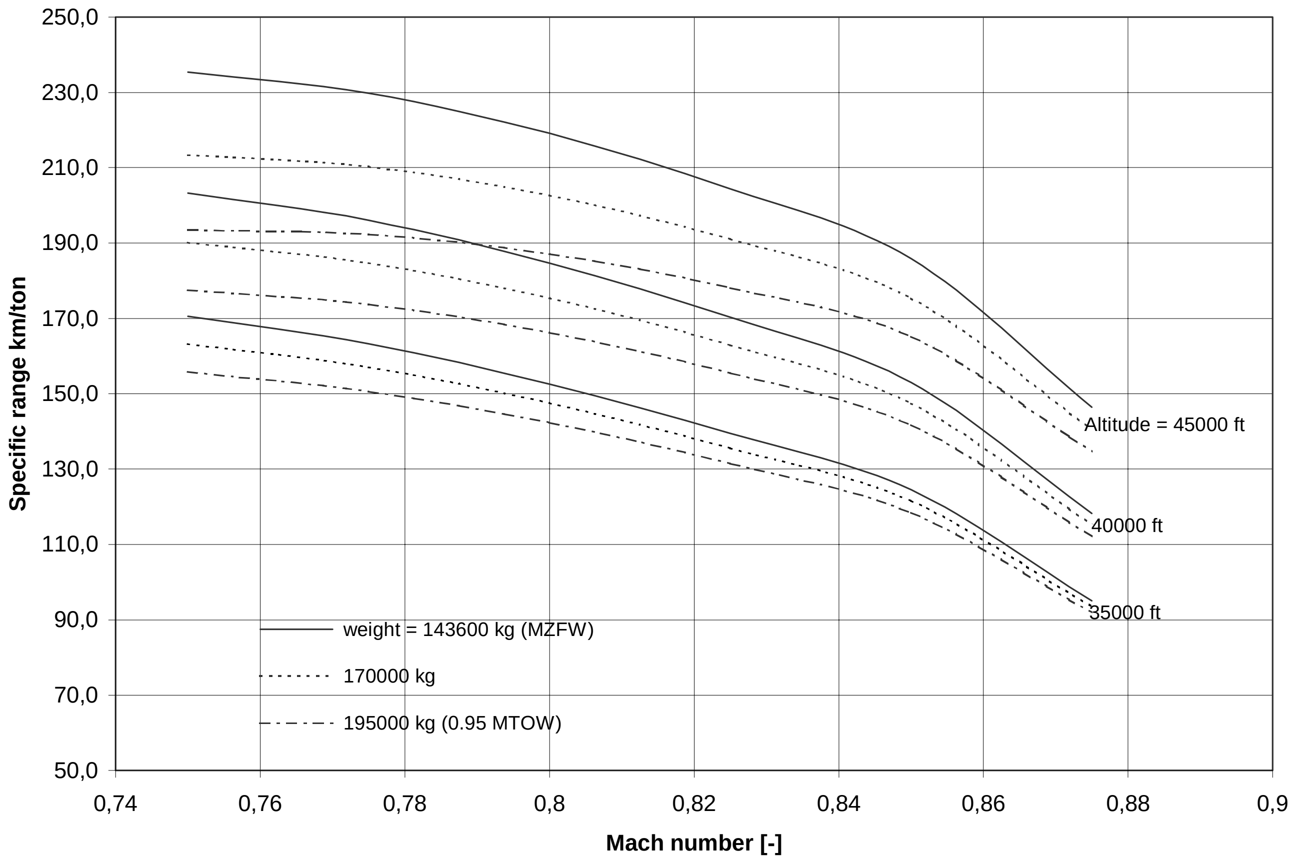

Fig. 8. Specific range of the flying wing.

[14, 20, 22]. The specific range improves with altitude and decreases with weight, as expected. But the important feature is that, due to the uncommon matching of aircraft variables [22,23], the best performances can be obtained at Mach numbers below common cruise; say between 0.7 and 0.75.

The key feature for a transport airplane is the payload-range diagram. In the present case, it has been computed with a three step cruise, at constant Mach number 0.8, including common international flight reserves [14,22]. The first step is only 1000 km, just to allow later cruising at 40000 ft for several hours, before ascending to 45000 ft in the last segment. Although the profile has not been optimised, it is considered close to maximum performance. The initial specification of flying to 10000 km with 300 passengers is achieved. On the other hand, the fuel efficiency for this route is 19.8 g/pas.km; exactly the same as that reported in [11].

The research work carried out includes preliminary estimations of the flight mechanics of the vehicle [24,25]. Some results are summarized here.

The stick fixed static margin in cruise is between 6 and 12 percent of the mean aerodynamic chord, which is assumed adequate; although at low speeds it could be necessary to use a stability augmentation system.

Short period and phugoid modes of dynamic longitudinal stability have been investigated in cruise conditions (0.85 MTOW, M=0.8, h=40000 ft). For the short period, $t_{1/2}$=3.1 s, T=12.8 s and ζ=0.46, which are very acceptable values. On its side, for the phugoid, $t_{1/2}$=209 s and T=106 s, with ζ_p=0.056, which are again satisfactory.

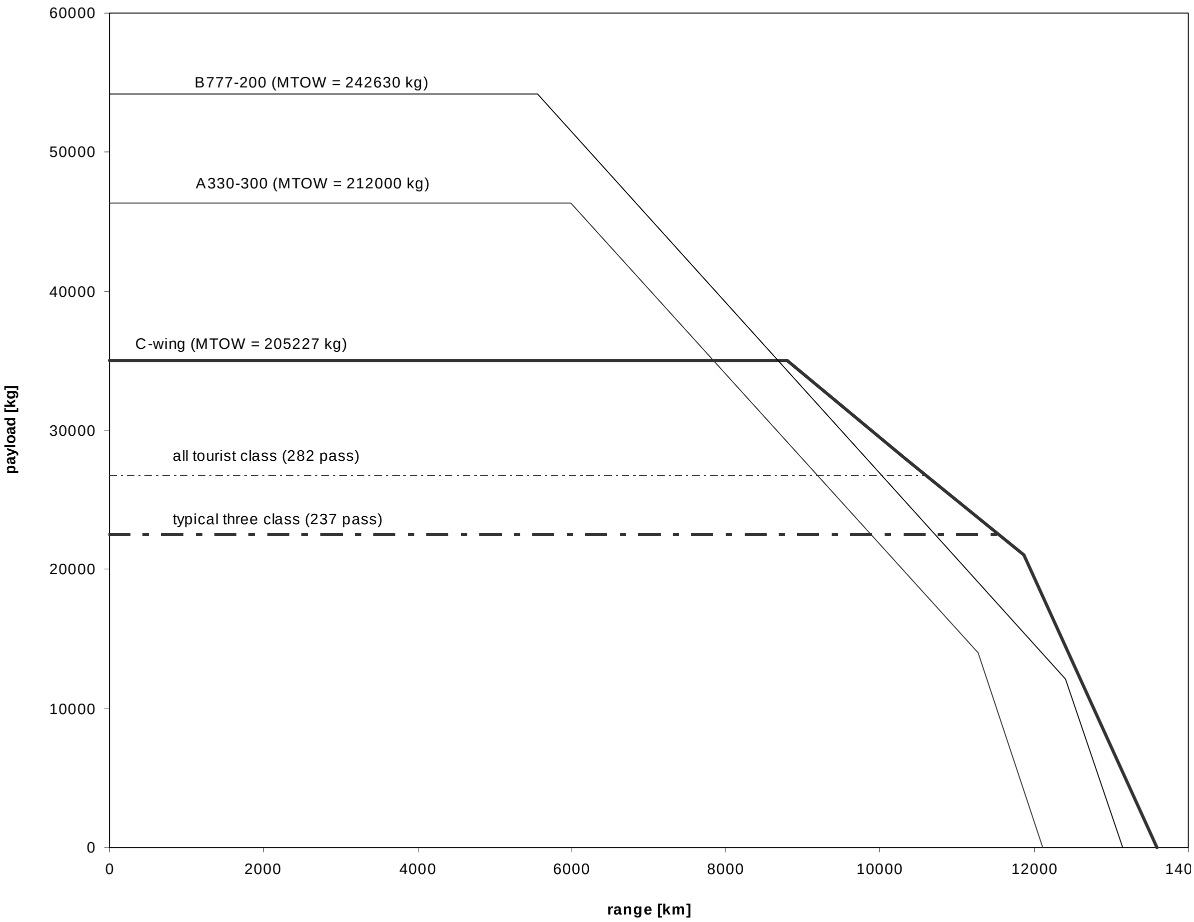

Fig. 9. Payload-range diagrams of the flying wing, A330-200 and B777-200.

In the dutch roll, one of the lateral-directional stability modes, the main characteristics are $t_{1/2}$=9.0 s, T=5.3 s and ζ=0.065. According to military standards, for class III aircraft, and category B flying conditions, this corresponds to level 2, which means minor deficiencies and would also benefit from a stability augmented system.

4 Comparison with conventional aircraft

In this section a comparison with the two most modern twins, of relatively similar capacity, is done. The selected airplanes are A330-200 and B777-200 and their data have been mainly taken from manufacturers' sources [26,27]. Both aircraft entered into service around mid 90s and are representative of the most advanced ability of airplane designers.

With respect to the mission, which is the base for selection and comparison, Fig. 9 shows that all three airplanes are capable of carrying 300 passengers up to or near 10000 km, which were the rounded values taken as main initial specification for the conceptual design of the flying wing. However, as it will be commented later, their maximum transport capacity is far from equal.

Because of the large configuration differences between conventional and C-wing aircraft, sizes do not compare well. The two ordinary layouts have almost the same length, span and height; but the flying wing is much shorter both in length and height and wider in span, although fitting perfectly into the 80x80 m box mentioned in the Introduction. The maximum width of the landing gear is 14.0 m against 12.4 and 12.7 m for A330 and B777, respectively.

Interestingly, the loading and unloading of passengers in airport piers requires fingers positioned at about 5 m above the ground for the two wide bodies, but only narrow body height (a bit more than 3 m) for the flying wing. On the other hand, the doors of cargo compartments are at similar height (around 3 m) in the three cases.

No major differences are found in airport terminal operations, provided that the rear doors of the flying wing are used for cabin cleaning, and galley and toilet servicing. In this situation passenger services, cargo/baggage handling and airplane servicing can be done simultaneously with the usual overlap of activities.

Main design weights, MTOW, MLW, OEW, etc, exhibit the differences corresponding to the diverse initial specification of each aircraft, the Boeing airplane showing the highest values. However, the ratio OEW/MTOW is almost the same in all three airplanes, in clear opposition to that reported in [11]. The flying wing has a lower MPL/MTOW ratio, not because of the configuration but because no special attempt has been done to define a maximum structural or volume-limited payload. Instead, only a very preliminary estimation of cargo compartment volume was performed.

In terms of design point, the flying wing has, obviously, a very low wing loading, less than half of the conventional aircraft, but about the same thrust over weight ratio. This is so because, although the C-wing has a much better aerodynamics, it has to fly at very high altitude to perform efficiently in cruise.

Passenger capacity is very similar in A330 and B777 and only about 75 percent of their values in the flying wing. Although the area per passenger is larger in this last, its capacity can not be increased proportionally, even in high density layout, for the need of dedicating more cabin area to aisles and exits for evacuation reasons [8].

It is in field and cruise performance where the flying wing exhibits its great potential. With unmatched take-off (1860 m) and landing (1320 m) field lengths the C-wing requires only narrow body-long runways against larger, although moderate, values for A330 and B777, typically in the order of 2300 m and 1600 m. And the range with 300 passengers is 8900 km for A330, 9730 km for B777, and 10230 km for the flying wing. Fuel efficiency is well expressed in terms of fuel burnt per passenger-kilometre [11,22,26] and, for the 300 passengers case, the values are 19.8, 21.5 and 23.5 g/pas.km for the C-wing, A330 and B777, respectively.

The maximum transport productivity, payload times range (PLxR), achieved by the aircraft are 3.07 10^6 kg.km for C-wing at MPL (35000 kg), 2.80 10^6 kg.km for A330 with PL=41370 kg) and 3.16 10^6 kg.km for B777 with PL=43940 kg.

A global transport productivity efficiency can be defined as (PLxR)max/(MTOWxR_G). The numerator corresponds to the actual maximum transport productivity achieved. The denominator represents the theoretical maximum transport capacity achievable, where R_G is the global range; i.e., half the Earth's circumference (20000 km). Its maximum, 100 percent, corresponds to carrying a payload equal to MTOW (i.e. an aircraft which would not require fuel, airframe, etc) to the antipodes. The value of this new non-dimensional parameter is 0.0749 for the flying wing, 0.0661 for the A330, and 0.0652 for the B777. The C-wing is, therefore, 13 percent more efficient than A330 and 15 percent more efficient than B777 as a transport vehicle.

5 Conclusions

The conceptual design of a 300 seat, wingspan-limited C-wing has been carried out. The results obtained with simple analytical and semi-empirical methods have been corrobor-ated, in some validation computations, by those of more complex methods. The main findings of the design process and the subsequent analysis are summarised in the next statements.

The medium size flying wing configuration is technically feasible and operationally efficient and can beat conventional airplanes of similar size. No infrastructure compatibility problems exist, if the maximum span is kept below 80 m.

The main advantages of the flying wing are in field and cruise performances, with take-off and landing field length values analogous to those of much smaller aircraft.

The medium size flying wing is 10-20 percent more efficient as a transport vehicle than conventional airplanes, measured in terms of global transport productivity.

The flying wing configuration may better exploit emerging technologies like LFC over a large fraction of the wetted area, composites and aeroelastic tayloring in primary structure, and ultra high bypass ratio engines mounted over the wing.

The main drawbacks of the C-wing configuration are the uncommon wing architecture, which may imply manufacturing and maintenance problems, uncommon cabin arrangement, which may be negatively perceived by pasengers, and increased passenger and cargo flight loads for increased distance to airplane axis.

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Most of this paper was written in very late hours by the leading author while sitting his second, new born daughter, Carmen, to whom he dedicates the research effort.

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