FLYING WINGS AND EMERGING TECHNOLOGIES: AN EFFICIENT MATCHING

Rodrigo Martínez-Val, José A. Martínez Cabeza and Emilio Pérez
Departamento de Vehículos Aeroespaciales, ETSI Aeronáuticos
Universidad Politécnica de Madrid, 28040 Madrid, Spain

Keywords: *flying wing, aircraft configuration, conceptual design*

Abstract

Flying wings are one of the most promising concepts to cope with the ever increasing air traffic demand, while improving the economic efficiency and respecting the environment, both in terms of emissions and noise. Consequently the major airplane manufacturers and many researchers have been carried out various analysis, at conceptual design level, to learn on problems and challenges proper of this configuration.

In a former paper [1] it was shown that not only very large but also medium size flying wings are technically feasible and operationally efficient and can beat conventional airplanes of similar capacity. The main advantages of the flying wings are in field and cruise performances, with take-off and landing field lengths values analogous to values of much smaller aircraft and fuel efficiency about 15-20 percent higher than conventional airplanes.

The present paper addresses four specific topics, related to emerging technologies: laminar flow control, vectored thrust, active stability and flying qualities, and emergency evacuation. Other potential advantages like intensive use of composites in the primary structure, aeroelastic tailoring, ultra-high bypass ratio engines, etc are not included.

1 Introduction

Most air traffic forecasts predict a remarkable increase over the next two decades, in spite of the serious downturn after year 2000 crisis and the terrorist attack of September 9, 2001. The overall RPK figure goes up at a pace between 4.7 and 5.1 percent [2,3,4]. Needless to say the predicted traffic growth varies from region to region, with USA and Western Europe at the bottom and Asia-Pacific Rim on top. And freight traffic will increase at even higher rates, also requiring a noticeable number of new airplanes as well as the conversion of ageing airliners. But this tremendous demand of around 20.000 new airplanes will have to cope with the continued pressure to achieve significant reductions in both direct operating cost and environmental impact; i.e. noise and emissions.

Commercial aviation has been mainly based over the last 50 years in what is currently called the conventional layout, characterised by a slender fuselage mated to a high aspect ratio wing, with aft-mounted empennage and pod-mounted engines under the wing [5]. A variant with engines attached at the rear fuselage was also developed during the 50s. But it seems that this primary configuration is approaching an asymptote in its productivity and capacity characteristics [6,7]. The A380 in the upper end, or new wide bodies like B7E7 at intermediate size are good examples of the steps taken by major manufacturers to tackle with the aforementioned growth and operational issues.

The ever changing market and technology scenario leads the process of designing new airplanes. And the major questions are always [8]: What does the market need? Which design fits best in the medium to long term scenario? And, which level of technology improvement or new research is required?

Within this framework one of the most promising configurations, new in the airline industry, is the flying wing in its distinct concepts: blended-wing-body, C-wing, tail-less aircraft, etc [9,10,11,12,13,14]. It may provide significant fuel savings and, hence, in emissions as well as noticeable noise reduction in take-off and landing. And this explains the great deal of activity carried out by the aircraft industry and numerous investigators throughout the world. However, as shown in many papers and reports, this configuration poses new challenges which need to be properly addressed.

By far, most of the publicised work deal with very high capacity aircraft, around 800 to 1000 passengers, in aiming at the foreseen growth in air traffic demand, between distant regions. But the forecasts are also very promising with medium capacity airliners, indicating a demand of some 5000 new airplanes of the A330-340 or B7E7, B777 category during the next 20 years.

Taking into account this important demand and the idea that a medium size flying wing will pose less or lower level problems than a gigantic 1000 seater, a precedent paper [1] had the objective of assessing the technical feasibility and operational efficiency of a 300 seats flying wing in C layout. The results were greatly encouraging in terms of efficiency and productivity, as well as regarding airport compatibility.

The present paper points towards confirming that relevant emerging technologies are very well matched to this type of airplane which, otherwise, does not exhibit serious issues that could impede its entry into service within the next two decades.

2 The C-flying wing configuration

As indicated above, a former paper has described the conceptual design of a C-type flying wing, which is now summarised in this paragraph. The initial specifications of the aircraft come from a common long range mission: 10000 km (5500 NM) with full passenger load (28500 kg for 300 pax) at M=0.8. These figures deserve some explanation. The number of passenger falls within the highly demanded intermediate segment and is only 10 percent more expensive in direct operating cost than a 600 seater and only 15 percent apart in DOC from a theoretical gigantic aircraft of 1500 passenger [12]. On its side, the mission range covers most interesting routes between Europe and USA, West US coast to Far East, etc. The selected Mach number, 0.8, is not fully optimised but simply representing common practice in studies of high subsonic airplanes [12,15]. With only minor modifications it could go up to 0.85.

A wing with fairly simple planform has been chosen as the base configuration; i.e. straight leading and trailing edges, and a nose bullet in the apex to accommodate the cockpit with adequate visibility [11]. Figure 1 shows a two view sketch of such concept. On the other hand, the overall layout belongs to the C-wing type, which exhibits the minimum induced drag among a large group of alternatives [12]. Along with the overall layout, the wing aspect ratio, taper ratio and relative thickness have to be selected. Four criteria were used for this purpose: economic trade-off between cost and productivity; maximum area per passenger, for comfort and emergency evacuation reasons; proper aerodynamic performance; and minimum MTOW. It goes without saying that the 80 m wing span limit has to be respected.

Figure 2 depicts an example of the type of trade off analysis carried out to determine the wing aspect ratio. The productivity increases sharply as the cabin area gets larger on reducing the aspect ratio, meanwhile there is a very low increase in direct operating cost, for the increase in induced drag. But if the aspect ratio diminishes below a certain threshold the aerodynamic performances and flying qualities deteriorate quickly. On the other hand, Fig. 3 represents the cabin area relative to gross wing area, as a function of aspect ratio and taper ratio. Low values for these design variables increase the cabin area, but again at the expense of worsening aerodynamic and structural issues: stall characteristics, wing tip rigidity, etc.

With respect to airfoils, slightly aft loaded, 15-17 percent thick sections are selected for the outer part of the wing, as well as modified reflexed shapes of 17 and 18 percent for the inner wing, in agreement with data reported in literature [10,11,12].

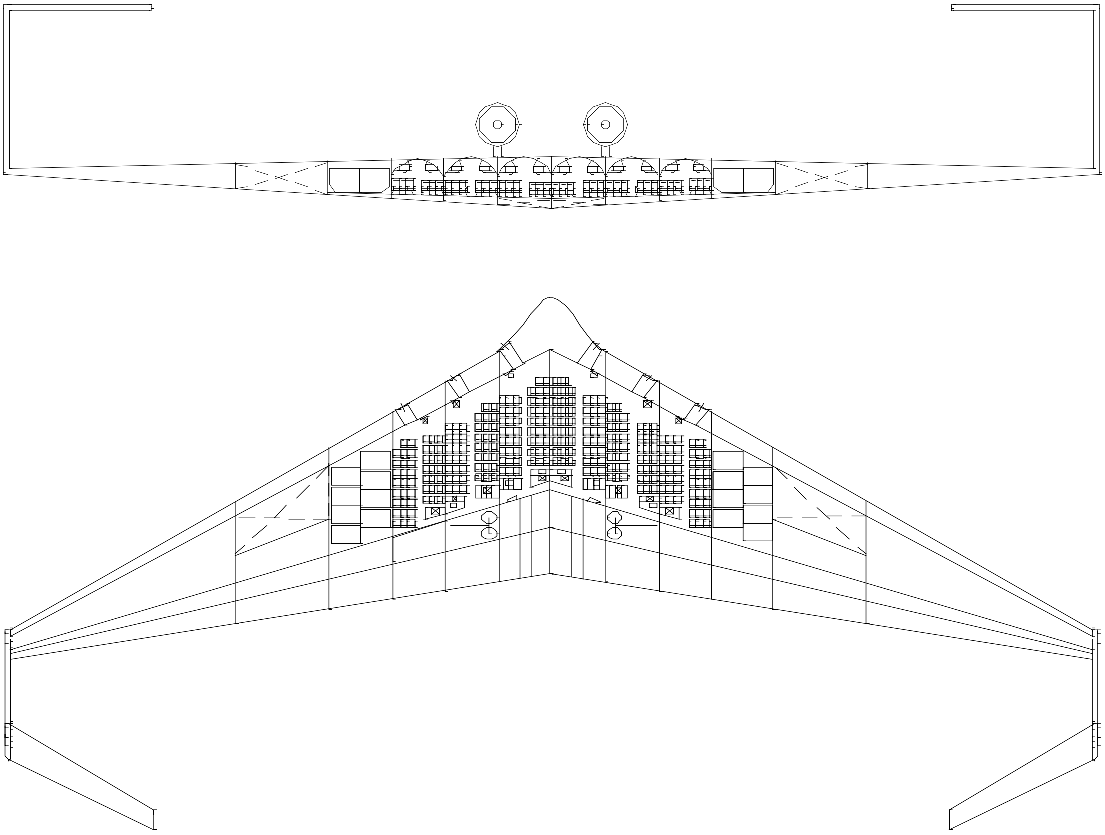

Fig. 1. Two view sketch of the flying wing, showing the internal arrangement.

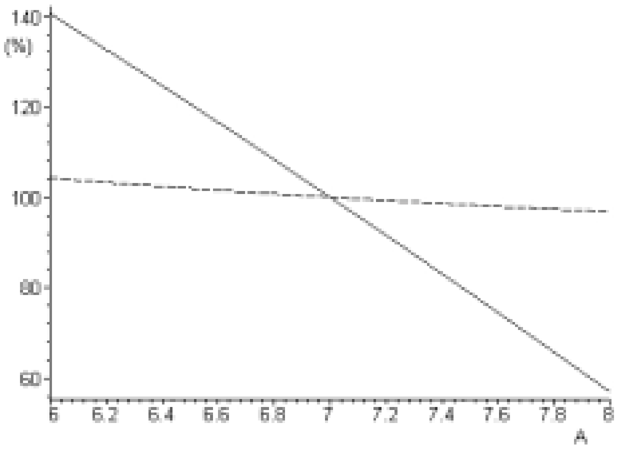

Fig. 2. Productivity and direct operating cost (dashed line) versus wing aspect ratio, non-dimensionalised with the values for A=7.

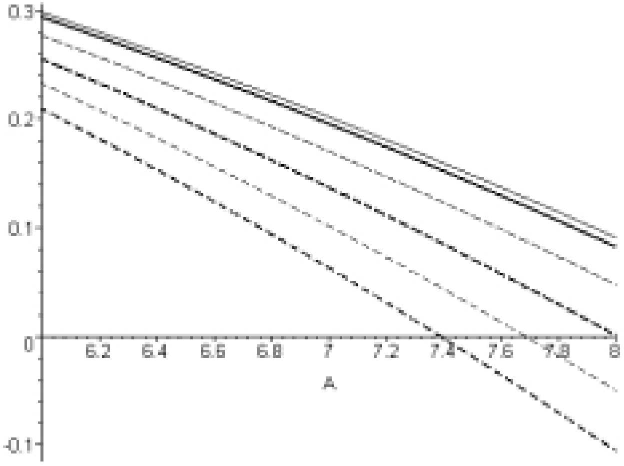

Fig. 3. Cabin area fraction of gross wing area, in terms of wing aspect ratio for taper ratio λ=0.1 (upper line), 0.11, 0.15, 0.2, 0.25 and 0.3.

The wing is arranged as a dual entity: a fully unconventional inner wing with passenger cabins and freightholds in both sides between the spars, located at 11 and 67 percent of the chord; plus engines, landing gear, and most equipment in the non-pressurized part; and an outer wing with fairly conventional architecture, including fuel tanks outboard of the cargo holds. 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 attach elevons which run over most of the trailing edge.

From the safety viewpoint this arrangement provides important advantages since uncontained engine debris can not impact on essential items. And, also, on the environment side, the flying wing offers low acoustic signature for the upper wing location of the engines and the absence of high lift devices at low speeds.

This structural solution of a vaulted double-skin ribbed shell layout is superior due to its weight saving, load diffusion and fail-safe features [16,17]. So, the passenger cabin is formed by a set of six parallel bays, each one with the traverse dimensions of A320, connected by slanted corridors in spanwise direction at the front and rear. The bays are separated by wing ribs. The minimum cabin height is 1.9 m [11] and occurs at the front and rear outermost corners, although most of the cabin is taller than 2.1 m. Overhead compartments are provided with 20 to 30 percent more space than in A320.

There are two symmetrical couples of type A doors located at the front corridor through the spar web, and another couple at the rear (see Fig. 4). All galleys, toilets and wardrobes are located at the rear of the cabin for aesthetic and operational reasons. This grouped location leads to efficiently servicing the airplane, without disturbing the normal passenger flux and providing additional emergency escape routes.

In this conceptual design the maximum foreseen capacity is 330 passengers, at 76-79 cm pitch, consistently with current regulations for three pairs of type A exits [18]. And diminishes to 237 seats in a three-class arrangement, corresponding to 0.97 square metres per passenger, an efficient solution according to current standards [11]. First class and business travellers occupy the central bays to benefit from improved comfort levels.

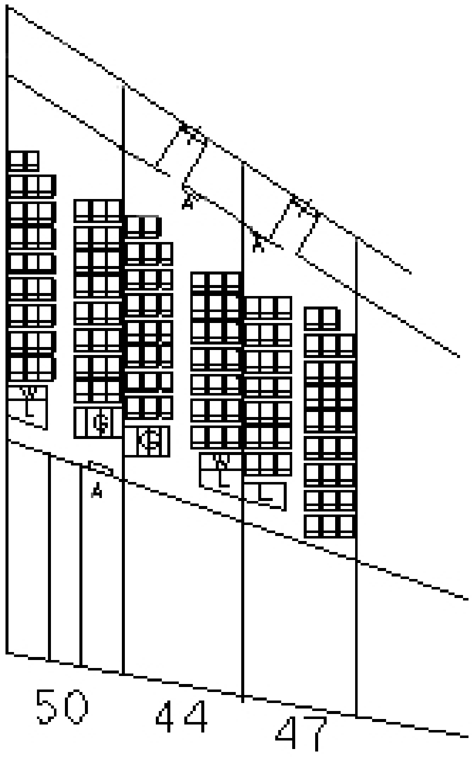

Fig. 4. Internal all-tourist arrangement of the cabin with 282 seats.

Selecting the wing loading and thrust over weight ratio is carried out according to four common criteria [19,20,21]: mid point cruise (at 45000 ft), take-off (below 2000 m), second segment climb, and landing (approach speed about 120 knots). The suitable design point is Wto/S=2250 Pa and Tto/Wto=0.25, including allowance for the remarkable thrust lapse from take-off to 45000 ft. (see Fig. 5) Moreover, unlike the blended-wing-body and other heavily loaded aircraft, this C-wing concept does not require high lift devices neither in take-off nor in landing.

The centre of gravity of the empty flying wing is at 32 percent of the mean aerodynamic chord. Most conditions fall within a 28-34 percent range, much shorter than that of conventional aircraft [19,22], and consistent with the location of the aerodynamic centre, estimated to be at 32 percent in cruise, as in [13]. The cg range can be shortened even more with an appropriate policy of fuel tank usage.

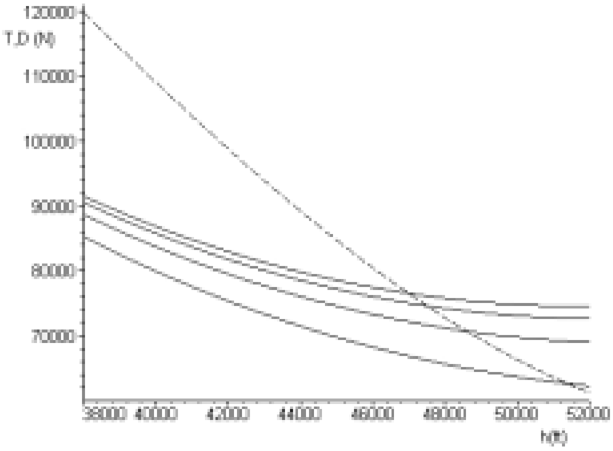

Fig. 5. Available thrust (dashed line) and aerodynamic drag in cruise at M=0.8, and W/Wto=0.95 (upper line), 0.9, 0.8 and 0.7 (bottom line), versus flight altitude.

Table 1. Main features of the C-flying wing

VARIABLE	VALUE
Maximum length	45.9 m
Maximum width	77.1 m
Maximum height	16.3 m
Wing area	892.9 m^2
Wing span	75 m
Aspect ratio	6.3
Taper ratio	0.11
c/4 sweep angle	30º
Cabin area	230.4 m^2
High density capacity	330 pas
Three class capacity	237 pas
Cargo hold volume	72 m^3
Maximum take-off weight	205200 kg
Operating empty weight	108600 kg
Maximum payload	35000 kg
Maximum fuel weight	75600 kg
Thrust to weight ratio	0.25
Wing loading	2254 Pa

A Mach number dependent parabolic drag polar is assumed in all aerodynamic and performance calculations [19,21,23]. The wingtip effect is evaluated as a multiplying term on the Oswald factor [12,24]. Additionally, the flying wing aerodynamics benefits from the very high Reynolds number and the relatively low wetted area, leading to (L/D)=23.4 in cruise, in good agreement with the values reported in other studies [10,11,13,25].

As shown in Fig. 1, vertical and horizontal tailplanes have been incorporated in the design to form a C-type layout. Both stabilizers have moderately low sizes, as corresponds to its secondary function in this configuration. The fin volume coefficient is 0.02, equal to that reported in [9] but much smaller than those of conventional airplanes [19]. The spars of the vertical tail are fitted to the wing spars. Since its torque box is much shorter in relative terms than that of the wing, the fin chord is around 40 percent larger, thus reducing the aspect ratio and structural problems. The presence of a horizontal tail is considered an important advantage, in terms of trimming and on improving stability and control. Therefore half-span horizontal stabilizers are fitted at the extreme of each vertical tail. Again a small tail volume coefficient, 0.1, is chosen for this purpose.

The engine, sized following performance requirements at Tto/Wto=0.25, is a high bypass ratio, latest technology turbofan like PW4000, RR Trent or GE90, rubberized to Tto=256 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. Just after take-off the maximum vertical speed is 19m/s (3700 ft/min). The service ceiling at 0.95 MTOW is above 45000 ft at M=0.8. The aircraft needs more than 30 minutes to climb up to an initial cruise altitude of 40000 ft, travelling some 300 km on the ground, and burning as much fuel as 0.02 MTOW.

Field performance is estimated with energy-based methods described in [19,20]. The take-off field length is as short as 1860 m without requiring high lift devices, while the landing field length is 1320 m. The maximum lift coefficient, C_{Lmax}, is 1.5 in all cases.

In this preliminary research work the best specific range performances are obtained at Mach numbers below common cruise; say between 0.7 and 0.75, too slow for a long range airliner. On considering a three step cruise at 40000, 43000 and 45000 ft, the initial range specification of 10000 km with 300 passengers is achieved. Although the profile has not been optimised [15], it is considered close to maximum performance. On the other hand, the fuel efficiency for this route is 19.8 g/pax.km; exactly the same as that reported in [9,13].

Among the flight mechanics estimations of the aircraft the stick fixed positive static margin in cruise is between 4 and 10 percent of the mean aerodynamic chord, which is assumed adequate, perhaps too high. However, at low speeds it could be necessary to use a stability augmentation system. The short period and phugoid modes have been investigated in cruise conditions: 0.85 MTOW, M=0.8, h=40000ft. For the short period, $t_{1/2}$=3.1s, T=12.8s and z=0.46, which are very acceptable values. On its side, for the phugoid, $t_{1/2}$=209s and T=106s, with z=0.056, which are again satisfactory.

In the Dutch roll, one of the main lateral-directional stability modes, the analogous figures are $t_{1/2}$=9.0s, T=5.3s and z=0.065. According to military standards, for class III aircraft, and category B flying conditions, this corresponds to level 2 [19,26], which means minor deficiencies and would also benefit from a stability augmentation system.

A comparison with conventional aircraft was carried out against the two most modern twins, of relatively similar capacity: A330-200 and B777-200.

The two conventional 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 all three perfectly fit into the 80x80 m box of ICAO Code Letter F [27].

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.

Interestingly, the loading and unloading of passengers in airport piers requires fingers positioned at about 5m above the ground for the two wide bodies, but only narrow body height of around 3m for the flying wing. On the other hand, the doors of cargo compartments are at similar height, around 2.5-3 m, in the three cases.

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. Fuel efficiency, expressed in terms of fuel burnt per passenger-kilometre [9,12] is 19.8 g/pax.km for the flying wing, and 21.5 and 23.5 g/pax.km for the A330 and B777, respectively.

The maximum transport productivity, i.e. payload times range, achieved by the C-wing is 3.07 10^6 kg.km at MPL of 35000 kg, which has not been optimised. The figure is 2.80 10^6 kg.km for A330, at PL=41370 kg and 3.16 10^6 kg.km for B777 with PL=43940 kg.

3 Emerging technologies

The precedent paragraph shows that a medium size C-type flying wing is technically feasible and operationally efficient and can beat conventional airplanes of similar capacity. Now it is time to assess the impact of emerging technologies and confirm the level of improvement, even without a complete optimisation process.

As indicated earlier, the flying wing has a fairly low wing loading in the order of 2000 Pa. That means low aircraft and section lift coefficients, with typical values of C_l= 0.25. On its turn this implies a moderate acceleration in the upper surface and, thence, a mild development of the boundary layer: although the wing chord is rather long, the counter pressure is very weak. So laminar flow control by means of boundary layer suction is easily achievable [28,29]. The selected structural arrangement of a vaulted double-skin shell is well fitted to LFC. The space between the pressurised inner cylindrical vessels and the outer skin can accommodate the required equipment for managing the boundary layer. And this occurs along the torque box as well as in the leading edge and up to the third false spar; that is almost 85 percent of the chord over around 40 percent of the wing area. The weight of such equipment and that of the structural reinforcement required by the suction drills and slots is about 2 percent of MTOW, not difficult to compensate with more intense use of composites in the wing structure.

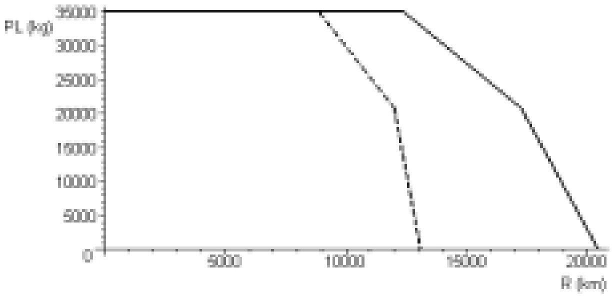

Fig. 6. Payload range diagrams corresponding to the baseline C-type flying wing (dashed line) and the improved performance laminar flow control wing.

The improvement in specific range is remarkable: around 30 percent. Moreover, since the drag decreases, the aircraft can fly higher, at more efficient altitudes, thus contributing to an additional increment in range. Figure 6 exhibits the overall gains in the payload-range diagram. For example, with a payload of 28500 kg (i.e. 300 passengers) the original C-type flying wing could fly a little more than 10000 km, while with LFC it goes up to some 14500 km in a two step cruise, at 45000 and 50000 ft. The range has been computed after allocating some extra reserve fuel to account for full failure in the LFC system at mid cruise. Otherwise, flying so high hardly increases the pressurisation loads but diminishes the gust loads and dirty deposition.

The new maximum productivity of the flying wing rises up to 4.3 10^6 kg.km, which is 41 percent higher than the baseline design. Including all fuel burnt during the flight the resulting efficiency is 14.6 g/pax.km, or 1.82 l/pax.100km, even much lower than the figure claimed as astounding for the A380 [7].

In the baseline design (see Fig. 1) the jet engines were mounted in pods over the wing near the trailing edge, with larger separation than for instance in the DC-10 or MD-11 airplanes. This location imposed some problems when trimming the aircraft, for the engine thrust produces a severe nose-down pitching moment. Also it worsens inspection and maintenance. Hence, in an attempt to compensate these drawbacks a study has been conducted to ameliorate the engine-wing integration. Figure 7 represents one of the solutions checked. The upper surface is channelled and faired to guide air into the nacelle. Needless to say this alteration in wing geometry takes only place between suitable ribs. The line of thrust is very little off-set with respect to the centre of gravity height (as shown in Fig. 7), thus cancelling out the aforementioned trimming problems.

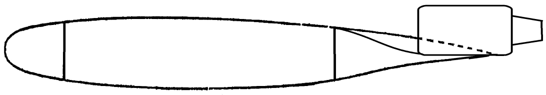

Fig. 7. Sketch of wing section and engine relative position.

But the main advantage considered here is the vectored thrust capability, VTC. This technology is already available for military engines [30]. After many years of development, current performance demonstrate 360º azimuthal nozzle manoeuvre, with deflection angles up to 0.40 rad, and rates of change in the order 2.0 rad/s. For example in take-off, using VTC for pitching control is equivalent to a deflection of about 10 degrees of flaperons along most of the trailing edge. Being close to the plane of symmetry, as indicated in Fig. 8, the engines are less useful for roll control. Thus, after take-off they can only provide an angular acceleration in roll of 0.02 rad/s^2, which is not negligible anyway.

Modern flight control systems provide active stability whenever they operate without failure [31]. In order to take full advantage of the concept, the flight control architecture must be designed with an adequate backup system. Moreover, in the case of long haul aircraft, the centre of gravity might travel substantially if no provision is taken to counteract such effect. In the flying wing under consideration, the main fuel tanks are located about mid wingspan, just outer the cargo holds, with an additional small tank below the fore part of the cabin, near the nose landing gear. Since the total volume is more than enough to carry out the mission, the cg can always be set at the appropriate location. So with the trimming and control provided by fuel, the vectored thrust and the active stability system, it is possible to eliminate the need of a horizontal tailplane, resulting in a lighter and more efficient aircraft. Fig. 8 depicts the planform which may be compared to the upper view of Fig. 1.

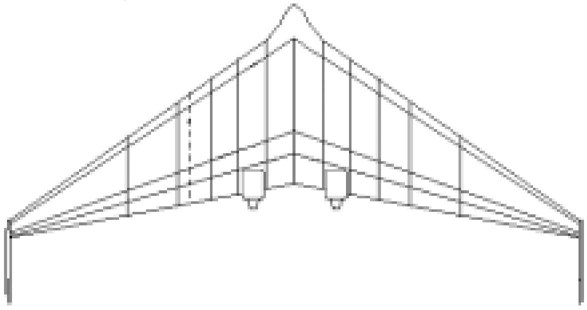

Fig. 8. New flying wing layout after incorporating laminar flow control, vectored thrust and active stability system.

The last point to be addressed in this research work is emergency evacuation. First of all it must be recalled that any aircraft have to fulfil appropriate requirements; i.e. American FAR rules [18] or its European equivalent [32]. In practical terms the key aspects are: the size and location of exits, the average distance from seat to exit in distinct scenarios, and the homogeneity of passenger flow through the various exits [33]. Since the flying wing cabin studied dispose of three type A pairs, two at the front and one at the rear, the maximum capacity can be 330 passengers. The exits located at the rear require better definition, but in principle may be used for evacuation and as servicing doors (see Fig. 9). According to the rules, only half of the exits can be used in the 90 second trials. If the front and rear exits are on either side of the plane of symmetry, which is one of the worst conditions, the average distance is about 7.1 m for the outermost leading edge door, and close to 10.3 m for the innermost, with 8.3 m in the rear one. The passenger count is 111,134 and 85, respectively. These figures are similar to those of airplanes with higher capacity, like A340-300, DC10-30 or L1011-200, which implies certain penalty for the extra wide cabin layout, but without representing any noticeable problem.

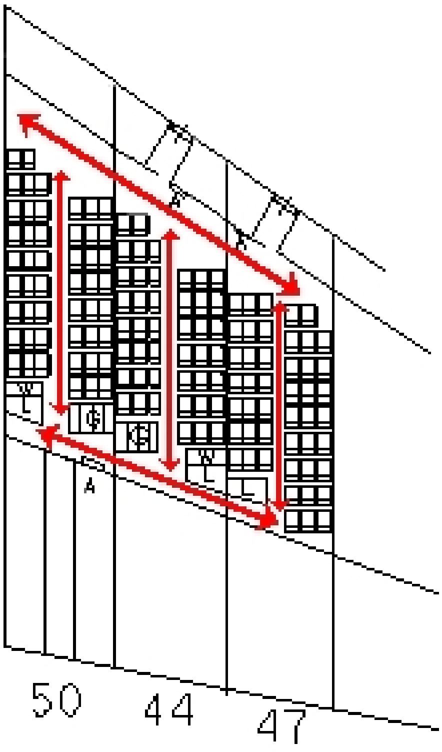

Fig. 9. Primary and secondary evacuation paths in the flying wing cabin.

Conclusions

The flying wing is one of the most promising and efficient configurations to cope with air traffic increasing demand and environmental issues, and do not pose noticeable problems. Even medium size flying wings, similar in passenger capacity to small wide bodies, exhibit an enormous improvement with respect to conventional airplanes in field and cruise performance, as well as in emissions and noise. Moreover the flying wing configuration may better exploit emerging technologies like laminar flow control, vectored thrust, active stability, etc. The main drawbacks are on the human factors side: passenger acceptance, which may be improved with imaginative interiors; slightly higher vertical accelerations in gusty weather, not actually affecting during very high altitude cruise; or a more difficult evacuation process. This last, which is abnormally absent in literature, should receive special consideration in future studies.

Acknowledgements

The authors appreciate the financial support of Universidad Politecnica de Madrid for the preparation and presentation of this paper.

On the other hand, two undergrad students, Messrs. Pedro Alfaro and Javier Pérez Martín, have actively and enthusiastically collaborated in the research work described here.

References

[1] Martínez-Val, R and Schoep, E. Flying wing versus conventional transport airplane: the 300 seat case. *Proceedings 22st ICAS Congress*, Harrogate, United Kingdom, CD-ROM, paper 113, September 2000.

[2] *Global Market Forecast 2001-2020*. Airbus, Blagnac (F), 2002.

[3] *Current Market Outlook 2003*. Boeing Commercial Airplanes, Seattle (USA), 2003.

[4] *The Outlook 2003-2022*. Rolls Royce PLC, London (UK), 2003.

[5] Anderson, JD. *The Airplane. A History of its Technology*. AIAA, Reston (VA, USA), 2002.

[6] Martínez-Val, R, Pérez, E, Muñoz, T and Cuerno, C. Design Constraints in the Payload-Range Diagram of Ultrahigh Capacity Transport Airplanes. *Journal of Aircraft*, Vol. 31, No. 6, pp. 1268-1272, 1994.

[7] Vigneron, Y. Commercial Aircraft for the 21st Century–A380 and Beyond. *AIAA/ICAS International Air & Space Symposium and Exposition*, Dayton (OH, USA), AIAA Paper 2003-2886, 2003.

[8] Strohmayer, A. and Schmitt, D. Scenario based aircraft design evaluation. *Proceedings 22st ICAS Congress*, Harrogate, United Kingdom, CD-ROM, paper 5102, September 2000.

[9] Denisov, VE, Bolsunovsky, AL, Buzoverya, NP, Gurevich, BI and Shkadov, LM. Conceptual Design for Passenger Airplane of Very Large Passenger Capacity in the Flying Wing Layout. *Proceedings 20th ICAS Congress*, Sorrento, Italy, Vol. II, pp. 1305-1311, September 1996.

[10] Denisov, VE, Bolsunovsky, AL, Buzoverya, NP and Gurevich, BI. Recent Investigations of the Very Large Passenger Blended-Wing-Body Aircraft. *Proceedings 21st ICAS Congress*, Melbourne, Australia, CD-ROM, paper 98-4.10.2, September 1998.

[11] Liebeck, RH, Page, MA and Rawdon, BK. Blended-Wing-Body Subsonic Commercial Transport. *36th Aerospace Science Meeting & Exhibit*, Reno (NV, USA), AIAA Paper 98-0438, 1998.

[12] McMasters, JH and Kroo, IM. Advanced configurations for very large transport airplanes. *Aircraft Design*, Vol. 1, No. 4, pp.217-242, 1998

[13] Bolsunovski, AL, Buzoverya, NP, Gurevich, BI, Denisov, VE, Shkadov, LM and Udzhukhu, AYu. Investigations on possible characteristics of FW superhigh seating capacity airplane. *Proceedings 22st ICAS Congress*, Harrogate, United Kingdom, CD-ROM, paper 116, September 2000.

[14] Mialon, B, Fol, T and Bonnaud, C. Aerodynamic Optimization of Subsonic Flying Wing Configurations. *20th AIAA Applied Aerodynamics Conference*, St. Louis (MO, USA), AIAA Paper 2002-2931, 2002.

[15] Isikveren, AT. Identifying Economically Optimal Flight Techniques of Transport Aircraft. *Journal of Aircraft*, Vol. 39, No. 45, pp. 528-544, 2002.

[16] Mukhopadhyay, V. Structural concept study of non-circular fuselage configuration. *AIAA/SAE World Aviation Congress*, Los Angeles (USA), Paper WAC-67, October 1996.

[17] Rodríguez, C, Martínez-Val, R and Gutiérrez, L. Structural weight estimation of a flying wing with a pressurized torque box. *Proceedings 4th International Seminar on Recent Research and Design Progress in Aeronautical Engineering and its Influence on Education*, Warsaw, Poland, Part 1, pp. 177-182, November 2000.

[18] *Part 25. Airworthiness Standards: Transport Category Airplanes*. Code of Federal Regulations. Title 14. Aeronautics and Space. Office of the General Register, Washington (USA), 1981.

[19] Torenbeek, E. *Synthesis of subsonic airplane design*. Delft University Press, Delft (NL), 1982.

[20] Roskam, J. *Airplane Design. Part I. Preliminary sizing of airplanes*. Roskam Aviation, Ottawa (KA, USA), 1985.

[21] Howe, D. *Aircraft Conceptual Design Synthesis*. Professional Engineering Publishing, London (UK), 2000.

[22] Roskam, J. *Airplane Design. Part 5. Component Weight Estimation*. Roskam Aviation, Ottawa (KA, USA), 1985.

[23] Roskam, J. *Airplane Design. Part 6. Preliminary calculation of aerodynamic, thrust and power characteristics*. Roskam Aviation, Ottawa (KA, USA), 1987.

[24] McCormick, BW. *Aerodynamics, Aeronautics and Flight Mechanics, 2nd* Ed. John Wiley & Sons, New York (USA), 1995.

[25] Liebeck, RH. Design of the Blended Wing Body Subsonic Transport. *Journal of Aircraft*, Vol. 41, No. 1, pp. 10-25, 2004.

[26] Roskam, J. *Airplane Design. Part 7. Determination of Stability, Control and Performance Characteristics: FAR and military requirements.* Roskam Aviation, Ottawa (KA, USA), 1988.

[27] *Annex 14. Part 1 Aerodromes*. International Civil Aviation Organisation, Montreal (CND), 2003.

[28] Joslin, RD. Aircraft Laminar Flow Control. *Annual Review of Fluid Mechanics*, Vol. 30, pp. 1-29, 1998.

[29] Poll, DIA. Laminar flow control for aircraft – Lessons from the past and prospects for the future. *Fluids 2000 Conference and Exhibit*, Denver (CO, USA), AIAA Paper 2000-2540, 2000.

[30] Martínez Cabeza, JA. La tobera vectorial de ITP. *Revista de Aeronáutica y Astronáutica*, No. 676, pp. 697-701, 1998.

[31] Sauvinet, F. Longitudinal active stability: key issues for future large transport aircraft. *Proceedings 22st ICAS Congress*, Harrogate, United Kingdom, CD-ROM, paper 4101, September 2000.

[32] *JAR 25. Large Aeroplanes. Joint Aviation Requirements*. Joint Aviation Authorities, Gatwick (UK), 1989.

[33] Martínez-Val, R and Hedo, JM. Analysis of Evacuation Strategies for Design and Certification of Transport Airplanes. *Journal of Aircraft*, Vol. 37, No. 3, pp. 440-447, 2000.