FLIGHT DYNAMICS OF THE FLYING WING

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Abstract

Flying wings are one of the most promising concepts for the future of commercial aviation, regarding the market, technology and environmental driving factors. The research reported here is part of a long term project on the 300 seats category flying wings. In several previously published works the feasibility, efficient performance and airport compatibility of the concept have been assessed. The present paper concentrates on the flight dynamic aspects of the aircraft, which have been scarcely analysed in open literature. The results obtained show that the flying wing configuration can be dynamically stable; however, the longitudinal and lateral-directional oscillations decay so slowly that a stability augmentation system would be required to assure an acceptable dynamic response of the aircraft.

1 Introduction

Air traffic has been increasing more or less constantly over the last decades, in spite of some severe downturns, such as those produced by the avian flue at the end of the 90s or the terrorist attack in September 2001. All forecasts predict that the pace will be even stronger for the great economic development of China, India, Brazil and other areas. The overall revenue passenger.kilometre figure will grow at a pace above 5 percent [1-3], well over the world economic growth [4, 5]. Freight traffic is expected to increase at even higher rates. All this aviation activity will require more than 25000 new jet airplanes and the conversion of a large number of ageing airliners in the next 20 years. But this tremendous demand will occur in an epoch of continued pressure to achieve significant reductions in both direct operating cost and environmental impact.

Commercial airplanes have evolved from uncomfortable converted bombers after World War I into what is currently called the conventional layout, appeared six decades ago. This ubiquitous arrangement is characterised by a slender fuselage mated to a high aspect ratio wing, with aft-mounted empennage and pod-mounted engines under the wing [6]. A variant with engines attached to the rear fuselage has also been used, mainly in business and regional jets. However, it seems that this paradigmatic configuration is approaching an asymptote around the size of A380 [7, 8].

The ever changing market and technology scenario is strongly leading to new designs and concepts: three-surface layout, joined wings, double fuselage, blended wing body, etc [9].

The flying wing appears as one of the most promising configurations in this framework. It has come under various concepts: blended-wing-body, C-wing, tail-less aircraft, etc. Its main advantage is the potential for significant fuel savings and, hence, for a much lower pollution. Since the engines can be located above the wing and the aircraft does not require complex high lift devices, this configuration results in a much quieter airplane. Consequently there is a great research activity on it, carried out by the aircraft industry, academia and research centres. In a wide range of studies at conceptual design level researchers are analysing cabin aspects, performances, airport compatibility, etc [10-14].

Several precedent papers [15-19], within a long term project, have demonstrated the technical feasibility and operational efficiency of a 300 seat flying wing in C layout. The results were greatly encouraging in terms of efficiency and productivity, as well as regarding airport compatibility. The work reported here concentrates in the flight dynamics of the flying wing, one of the less studied aspects of this novel concept.

2 CONCEPTUAL DESIGN

A full description of the conceptual design of the flying wing can be found in [18]. This section summarises the main features, required for a better understanding of the flight dynamics analysis which will be presented later.

The initial specifications correspond to a common long range mission: 10000 km with full passenger load (300 passengers or 28500 kg) at M=0.8. This mission covers many interesting routes between Europe and the USA, West US coast to Far East, etc.

Figure 1 shows an artistic view of the aircraft: straight leading and trailing edges, and a nose bullet in the apex to accommodate the cockpit with adequate visibility.

Figure 1. Artistic view of the flying wing

The overall layout belongs to the C-wing type, which exhibits the minimum induced drag among a large group of alternatives [9, 11]. To avoid airport compatibility problems it has been designed to respect the 80 meters ICAO F category wing span limit [20]. Table 1 shows the main variables of the flying wing.

Structurally, the wing has been designed as a dual entity: an unconventional inner wing with pressurised torque-box between the spars, for passenger cabins and holds; and an outer wing with fairly conventional architecture, including fuel tanks immediately outboard of the cargo holds. The two view sketch depicted in Fig. 2 helps in clarifying the former description.

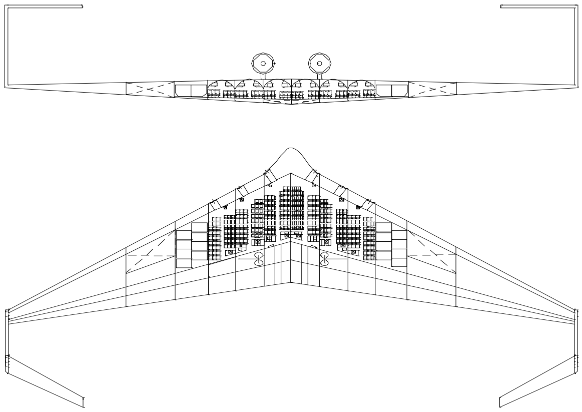

Figure 2. Two view sketch of the flying wing, showing the internal arrangement

Table 1. Main features of the flying wing

VARIABLE	VALUE
Overall length	46 m
Overall width	77 m
Wing area	893 m^2
Wing span	75 m
Aspect ratio	6.3
c/4 sweep angle	30º
Three class capacity	237 pax
Maximum take-off weight	205200 kg
Operating empty weight	108600 kg
Maximum payload	35000 kg
Thrust to weight ratio at take-off	0.25

The structural solution adopted for the inner wing is a vaulted double-skin ribbed shell layout, which exhibits lower weight and better fail-safe behaviour than a reinforced thin semi-monocoque shell [21, 22] for flying wings of this size.

Airfoil selection has been one of the key steps since airfoil characteristics are determinant for cabin arrangement, structural rigidity, performances and stability. The airfoil relative thickness is kept constant at 17 percent over all wing span and the spars run at 11 and 67 percent of the chord. The relative thickness is close to the unacceptable border [23].

The passenger cabin (see Fig. 3) is formed by a set of six parallel bays, each one similar to a narrow body fuselage segment. They are chordwise separated by wing ribs and are connected by slanted corridors in spanwise direction at the front and rear.

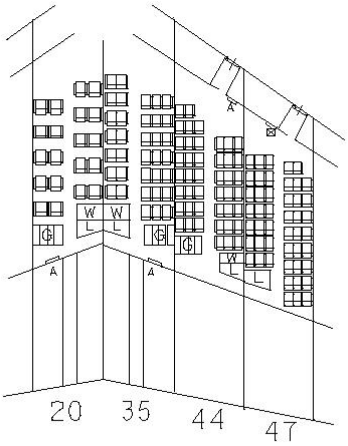

Figure 3. Cabin arrangement in three class layout. The outer bays are symmetrical

There are two main doors at the leading edge, on the port board side. The emergency exits include the aforementioned doors plus their starboard twins and a pair of symmetrical doors at the trailing edge. Galleys, toilets and wardrobes are located at the rear of the cabin for aesthetic and operational reasons. The trailing edge doors are used for cabin servicing. The maximum foreseen capacity is around 320 passengers, at 76 cm pitch, consistent with current regulations for three pairs of type A exits [24]. Three-class seating can accommodate around 240 passengers.

3 PERFORMANCES

Analogous to the former section, the detailed performances can be found in [18], but a summary is reported here.

Field performances were estimated with energy-based methods [25] empirically adjusted with data of airliners of the same seating size. The calculated take-off field length is 1860 m without requiring high lift devices, while the landing field length is 1320 m, again without high lift devices.

Climb and cruise performances were calculated as a function of weight, Mach number and altitude. The maximum vertical speed after take-off is 19 m/s (3700 ft/min). The aircraft takes near 30 minutes and around 300 km to climb up to an initial cruise altitude of 41000 ft. In this first part of the flight it burns fuel equivalent to 0.025 W_{to}. The service ceiling at 0.95 W_{to} is above 45000 ft at M=0.8. Typical lift to drag ratio in cruise is in the range 23-24, since the flying wing aerodynamics benefits also from the very high Reynolds number and the relatively low wetted area [9, 10, 13, 14, 18].

Because of its uncommon characteristics, the flying wing has to cruise at higher altitudes than conventional airliners. This is so for, on one side, the aircraft is in lift to weight balance; and, on the other side, it must fly at maximum range conditions [26, 27], these last depending on the drag polar parameters. Fulfilling both requisites leads to

$$p_{cr} = \frac{2}{\gamma} \frac{W_{cr}/S}{C_{Lcr} M_{cr}^2} = \frac{2}{\gamma} \frac{W_{cr}/S}{M_{cr}^2 \sqrt{\beta C_{D0} \pi A \varphi}} \qquad (1)$$

Where subscript *cr* stands for cruise, *p* is pressure at flying altitude, *W* is weight, *S* wing area, C_L lift coefficient, *M* Mach number, γ=1.4 in air, *A* the wing aspect ratio, φ a parameter in the drag polar that incorporates the effects of both vortex and viscous induced drag, and β a parameter related to the Mach number dependence of the specific fuel consumption [26, 28]. With ordinary Mach number, lower C_{D0} and much lower wing loading than conventional airliners, the flying wing must fly at 41000-47000 ft, to benefit from its intrinsic design features.

A three step cruise at 41000, 43000 and 45000 ft satisfies the initial range specification of 10000 km with 300 passengers (i.e. 28500 kg). The overall fuel burnt is 19.8 g/pax.km; the same value reported by other authors for larger blended-wing-body aircraft [10, 14]. This represents a 15-20 percent reduction from conventional airliners of similar size.

Laminar flow control, LFC, has been studied as a means of further improving the overall performances of the aircraft. On one side it has a low wing loading, which implies moderate acceleration over the upper surface and mild development of the boundary layer. On another side, the vaulted double-skin shell arrangement provides efficient load carrying features and enough space to accommodate LFC devices. If LFC is applied in suitable areas the parasitic drag coefficient diminishes importantly and the overall fuel burnt is reduced down to some 14.6 g/pax.km.

4 FLIGHT DYNAMICS

As indicated earlier airfoil selection has been a key point in the present research. The main objective has been to design the aircraft with suitable cruise lift coefficient (around 0.2) at near zero angle of attack, with almost zero pitching moment around the centre of gravity, while behaving with acceptable dynamic characteristics.

The airfoil relative thickness has been kept constant spanwise at 17 percent; in the cabin and cargo holds for internal height requirements; in the outer part of the wing for the need of sufficient wing depth to carry the bending and torque loads on the wing itself and the loads coming from the vertical and horizontal stabilizers.

But, for trimming purposes three different airfoils have been used: in the central part, approximately covering the passenger cabins and cargo holds, very mildly reflexed (upward rear curvature) airfoils have been used; in the outer section, slightly aft loaded airfoils have been selected; obviously there is an intermediate area of transition, around the area where the fuel tanks are located, of almost symmetric sections.

Table 2 summarizes some aerodynamic coefficients of the flying wing at low speed as well as in cruise conditions. It includes the position of the stick fixed neutral point [29-32]. These results provide a static margin of about 4-10 percent of the mean aerodynamic chord, which is considered adequate, perhaps slightly high [23, 29].

Table 2. Aerodynamic coefficients of the flying wing

M=0	M=0.83
$C_{L\alpha}$=4.37 rad-1 $C_{m\alpha}$=-1.76 rad -1 N_0=40.4% MAC	$C_{L\alpha}$=5.66 rad-1 $C_{m\alpha}$=-2.37 rad -1 N_0=41.9% MAC

The rigid body dynamic stability has been studied at 0.85 MTOW and cruise conditions, i.e. M=0.8, h=41000 ft. In the longitudinal modes, the matrix representing the dynamic behaviour [30-32] is:

$$A=\begin{bmatrix}-0.0026 & 0.0187 & 0 & -9.81\\ -0.0371 & -1.100 & 265.3 & 0\\ -0.0003 & -0.133 & -0.218 & 0\\ 0 & 0 & 1 & 0\end{bmatrix} \quad (2)$$

The corresponding eigenvalues are

$$\lambda_{1,2}=-0.0013\pm0.0355i \quad (phugoid)$$
$$\lambda_{3,4}=-0.6587\pm5.9325i \quad (short\ period) \quad (3)$$

The real and imaginary parts are used to compute the period and time to halve of both oscillations, that are presented in Table 3.

Table 3. Longitudinal dynamic stability modes

Phugoid	Short period
$t_{1/2}=\dfrac{0.69}{0.0013}=531s$	$t_{1/2}=\dfrac{0.69}{0.6597}=1.05s$
$T=\dfrac{2\pi}{0.0355}=177s$	$T=\dfrac{2\pi}{5.9325}=1.06s$

The phugoid damping ratio is [31]

$$\varsigma_p=\frac{0.0013}{\sqrt{0.0013^2+0.0355^2}}=0.0366 \quad (4)$$

Analogously, for the short period oscillation the dumping ratio is ς_s=0.1104.

These results indicate that both dynamic modes are so slowly damped that are almost unacceptable [23, 29]. Consequently this aircraft would require a stability augmentation system to assure an adequate dynamic response.

Regarding the lateral-directional modes the corresponding matrix is [30-32]

$$A = \begin{bmatrix} 0.0716 & 0.0063 & -1.0050 & 0.037 \\ 0.107 & -2.0665 & -0.0173 & 0 \\ 1.4453 & 0.1187 & -0.0997 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad (5)$$

and the eigenvalues are:

$$\lambda_{sp} = -0.00018$$
$$\lambda_r = -2.0675 \quad (6)$$
$$\lambda_{Dr} = -0.0134 \pm 1.2035\, i$$

for the spiral mode, roll subsidence and Dutch roll respectively. Table 4 shows the period and time to halve for the Dutch roll oscillation.

Table 4. Main features of the Dutch roll stability mode

Dutch roll
$t_{1/2} = \frac{0.69}{\lvert\eta\rvert} = \frac{0.69}{0.0134} = 51.5\,s$
$T = \frac{2\pi}{\omega} = \frac{2\pi}{1.2035} = 5.221\,s$

The Dutch roll damping ratio is ς_{Dr}=0.011; so the oscillation decay is too long indicating a marginally unacceptable dynamic behaviour, which would again require a stability augmentation system.

5 CONCLUSIONS

The flying wing appears as a promising configuration in the current scenario of increasing air traffic demand and rising concerns over pollution and noise generated by aircraft. A series of previous papers have shown the technical feasibility and operational efficiency of a 300 seats flying wing, which exhibits unmatched field performances and fuel savings in the order of 20 percent compared to conventional airliners.

The flying wing configuration has always been associated to insurmountable stability problems since its early days in the 30s and 40s. However the present research shows that with suitable wing airfoil spanwise arrangement this type of aircraft can be dynamically stable. Some important stability problems are still persistent since the phugoid, short period and Dutch roll modes exhibit too long decays, which implies that the airplane would require a stability augmentation system. Further research is needed to gain understanding on the involved factors and, eventually, finding ways of improving the dynamic behaviour.

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