Flying wing trailing vortices.
Reducing a technological hazard

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Abstract
The flying wing is being studied as one of the future promising concepts that could alleviate some problems of the air transportation system, for exhibiting better aerodynamics and reduction of fuel burn, pollution and noise than conventional aircraft; and for flying in unused flight levels. Hence, this configuration is receiving a great deal of attention from various perspectives: performance and control; passenger acceptance and evacuation; airport compatibility; etc. This paper addresses the problem of trailing vortices shed from the flying wing. All airplanes, in any part of the flight, produce an intense wake mainly characterized by a pair of counter-rotating vortices, originated at the wing tips. The wake thus formed is very severe, with induced velocities higher than those found in natural atmospheric turbulence, although it decays further downstream. This phenomenon obliges to maintain certain safety distances in take-off and landing maneuvers which, in its turn, imply a time-lag between subsequent operations imposing a limit on the number of movements per runway. For various reasons, in-flight encounters are rare. The present paper provides estimations of core size, induced velocities and other relevant features of the wake of the flying wing, and shows that it is far less hazardous than that of conventional aircraft of the same size.

Keywords
Vortex wake, Flying wing, Airport capacity

1. Introduction

World air traffic is growing at a remarkably high rate, even in spite of serious downturns caused by the year 2000 crisis, the terrorist attack of September 9, 2001 or the Asiatic avian influenza. Most forecast show that the overall RPK figure goes up at a pace between 4.7 and 5.1 percent (Airbus 2002, Boeing 2003) noticeably over the world economic growth. Needless to say this growth varies from region to region, with USA and Western Europe at the bottom and Asia-Pacific Rim on top, including China in a conspicous position. And air freight is expected to increase at even higher rates, also requiring a number of new airplanes as well as the conversion of ageing airliners. But this tremendous demand of around 20.000 new transport airplanes in the next 20 years will have to cope with a continued pressure to achieve significant reductions in both direct operating cost and environmental impact. On the other hand, as a mid term threat to all this aviation activity, several main hubs already exhibit congestion troubles and there are some strategic areas, like Western Europe or the Northeast US coast, with saturated airspace.

Interestingly, 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 (Anderson 2002). A variant with engines attached at the rear fuselage was also developed during the 50s and it is still broadly used in business and regional jets. However, it seems that this primary configuration is approaching an asymptote in its productivity and capacity characteristics (Martinez-Val et al 1994, Vigneron 2003). The A380 in the upper end or new wide bodies like B7E7 and A350 at an intermediate size are good examples of the steps taken currently by major manufacturers to tackle with the aforementioned growth and operational issues.

But since the market and the technology scenarios are continuously changing, the designers and researchers are also aiming at novel concepts. Within this framework one of the most promising configurations, new in the airline industry, is the flying wing in its distinct arrangements: blended-wing-body, C-wing, tail-less aircraft, etc. It may provide significant fuel savings and, hence, decrease in emissions as well as noticeable noise reduction in take-off and landing. This explains the great deal of activity carried out by the aircraft industry and numerous investigators throughout the world to perform conceptual design level studies of this aircraft layout. Most of the publicised works deal with very high capacity aircraft, close to 1000 passengers, aiming at the foreseen growth in air traffic demand between distant regions (Denisov et al 1996, Liebeck et al 1998, McMasters and Kroo 1998, Bolsunovski et al 2000, Mialon et al 2002). But the forecasts are very promising too for medium capacity airliners, indicating a demand of some 5000 new airplanes of the A330-340-350 or B7E7-777 category during the next 20 years. In fact, the average seating capacity of the new fleet is around 270. So, some studies are addressing the 300 seats class as well (Bradley 2004, Martinez-Val et al 2005).

The introduction of a new airliner paradigm requires suitable analysis of many key issues, like productivity, airport compatibility, passenger acceptance, internal architecture, emergency evacuation, etc. The present paper provides a description of one of such new aircraft, followed by a phenomenological account of the vortex wake pattern, to finally compare the main features of the flying wing wake with those of current wide body airplanes. The results show that the new paradigm exhibits important advantages in this field as well.

2. The flying wing concept

As indicated above, most papers published on the flying wing configuration deal with a specific layout called the blended-wing-body arrangement (Denisov et al 1996, Liebeck et al 1998, McMasters and Kroo 1998, Bolsunovski et al 2000, Mialon et al 2002, Bradley 2004, Liebeck 2004). Its most distinctive feature is the absence of a recognizable fuselage which is substituted by the thickening of the wing in the central part. They are very large aircraft designed to carry between 800 and 1500 passengers in routes of about 13000 km (7000 NM), with wingspan well above the new International Civil Aviation Organization (ICAO) class F limit of 80 meters, as depicted in Fig. 1. The BWB advantage results from arranging the passenger and freight cabins into two or more decks that extend spanwise providing structural and aerodynamic synergy, since the cabin is actually part of a very thick wing. The concept reduces the wetted area, meanwhile the thick central section provides efficient rigidity to withstand bending and torque moments. Several architectural arrangements have been tried to accommodate the passengers, being the separate pressure shell and the integrated skin shell the two most promising ones (Liebeck 2004). The engine installation (buried, semi-submerged, pod-mounted above or below the wing, etc) and the wing planform are still matter of discussion. In this last case because of the attempt of using that concept for the development of a complete family of aircraft with capacities ranging from 200 to 1000 passengers (Willcox and Wakayama 2003, Bradley 2004, Liebeck 2004).

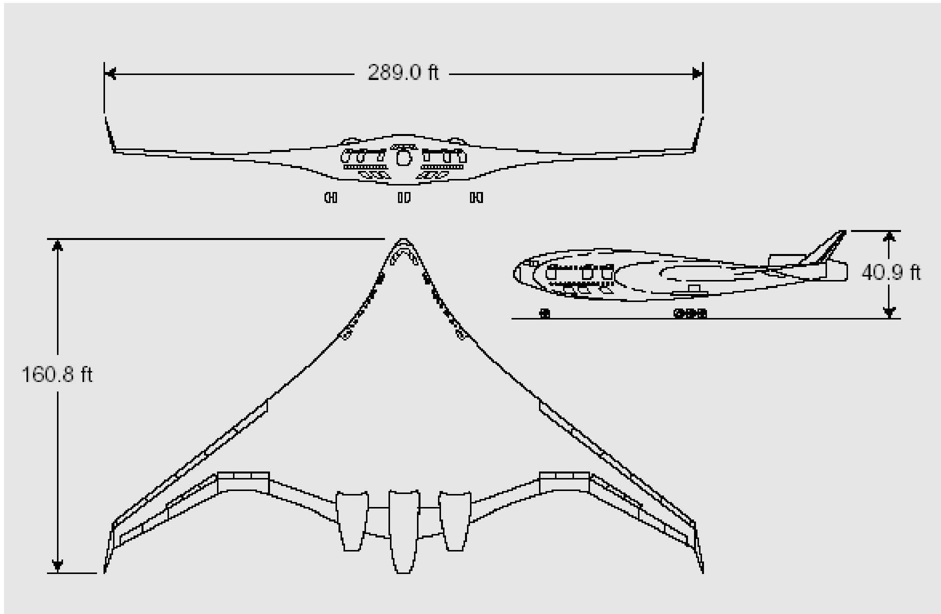

Figure 1: Three view sketch of a blended-wing-body

However, as explained before, the 300 seats class is more likely to be the first commercial flying wing in a mid term future. Accordingly the majority of the present paragraph is devoted to describe the key points of a medium size passenger flying wing. A detailed description can be found elsewhere (Martinez-Val and Schoep 2000, Martinez-Val et al 2005).

Because of the remarkable advantages in range and field performances, this flying wing is better matched to long and very long routes of 10000 km (5500 NM) or more at maximum payload. This mission range covers most interesting routes between Europe and USA, between Europe or the West US coast and the Far East, etc. The aircraft is supposed to fly at high subsonic speed (i.e. Mach numbers between 0.80 and 0.85) and flight levels between 400 and 500, thus alleviating the airspace commonly used by airliners.

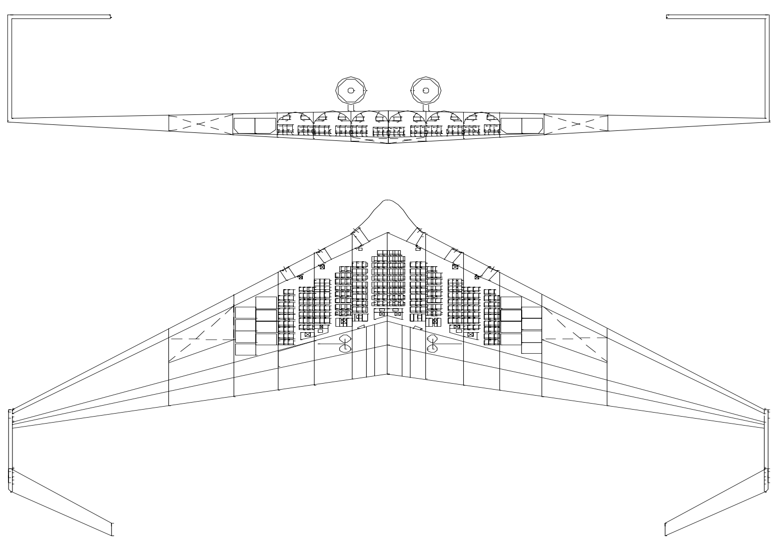

Figure 2: Two view sketch of a medium size C flying wing

The wing planform can be as simple as a trapezoidal shape with straight leading and trailing edges (or with a minimum kink), except for the presence of a nose protuberance in the apex to house the cockpit with adequate visibility. Figures 2 and 3 show two view sketches of the medium size flying wing in the C and U-wing arrangements (this last without horizontal tailplane). The wing aspect ratio, taper ratio and relative thickness have been selected following four criteria: proper aerodynamic performance; minimum take-off weight for the mission (MTOW); adequate trade-off between operating cost and productivity; and maximum area per passenger. It goes without saying that the new 80 meters wing span limit of ICAO F category is respected (ICAO 2003).

From the architectural point of view the wing itself is arranged as a dual entity: a fully unconventional inner wing with pressurized torque-box between the spars, located at 11 and 67 percent of the chord, for passenger cabins and freight holds; and an outer wing with fairly conventional semi-monocoque 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 part of the trailing edge. The engine nacelles can be mounted over the wing or semi-submerged; in both cases attached to the rear and third spars, and some main ribs.

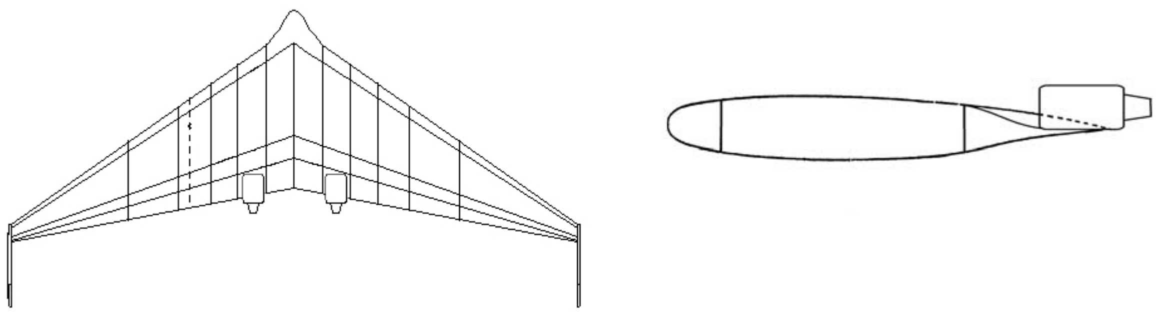

Figure 3: Planform and section sketches of a U flying wing

To offer appropriate inner space and structural rigidity without too much penalizing the aerodynamic drag or the control qualities of the aircraft, slightly aft loaded airfoils, 15 percent thick, are chosen for the outer part of the wing as well as modified reflexed shapes of 17 and 18 percent for the payload-carrying inner part. The structural solution adopted for this last one is a vaulted double-skin ribbed shell layout, which is superior to a reinforced semi-monocoque shell, for its weight saving, load diffusion and fail-safe features (Mukhopadhyay 1996, Rodriguez et al 2000). The passenger cabin is, thus, formed by a set of six parallel bays, each one with generous narrow body traverse dimensions, connected by slanted corridors in spanwise direction at the front and rear of all cabins. Except in these corridors the bays are separated by wing ribs. The minimum cabin height is 1.9 m, although most of the cabin is taller than 2.1 m. Overhead compartments are provided with around 25-30 percent more space than in A320. There are two symmetrical couples of type A doors located sidewise at the front corridor through the spar web, and another couple at the rear (see Fig. 4). 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 (FAR 1996), and goes down to some 230 seats in a three-class arrangement.

Wing loading and thrust over weight ratio are selected according to four common criteria: mid point cruise capability at 45000 ft, take-off field length below 2000 m, second segment climb angle, and approach speed below 130 knots. Suitable design points are around Wto/S=2000 Pa (i.e. between one third and one fourth of a conventional airplane) and Tto/Wto=0.25, including allowance for the remarkable thrust lapse from take-off to 45000 ft. Because of its low wing loading, unlike the blended-wing-body and other heavily loaded aircraft, these medium size concepts do not require high lift devices in take-off nor in landing. The maximum lift coefficient is estimated to be close to 1.5 in low subsonic speed.

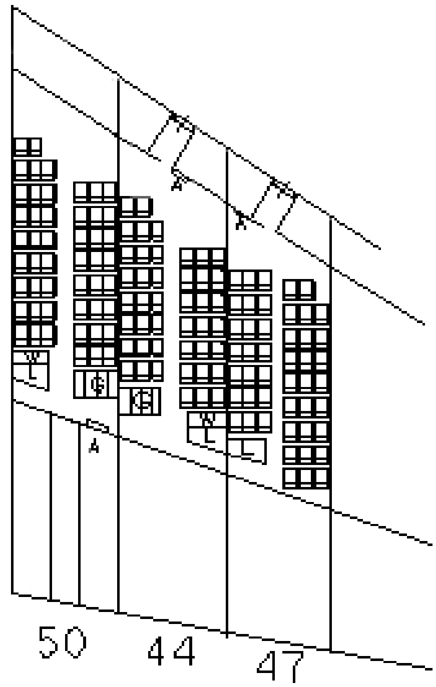

Figure 4: Internal all-tourist arrangement of the cabin with 282 seats.

Certain emerging technologies, namely laminar flow control, vectored thrust and active stability, may provide additional gains and exploit all the potential of the configuration. Thus, because of the double shell structural arrangement and of the low wing loading, with lift section coefficients in the order of 0.25, the flying wing is well matched to laminar flow control technologies. The space between the pressurized inner cylindrical vessels and the outer skin can accommodate the required equipment for suctioning and managing the boundary layer which evolves more smoothly than in conventional airplanes. And this occurs throughout the torque box as well as in the leading edge; that is almost 80 percent of the chord over around 40 percent of the wing area. The estimated weight of such equipment and that of the structural reinforcement required by the suction drills and slots is only about 1.5-2 percent of MTOW. On its turn, locating the engines aligned with the center of gravity with semi-submerged intakes and providing the nozzles with vectored thrust capability (VTC) produces a decrease in drag coefficient and an increase in total pressure recovery, and greatly enhances the control of the aircraft.

The flying wing compares rather well with conventional aircraft. In this section a few items are considered, taking as reference two modern twins of relatively similar capacity: A330-200 and B777-200. These two airplanes have almost the same length, span and height, but the flying wing is much shorter although wider in span. No major differences are found in airport terminal operations. If the rear doors of the flying wing are used for cabin cleaning, and galley and toilet servicing, passenger deplaning and boarding, 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 5 m above the ground for the two wide bodies, but only narrow body height of around 3 m 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 greater potential with unmatched take-off and landing field lengths of around 1900 and 1350 m, respectively. Fuel efficiency, expressed in terms of fuel burnt per passenger-kilometer is 19.8 g/pax.km for the C-flying wing, 21.5 and 23.5 g/pax.km for the A330 and B777, respectively, and goes down to 14.6 g/pax.km in the U layout with laminar flow control. The laminar flow control technology provides up to 35 percent range extension or, alternatively, may save 15 percent of take-off weight (Martinez-Val et al 2005).

3. The vortex wake

The lift produced by a wing results from the pressure difference in its upper and lower parts, with suction and overpressure respectively. Since the air tends to flow to the regions of lower pressure there is an inwash effect over the upper skin and an outwash in the lower one. Both sum up to the prevalent stream to produce a swirling flow at the wing tip. On the other hand, there is a discontinuity in speed at the trailing edge formed by the boundary layers shed from the upper and lower parts of the wing. These shear layers have a high degree of vorticity, essentially aligned in spanwise direction. The swirling effect at the wing tip entrains the shear layers which roll up very quickly. All the vorticity existing in the flow is then concentrated in a horse-shoe arrangement which goes downstream up to infinity (Rossow 1999). As a matter of fact there is also a starting vortex line, counter-rotating with respect to the vorticity in the upper skin, that has already disappeared due to viscosity and other effects. Figure 5 presents a sketch of the process.

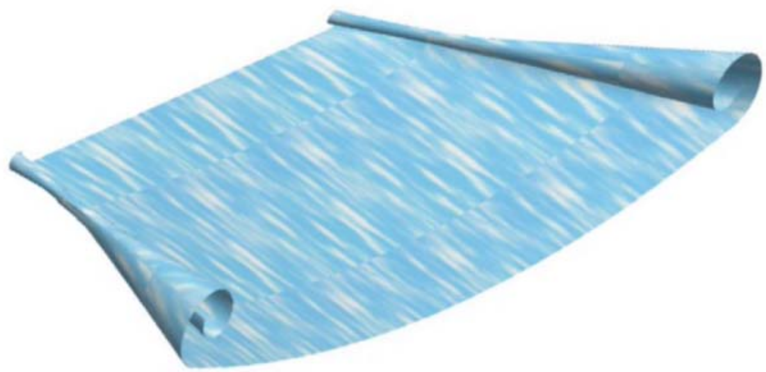

Figure 5: Sketch of the vortex roll-up process in the near wake of a wing.

The wake of the airplane greatly varies downstream, with three different regions according to the dominant phenomena (Rossow 1999, Gerz et al 2002). In the near field, which extends up to some 6-7 wingspans (Darracq et al 2001), the flow physics may be well explained with potential theory; paradoxically, since all the interesting flow regions (boundary layers, shear layers, or wing tip swirls) are fully viscous. The wing tip flow experiences an upwash movement, meanwhile the trailing shear layers descend smoothly. As shown in Fig. 5 the vorticity is distributed over trailing edge and the wing tips vortex filaments, but the powerful entrainment produced by these last results in the concentration of all vorticity in the wing tip vortex tubes, leaving an inviscid trailing wake after a very short distance (McCormick 1994). When the airplane is in a low speed configuration, i.e. when it has deployed its high lift system, the vortex wake is much more complicated, for each flap outer end acts like a wing tip swirl and generates its own vortex. Thus, an airplane in take-off or landing configuration has a multi pair vortex system. Nevertheless all vortices in the same side of the airplane coalesce and form a single, greater core, again only a few spans downstream.

Further downstream, between 7 and 13 wingspans, the vortical system is fully developed. Irrespectively of the airplane configuration the strength of the final vortex core, i.e. its circulation, depends on the weight, wingspan and speed of the airplane. The flow arrangement holds this pattern for long distances.

From the aviation operation viewpoint the most interesting region lies beyond 40 wingspans, i.e. several miles behind the airplane, for this is the ordinary separation between subsequent aircraft using the same path. And this is so precisely because of the safety issues associated to the wake as will be shown later. In the far field (40-200 wingspans) the vortex cores, which have already grown up and diffused, may become unstable (Crow 1970). A few different patterns can be formed: diffused turbulence after breakdown, strings of isolated rings, etc. When this entangled flow pattern appears, the wake is not any more dangerous to other airplanes. But in the absence of natural perturbations, the horse-shoe arrangement may subsist enormous distances.

Wake turbulence is a very serious issue that affect safety, but it also affects the capacity of the air traffic system for its influence in the number of runway operations. The problems with wake vortices were first considered matter for concern after the advent of the B747 in the early 70s. Pilots of small and medium size aircraft flying behind B747 reported suddenly strong turbulence that even caused some air accidents. To avoid such wake vortex encounters aviation authorities have established safe time and distance separations for runways and airways. Table 1 contains aircraft separation in the terminal area when flying in low speed configuration (Rossow 1999, Gerz et al 2002). These standard separations are currently a matter for debate since, on one side, relaxing the figures might alleviate the congestion in some busy airports and, on another side, new wing designs and new configurations of aircraft might result in a quicker decay of the horse-shoe flow pattern.

Table 1: ICAO aircraft separation to avoid vortex encounters.
Note: for all other combinations the minimum radar separation of 3 NM (79 sec) applies.

Leader aircraft (Max. take-off weight)	Follower aircraft	Separation (nautical miles)	Time delay (s) (app. speed 70 m/s)
Heavy (>136000 kg)	Heavy	4	106
Heavy	Medium	5	132
Heavy	Light	6	159
Medium (<136000 kg) (>7000 kg)	Light	5	132

As indicated before, the roll-up and vorticity concentration phases in the near field can be well described by potential theory. Several models have been developed to determine the main features of the vortex cores thus formed: mainly tangential speed, size and circulation; both in the viscous core as in the potential outer region (Corjon and Poinsot 1996, Rossow 1999, Gerz et al 2002). Table 2 gathers some of these models and Figs. 6 and 7 depict the induced velocity and circulation profiles associated to the various models. The Rankine theory was widely accepted over decades, but overestimates the induced speed. Some refinements elaborated by Lamb, Hallock-Burnham and other researchers seem to be closer to reality. For its physical meaning, simplicity and reliable results, the Hallock-Burnham model will be the base for all computations in the next paragraph. On another side, the present work does not include any influence of the real atmosphere, like wind or natural turbulence (Greene 1986, Sarpkaya 2000).

4. The wake of the flying wing

To better understand the features of the wake of the flying wing, the values corresponding to a very large capacity BWB are compared to those of A340-300 and B747-400, two well known wide bodies, commonly used for very long routes. The A340-300 is currently the second largest member of the Airbus family. It is a four engine airplane that may carry around 250 passengers plus additional payload up to distances of some 13000 km (7000 NM). Its main geometrical variables are: wingspan of 60.5 m and overall length equal to 63.7 m. On its side, the B747-400 is also a four engine aircraft, designed to carry more than 400 passengers at distances of about 12000 km (6600 NM), with a wingspan of 64.4 m and a total length of 70.7 m. As stated earlier the BWB would be a three engine aircraft which could carry around 800 passengers in the same type of routes, being much wider (88.1 m of wingspan) and shorter (49.0 m) than the conventional airplanes used for comparison.

Table 2: Vortex-induced speed by various vortex models.

Rankine	$v_{\theta r} = \left(\frac{\Gamma_0}{2\pi}\right)\frac{r}{r_c^2}$ $\Gamma_r = \left(\Gamma_0\right)\frac{r^2}{r_c^2}$ $r \le r_c$ $v_{\theta r} = \frac{\Gamma_0}{2\pi r}$ $\Gamma_r = \Gamma_0$ $r > r_c$
Lamb-Oseen	$v_{\theta r} = \left(\frac{\Gamma_0}{2\pi r}\right)\left[1 - e^{-1,2526\left(\frac{r}{r_c}\right)^2}\right]$ $\Gamma_r = \Gamma_0\left[1 - e^{-1,2526\left(\frac{r}{r_c}\right)^2}\right]$ Valid for all r
Hallock-Burnham	$v_{\theta r} = \left(\frac{\Gamma_0}{2\pi}\right)\frac{r}{r^2 + r_c^2}$ $\Gamma_r = \left(\Gamma_0\right)\frac{r^2}{r^2 + r_c^2}$ Valid for all r
Hoffman-Joubert	$v_{\theta r} = v_{\theta c}\left(\frac{r}{r_c}\right)$ $\Gamma_r = \Gamma_c\left(\frac{r}{r_c}\right)^2$ $r \le r_c$ $v_{\theta r} = v_{\theta c}\left(\frac{1 + ln\left(\frac{r}{r_c}\right)}{\frac{r}{r_c}}\right)$ $\Gamma_r = \Gamma_c\left(1 + ln\left(\frac{r}{r_c}\right)\right)$ $r > r_c$

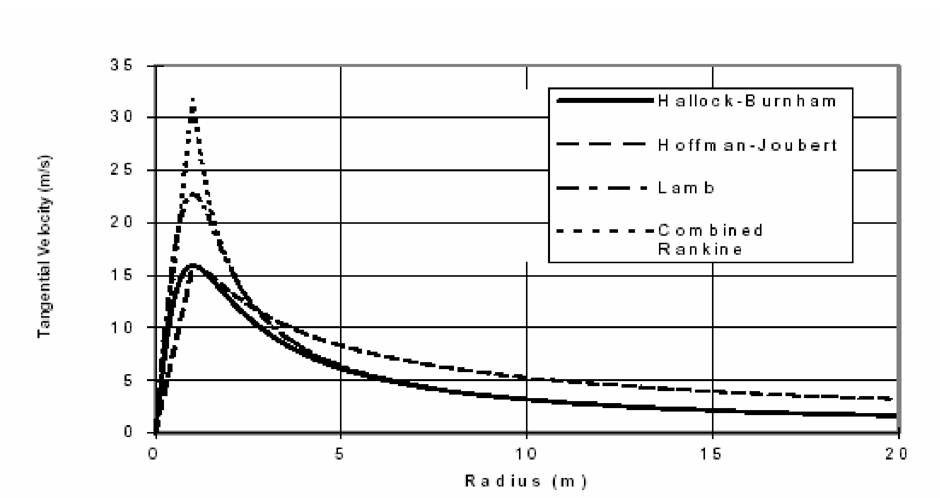

Figure 6: Tangential velocity profiles provided for various models (Hinton and Tatnall 1997).

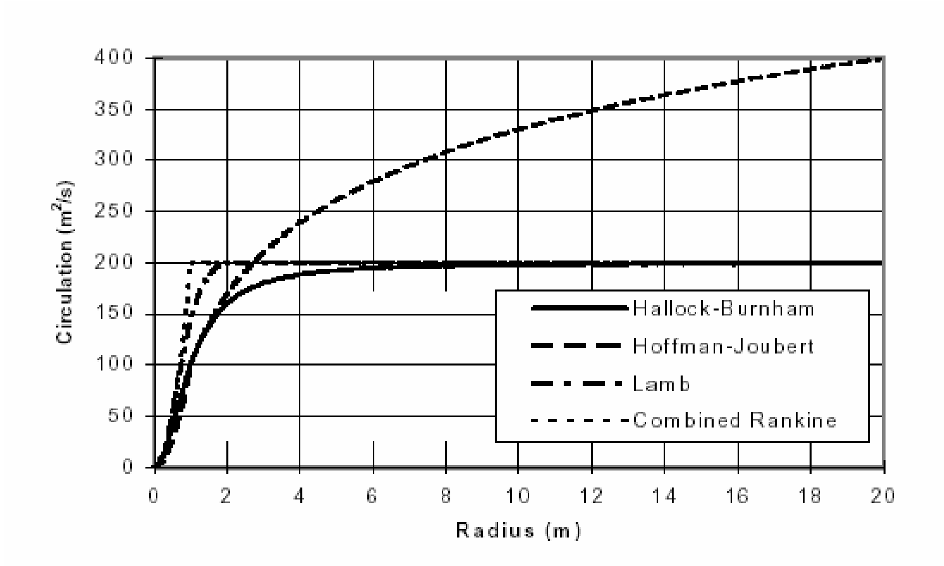

Figure 7: Circulation profiles provided for various models (Hinton and Tatnall 1997).

Table 3 summarizes the main features of the three aircraft and the main parameters of their wakes. Clearly the B747 produces the highest circulation in take-off, cruise or landing. It exhibits the minimum time scale as well, which implies that its wake is the oldest for having evolved appreciably more than those of A340 or BWB. From the fluid physics point of view the non-dimensional time is the most appropriate to make comparisons (Gerz et al 2002), although from flight mechanics or operational perspective it is the downstream distance what matters. Conversely, the BWB shows a less active and younger wake.

Table 3: Wake parameters of A340-300, B747-400 and BWB

Parameter	Unit	Take-off			Cruise			Landing		
		A340	B747	BWB	A340	B747	BWB	A340	B747	BWB
M	[kg]	257000	396900	373310	187500	273000	273000	187500	273000	273000
B	[m]	60,3	64,4	85,2	60,3	64,4	85,2	60,3	64,4	85,2
V	[m/s]	82,3	80,8	91,0	246,0	255,0	251,0	75,0	80,0	74,0
A		9,260	7,000	10,000	9,260	7,000	10,000	9,260	7,000	10,000
C_L		1,594	1,692	1,023	0,383	0,344	0,289	1,400	1,187	1,132
P	[kg/m^3]	1,189	1,189	1,189	0,404	0,404	0,404	1,189	1,189	1,189
$s = \pi/4$		0,785	0,785	0,785	0,785	0,785	0,785	0,785	0,785	0,785
$b_0 = s\,b$	[m]	47,4	50,6	66,9	47,4	50,6	66,9	47,4	50,6	66,9
$\Gamma_0 = Mg / (\rho V s b)$	[m^2/s]	543,7	800,8	505,3	390,2	513,2	393,9	435,3	556,3	454,4
$t_0 = 2\pi s^2 b^2 / \Gamma_0$	s	25,92	20,07	55,74	36,12	31,32	71,49	32,38	28,89	61,98
$w_0 = \Gamma_0 / 2\pi b_0$	[m/s]	1,8	2,5	1,2	1,3	1,6	0,9	1,5	1,8	1,1
$v^* = V / w_0$		45,0	32,1	75,8	187,6	157,9	268,0	51,3	45,7	68,5

The radius of the core, where the maximum velocity is reached, computed according to Eq. 1 is depicted in Fig. 8 in terms of the downstream distance for the three flight conditions analyzed.

$$r_c = 0.0125\sqrt{\Gamma_0\, t} \tag{1}$$

It is interesting to note that the vortex tubes are narrower in cruise than in take-off or landing. No great differences exist among the three aircraft, but the B747's cores are always larger.

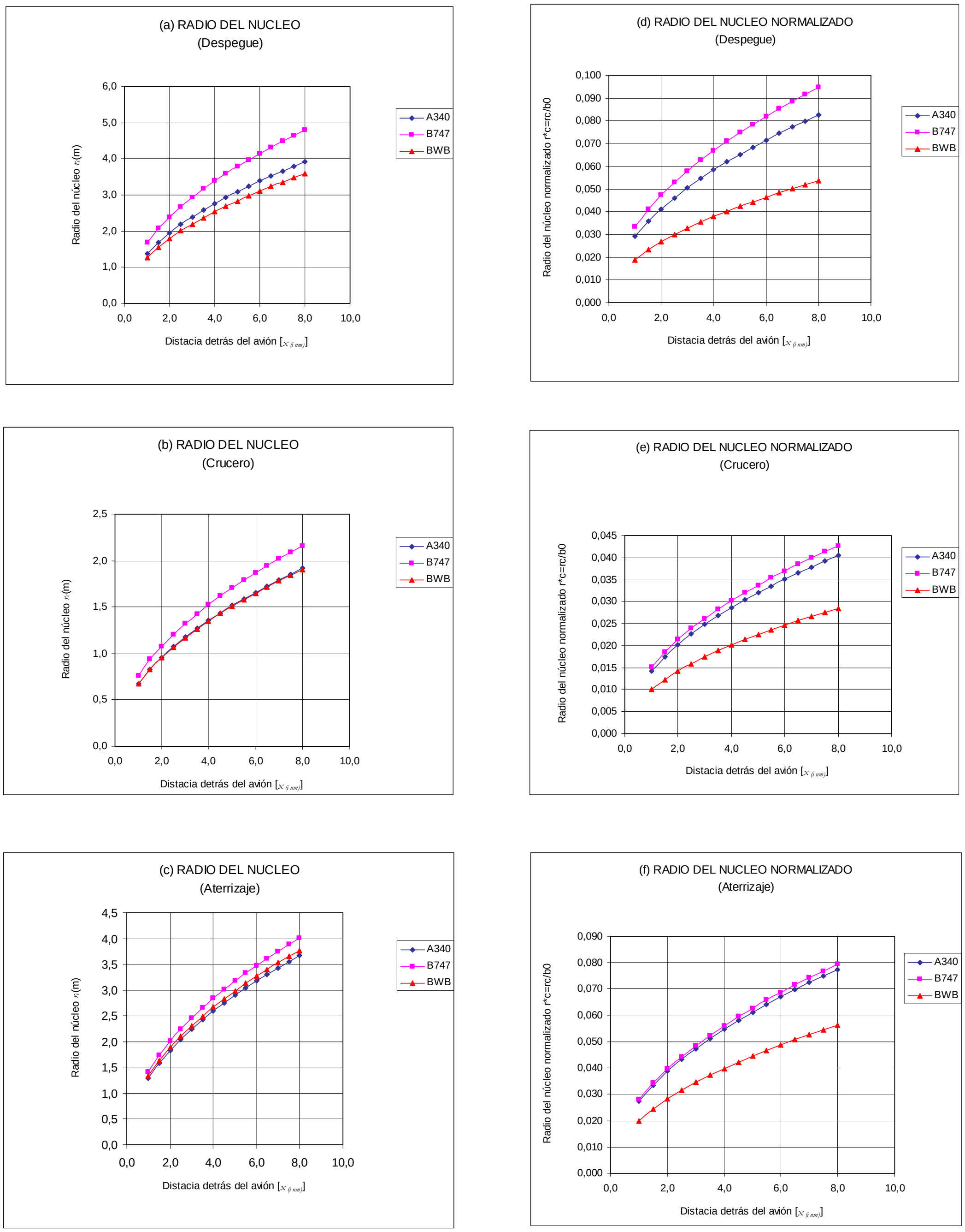

Figure 8: Actual and normalized radius of the vortex core.

On the other hand, following the Hallock-Burnham model, the maximum tangential velocity is achieved at the radius of the vortex core already computed (see Eq. 1) through the following expression:

$$v_{\theta c} = \frac{\Gamma_0}{4\pi r_c} \tag{2}$$

The results of Eq. (2) are represented in Fig. 9. By far, the cruise wake is the most powerful one. However, since airplane to airplane separation is rather large in the same airway, wake encounters are seldom reported. If the wind takes the wake up or down to other flight levels, the proper wind introduces instabilities that destroy the wake. But in take-off and landing the induced velocities are still very important, above 15 m/s (50 ft/s), even several miles behind the aircraft. The danger is very clear, but the interesting result is that the giant BWB generates similar swirling perturbation than the A340, an airplane with much smaller capacity.

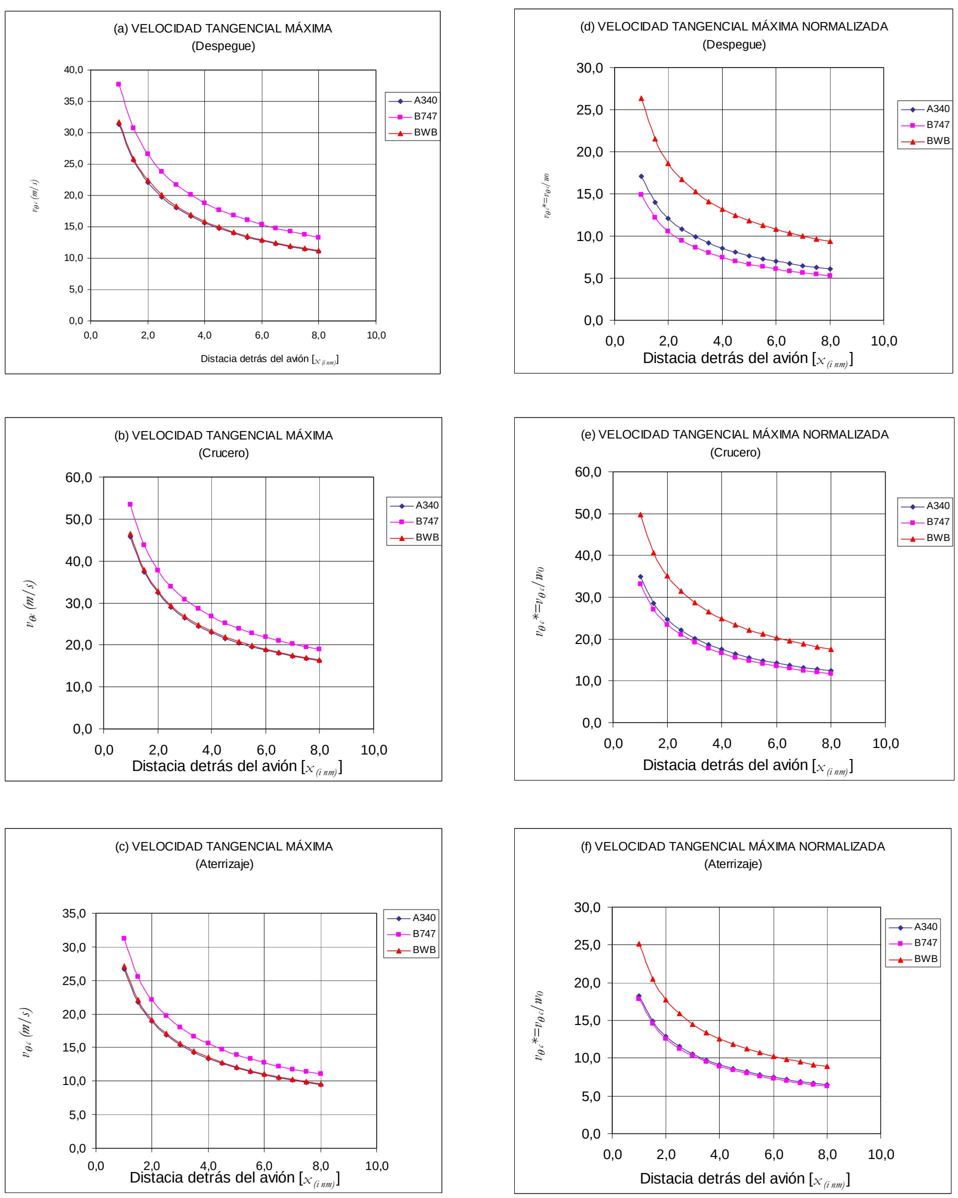

Figure 9: Actual and normalized maximum velocities in the wake vortex.

Conclusions

The main conclusions of the present work are as follows:

1. The flying wing is one of the most promising new aircraft concepts for the future of the air transportation system;
2. The flying wing offers better field and range performances than conventional aircraft and can better exploit the benefits of emerging technologies;
3. The flying wing do not pose major airport or airspace operational problems provided it fits within the largest ICAO size limits;
4. The wake produced by the flying wing is very moderate in terms of induced velocity or other parameters. As a matter of fact it is comparable to the wake of conventional aircraft of much smaller size;
5. The entry into service of the flying wing as well as other novel airplane concepts, or other novel wing configurations, may largely reduce the hazards associated to wing tip vortices.

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