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Wake of Transport Flying Wings

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Flying wings are among the most promising concepts regarding the ever-increasing air traffic demand. They could help in improving economic efficiency and would be environmentally friendly, both in terms of emissions and noise. This paper addresses the problem of trailing vortices shed from the flying wing, arranged as a pair of counter-rotating vortex tubes as in conventional aircraft. The turbulence produced by the wake obliges airports to maintain certain time and distance separation between aircraft in takeoff and landing maneuvers, imposing a limit on the number of movements per runway. With the help of a simple model, the present paper provides preliminary estimations of circulation, core size, induced velocities, and other relevant features of the wake of transport flying wings and shows that it is less hazardous than that of conventional aircraft of similar size.

I. Introduction

FOR the last 50 years, commercial aviation has mainly been based on what is currently called the conventional layout aircraft, characterized by a slender fuselage mated with a high aspect ratio wing, with aft-tail planes and pod-mounted engines under the wing [1]. During the 1950s, a variant with engines attached to the rear fuselage was also developed and is still widely used in business and regional jets. However, it seems that this conventional configuration is approaching an asymptote in terms of its productivity and performance characteristics [2,3]. For this reason, designers and researchers are now considering novel concepts.

One of the most promising configurations is the flying wing in its different arrangements: blended wing body (BWB), C wing, tailless aircraft, etc. It is not a fully novel concept, because it was considered by Horten, Northrop, and others [4,5] from the mid 1930s to the mid 1950s. The flying wing's principal advantage comes from arranging the passenger and freight cabins in one or more decks that extend spanwise, providing structural, aerodynamic, and payload synergy [6–9]. Nevertheless, this layout is hard to engineer. This configuration also has the potential to provide significant fuel saving and, hence, some decrease in emissions. Furthermore, it would also have the benefit of noticeable noise reduction during takeoff and landing.

The introduction of a new aircraft paradigm must be backed up by suitable analysis, albeit of an approximate nature, of the key issues such as productivity, airport compatibility, passenger acceptance, etc. The present paper concentrates on preliminary estimations of the vortex wake characteristics: circulation, vortex core size, and induced velocities; all of them affect aircraft separation in takeoff and approach.

II. Vortex Wake

The wake of the airplane varies downstream, with three different regions according to the dominant phenomena [10,11]. In the near field, which extends up to some six–seven wingspans, the vorticity concentrates in a horseshoe vortex arrangement, aligned in the flight-path direction. Further downstream, between 7 and 15 wingspans, the vortex system is fully developed. From the aviation operation viewpoint, the most interesting region lies beyond 40 wingspans [i.e., several kilometers (or miles) behind the airplane], for this is the ordinary separation between subsequent aircraft using the same path. The persistence of the aforementioned flow pattern depends on the level of natural or induced perturbations, but it may subsist very long distances downstream. The strength of the vortex core (i.e., its circulation) depends on the weight, airspeed, air density, and effective wingspan (which depends on the circulation distribution and the physical wingspan).

Wake turbulence is a very serious issue that may affect safety as well as the capacity of the air traffic system, because of its influence on the number of runway operations [10–12]. To avoid wake vortex encounters, aviation authorities have established safe time and distance separations for runways and airways. Table 1 contains aircraft separation distances in the terminal area for aircraft in low-speed configuration [13]. These standard separations are currently a matter for debate, because relaxing the figures might alleviate the congestion in some busy airports, and new wing designs and new aircraft configurations might result in a quicker decay of the horseshoe flow pattern [12,14].

Several models have been proposed to determine the main features of the vortex wake [10,12,15]. For its physical relevance and simple and reliable results, the Hallock–Burnham model [15] will be used for all computations in the present work. According to this model, the circulation Γ varies, as indicated in Eq. (1).

$$\Gamma = \Gamma_0 \frac{r^2}{r^2 + r_c^2} \tag{1}$$

where Γ_0 and r_c are the initial circulation and core radius of the vortex tube, respectively, and r is the radial distance to the center of the tube. The effect of downstream distance x is implicit through r_c, which enlarges by diffusion, after the passage of the aircraft at speed V, following Eq. (2).

$$r_c = 0.0125\sqrt{\Gamma_0 x / V} \tag{2}$$

The initial circulation of the aircraft wake Γ_0 is computed in terms of the airplane weight W (equal to lift), its wingspan b, and the air density ρ, under the hypothesis of an elliptic spanwise lift distribution, as shown in Eq. (3) [11].

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Table 1 ICAO aircraft separation in approach to avoid vortex encounters

Leader aircraft (max takeoff weight)	Follower aircraft	Separation, n mile	Time delay, s (app. speed 70 m/s)
Heavy (greater than 136,000 kg)	Heavy	4	106
Heavy	Medium	5	132
Heavy	Light	6	159
Medium (less than 136,000 kg, greater than 7000 kg))	Light	2	132

[a]For all other combinations, the minimum radar separation of 3 n mile (79 s) applies.

Table 2 Aircraft and wake parameters of A330-200, B777-200, and flying wing FW300

		Takeoff			Cruise			Approach	
Variable	A330	B777	FW300	A330	B777	FW300	A330	B777	FW300
M, kg	230,000	263,080	185,100	205,010	231,330	161,000	181,980	213,190	160,000
b, m	60.3	60.9	77.0	60.3	60.9	77.0	60.3	60.9	77.0
V, m/s	82.3	88.4	55.8	242	248	236	72.6	71.1	51.9
A	10	8.7	6.3	10	8.7	6.3	10	8.7	6.3
Γ_0, m^2/s	458.9	508.1	422.6	449.1	514.2	419.1	411.6	512.0	392.7

$$\Gamma_0 = \frac{4W}{\pi\rho V b} \tag{3}$$

The tangential velocity induced by the vortex tube v_θ can then be expressed as

$$v_\theta = \left(\frac{\Gamma_0}{2\pi}\right)\frac{r}{r^2 + r_c^2} \tag{4}$$

Equations (1) and (4) are a refinement of the classical Rankine theory [16], from which the discontinuity at r_c has been eliminated. The maximum induced velocity occurs exactly at r_c.

On the other side, some real atmosphere factors (such as wind, natural turbulence, or ground effect [17–19]) have not been taken into account in this formulation.

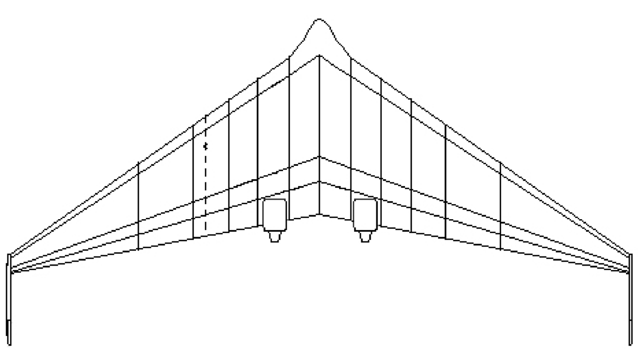

Fig. 1 Planform sketch of flying wing FW300.

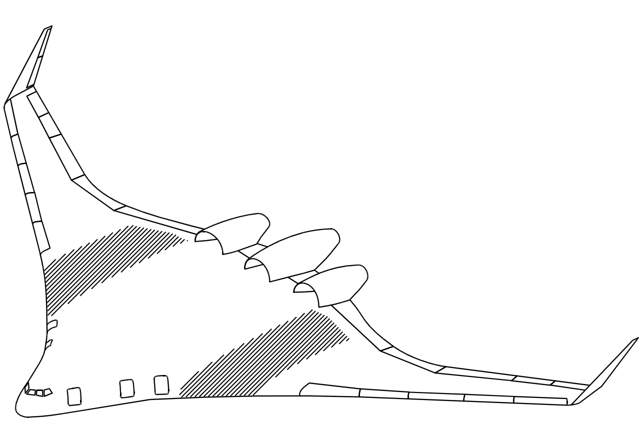

Fig. 2 Perspective sketch of an ultra-high-capacity blended-wing-body aircraft.

III. Wake of the Flying Wings

To better understand the wake characteristics of transport flying wings, the results of the current work are presented in the form of two comparisons. First, a medium-sized flying wing of the 300-seat class, FW300 [9], depicted in Fig. 1, is compared with the A330-200 and the B777-200. Second, a comparison is performed between a BWB in the 800-seat class (see Fig. 2) [8] and two large widebodies: the A380-800 and the B747-400.

Tables 2 and 3 summarize the main features of these aircraft and the main parameters of their wakes at takeoff, cruise, and approach. In these tables, M is the mass, b is the wingspan, V is the velocity, A is the aspect ratio, and Γ_0 is the initial circulation.

The presence of winglets on the A330 and A380 and vertical fins on the FW300 and BWB affect the formation of the wake. Following the literature, these devices produce a reduction of some 20–25% in induced drag due to two effects [20]: a forward force on the vertical element and a modification of the spanwise circulation distribution, mainly near the wingtip. In the first-order estimation of the present work, and to be on the conservative side, both effects are considered to be of similar strength. This is equivalent to enlarging the wingspan by a factor within the range 1.04–1.06, depending on the size and geometry of the device.

Table 2 shows that the FW300 produces the smallest circulation for the three flight conditions considered: some 5–10% lower than the A330 and 20–25% lower than the B777. The largest differences are observed for the approach phase.

The maximum tangential velocity is determined from Eqs. (2) and (4) as

$$v_{\theta\,\max} = \frac{\Gamma_0}{4\pi r_c} = \frac{20}{\pi}\sqrt{V\Gamma_0/x} \tag{5}$$

The results obtained for these medium-sized aircraft are represented in Fig. 3. As a direct effect of speed, the cruise wake is very strong. At 8 n mile downstream of the leading aircraft, the maximum induced velocity is still larger than 15 m/s (50 ft/s) for all three aircraft. However, because in real air traffic conditions, airplane-to-airplane separation is much larger in the same airway and wind and instabilities weaken the vortex, severe wake encounters are seldom reported [10,11]. The differences among the three airplanes are always within 10%, which means that the influence of the configuration in cruise conditions is relatively negligible.

In takeoff and approach maneuvers, the induced velocities provided by the model are significant, even several miles behind the aircraft, implying a real danger to following aircraft. The FW300 generates the least intense wake, about 20% less intense than the B777 in approach and some 25% in takeoff. The B777 produces a maximum induced velocity of 12.6 m/s at a separation of 5 n mile (i.e., for a narrow-body follower aircraft), compared with only 9.4 m/s in the case of the FW300. In takeoff, the corresponding

Table 3 Aircraft and wake parameters of A380-800, B747-400, and BWB

Variable	Takeoff			Cruise			Approach		
	A380	B747	BWB	A380	B747	BWB	A380	B747	BWB
M, kg	560,000	396,900	373,300	460,500	320,200	317,900	361,000	285,800	273,000
b, m	79.8	64.4	85.2	79.8	64.4	85.2	79.8	64.4	85.2
V, m/s	97.6	97.3	91.0	246.0	251.0	251.0	76.2	80.0	74.0
A	7.5	7.7	7.0	7.5	7.7	7.0	7.5	7.7	7.0
Γ_0, m^2/s	712.0	633.3	472.4	762.4	639.4	573.2	587.9	554.6	424.8

figures at 6 n mile are 12.8 m/s for the B777 and 9.3 m/s for the FW300.

These results show that the flying wing [which, for its weight, belongs to the heavy aircraft category ($W > 136,000$ kg)] could be considered within the medium-weight category in terms of airport operations (i.e., time and distance separation). To this end, a further comparison has been carried out against the A320-200 and the B757-200. The corresponding airplane and wake features for these two aircraft are presented in Table 4. Again, an equivalent larger wingspan ($b = 35.5$ m, that is, a factor of 1.04) has been used in computing the wake of the A320 to account for the winglets effect.

The wake of the FW300 exhibits greater intensity than that of the smaller aircraft. The difference is, however, only around 15% compared with the B757 in takeoff or cruise and less than 10% difference on approach. For the A320, which is a much smaller airplane, the difference increases up to 50% in cruise. The vortex

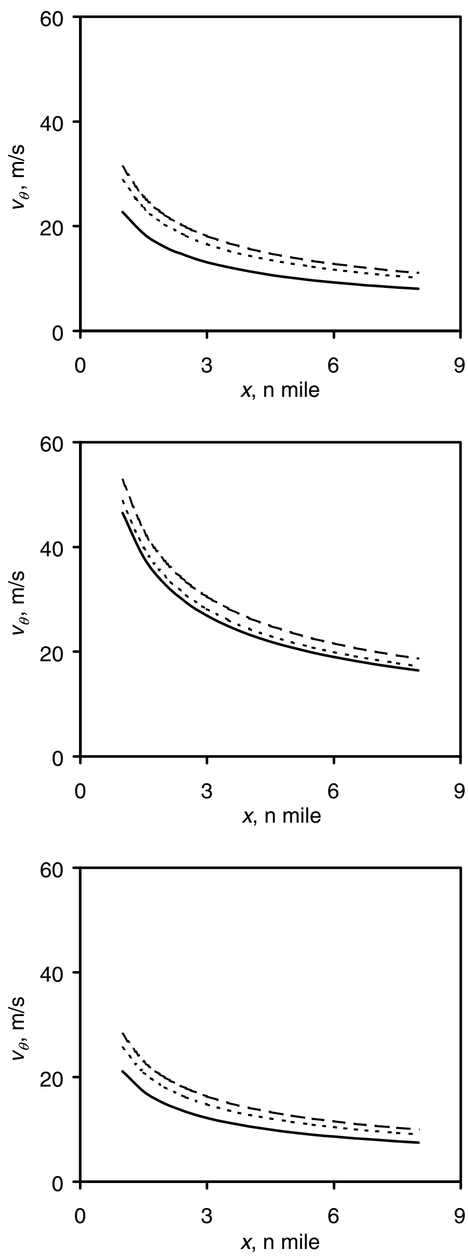

Fig. 3 Evolution of maximum induced velocity with downstream distance for the A330 (dotted line), B777 (dashed line), and FW300 (solid line); takeoff (top), cruise (center), and approach (bottom).

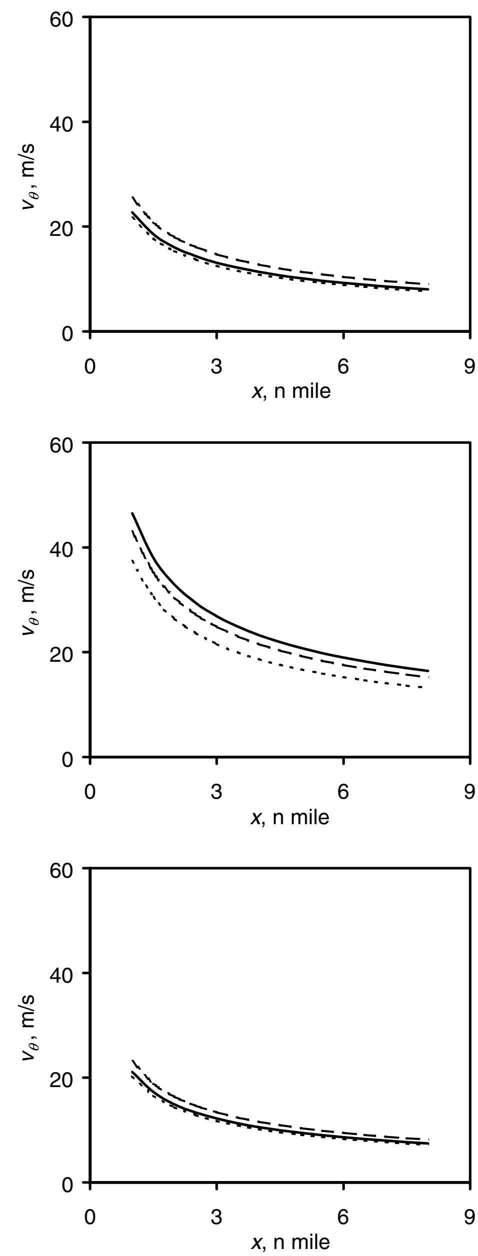

Fig. 4 Evolution of maximum induced velocity with downstream distance for the A320 (dotted line), B757 (dashed line) and FW300 (solid line); takeoff (top), cruise (center), and approach (bottom).

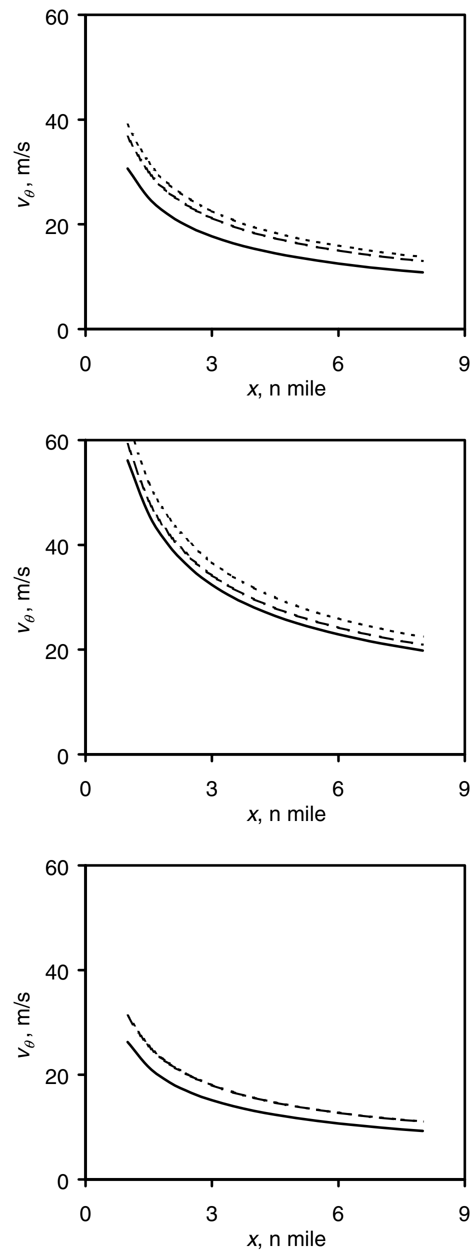

Fig. 5 Evolution of maximum induced velocity with downstream distance for the A380 (dotted line), B747 (dashed line) and BWB (solid line); takeoff (top), cruise (center), and approach (bottom). The A380 and B747 are hardly distinguishable in approach.

cores of the A320 and the B757, although thinner, are of the same order of magnitude in radius as those of the larger aircraft.

The maximum induced velocities in the wake are shown in Fig. 4 for the A320, the B757, and the FW300. Interestingly, the FW300 induces lower tangential velocities than the B757 (a rather smaller airplane, except in cruise), which is a condition of minor importance from the safety perspective, as indicated earlier. As a matter of fact, the wakes of the FW300 and the A320 are extremely similar in terms of induced velocities. This result strongly supports the hypothesis that the wake of a flying wing would be far less harmful than that of airplanes with analogous missions and would compare rather well with much smaller aircraft.

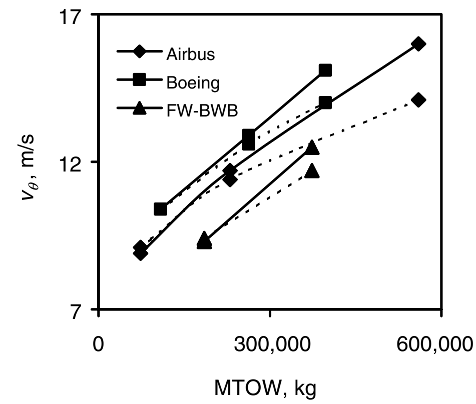

Fig. 6 Maximum induced velocity as a function of maximum takeoff weight (MTOW) at a separation distance of 6 n mile in takeoff (solid lines) and 5 n mile in approach (dashed lines) for the Airbus, Boeing, and flying wings analyzed.

With the aim of confirming this finding, the same procedure has been applied to an 800-seat class blended wing body [8] of the type shown in Fig. 2. In this case, the comparison is performed against the A380 and the B747-400. Consistently with the former cases, the wingspans have been modified with the following factors: 1.04 for the A380 and the B747; 1.06 for the BWB.

As expected, the wake circulation gets larger with aircraft size. Figure 5 depicts the wake intensity in terms of induced velocity as it evolves downstream. The two conventional aircraft behave rather similarly, although the A380 wake is slightly more intense, in accordance with a recent joint survey [21]. The values provided by the model for the BWB wake are around 15–20% lower than those of the aforementioned widebodies.

To get a comprehensive idea of the size and configuration effects on the wake at low speed, Fig. 6 shows the maximum induced velocity behind all the aircraft analyzed in this study, at a separation distance of 6 n mile in takeoff and 5 n mile in approach. These values are in accordance with International Civil Aviation Organization (ICAO) standards and take into account that takeoff speeds are larger than approach speeds in all cases, as shown in Tables 2–4.

The results indicate that size effects are more important in takeoff than in approach. On the other hand, the wake in approach is commonly less intense than in the other flight conditions, except for the smaller airplanes, whereas the takeoff and approach wakes have similar characteristics. There is a consistent shift of some 5–7% in induced velocities between Airbus and Boeing airplanes. This is due to differences in design philosophies that translate into differences of wing loading and, remarkably, of aspect ratio. The flying wing configuration exhibits a decrease of about 10–15% with respect to Airbus aircraft and of some 15–20% on Boeing aircraft over the studied size range.

Conclusions

From an operational point of view, the wake produced by a flying wing aircraft would be very moderate in terms of induced velocity.

Table 4 Aircraft and wake parameters of A320-200 and B757-200

	Takeoff		Cruise		Approach	
Variable	A320	B757	A320	B757	A320	B757
M, kg	73,500	108,800	67,500	96,200	64,500	89,800
b, m	33.8	38.1	33.8	38.1	33.8	38.1
V, m/s	74.0	80.0	236	242	66.8	67.0
A	9.5	8.0	9.5	8.0	9.5	8.0
Γ_0, m^2/s	290.9	371.3	270.5	350.3	282.8	365.8

Preliminary estimations show that the maximum induced velocities are noticeably smaller than those produced by conventional airplanes of similar capacity and are comparable to much smaller aircraft. This could imply, in a future scenario, some alleviation of runway congestion problems and a consistent increase in the flow of passenger traffic. These conclusions add new arguments in favor of the flying wing, one of the most promising configurations being studied as a means to address increasing air traffic demand and related environmental issues.

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