WakeNet — the European Thematic Network on Wake Vortex

Aircraft Wake Vortices

– A position paper –

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6. April 2001

Summary

This position paper discusses the problem of aircraft wake vortices. It presents a consolidated view of research and industry partners in WakeNet* on the current status of knowledge on the nature and characteristics of aircraft wakes and on technical and operational procedures of minimizing and predicting the vortex strength and avoiding wake encounters.

Methodological aspects of data evaluation and interpretation, like the description of wake ages, the characterization of wake vortices, and the proper evaluation of wake data from measurement and simulation, are addressed in the first part. In the second part an inventory of our knowledge is given on vortex characterization and control, prediction and monitoring of vortex decay, vortex detection and warning, vortex encounter models, and wake vortex safety assessment. Each section is concluded by a list of questions and required actions which may help to guide further research activities.

The primary objective of the joint international efforts in wake vortex research is to avoid potentially hazardous wake encounters for aircaft. Shortened aircraft separations (even for very large transport aircraft) under most meteorological conditions, whilst keeping or even increasing the safety level, is the ultimate goal. Reduced time delays on the tactical side and increased airport capacities on the strategic side will be the benefits of these ambitious ventures for the air transportation industry.

Keywords

Aircraft wake, data evaluation harmonization and interpretation, characterization and control, prediction and monitoring, detection and warning, encounter and safety assessment.

* WakeNet – the European Thematic Network on Wake Vortex – joins partners from research and industry to collocate the wide spread efforts and to stimulate and guide ongoing and future work in *RD&T* for aircraft wake vortices. The WakeNet is active from May 1998 to April 2001 and is financed by the European Union. Members are EADS Airbus Germany (former DASA-Airbus, coordinator), NLR The Netherlends (coordinator deputy), AUK Great Britain (former BAE-Systems-Airbus), CERFACS France, DERA Great Britain, DLR Germany, EADS Airbus France (former Aerospatiale-Matra-Airbus), IFALPA Great Britain, LBA Germany, NATS Great Britain, ONERA France, and Thomson-CSF Sextant France.

Other members, although with limited involvement, include representatives of airlines, airports and ATM authorities.

Activities and news in WakeNet may be found on http://www.cerfacs.fr/˜ wakenet.

Contents

1 Introduction

The purpose of this paper is to summarize the todays knowledge on aircraft wake vortices and to present a consolidation of views of European research, aircraft manufacturers and air transportation industry and services.

It is believed that all parties will benefit from such an effort of describing the state of the art in characterization and control, prediction and monitoring, detection and warning, and encounter and safety assessment of wake vortices.

The idea for this paper came from the 2nd WakeNet Workshop held from 11. to 12. October 1999 in Oberpfaffenhofen, Germany, which focused on "Prediction of far field vortex location and decay". Since then, much input came from various partners, especially after the 3rd Workshop held from 22. to 23. May 2000 in Malvern, Great Britain, on "Measurement techniques for vortex wakes", and the 4th Workshop held from 16. to 17. October 2000 in Amsterdam, The Netherlands, on "Wake vortex encounter".

1.1 Motivation

Wake turbulence is one of the main reasons for capacity problems in the air–transport industry. The lift force exerted on aircraft wings produces vortices with long life–times in their wake. Especially during an aircraft's critical landing phase these can endanger any aircraft following close behind. Serious problems with wake vortices were first recognized back in the 1970s when the Boeing 747 came into service. Pilots of smaller aircraft who followed the much heavier B 747 in to landing reported suddenly strong turbulence that even caused some aircraft to crash.

To avoid such wake vortex encounters, follower aircraft must maintain a safe distance from a landing aircraft up ahead of them. Consequently, the Federal Aviation Administration (FAA) of the USA and the International Civil Aviation Organization (ICAO) devided aircraft into three weight classes and established safe separations in the terminal area for each combination of these classes, see Table 1. The separations are based on the maximum take-off weights of leader and follower aircraft and must be observed when the airport operates under Instrumented Flight Rules (IFR). When Visual Flight Rules (VFR) apply, the separations may be relaxed on the pilot's request.

These standard separations limit the capacity of many airports already today. In view of the strong growth of air traffic, increasing demands on the capacity and safety of international airports have to be faced. In the context of airport operation the following points can be made today:

- Current separation minima are effective — no accidents world–wide for aircraft operating under IFR. All reported wake–turbulence related accidents have happened under VFR.
- Nevertheless, vortex encounters occur in daily practise (e.g., about 80 per year on average at London–Heathrow International Airport).
- The current separation standards are largely empirical and lack full rationale.
- Evidence is enhanced that the current standards are over protective or indeed not fully adequate.
- Airport capacity is ultimately limited by the separation standards.

Table 1: ICAO aircraft separation distances to avoid wake vortex encounter.

Leader aircraft (max. take-off weight)	Follower aircraft	Separation [nautical miles]	Time delay [sec] (approach speed 70 m/s)
Heavy (≥ 136.000 kg)	Heavy	4	106
Heavy	Medium	5	132
Heavy	Light	6	159
Medium (< 136.000 kg) (> 7.000 kg)	Light	5	132

For all other combinations, the minimum radar separation of 3 NM (79 sec) or 2.5 NM (66 sec) applies.

In order to increase airport capacities whilst at least maintaining safety levels, the knowledge of wake vortex behaviour under varying meteorological conditions achieves considerable significance. Moreover, the possibility that constructive measures for vortex control at the wings and flaps of aircraft may alleviate the strength of the shed vortices and result in their quicker decay is of utmost importance, especially when designing new very large aircraft like the Airbus 380.

A number of studies of airport operation have been conducted for various scenarios including the extreme limit of no restrictions dictated by wake vortex separation. In this situation capacity gains of order 10-20% have been suggested; clearly such gains are not realistic, but nevertheless increased knowledge could lead to two types of improvement which may be classified as *tactical* or *strategic*.

- On the *tactical* side we expect considerable scope for local hour–by–hour Airtraffic Control (ATC) decisions to reduce separations based on meteorological and wake–vortex monitoring information. Potentially large fuel savings and reduction of delays, particularly for aircraft in holding patterns, should be attainable.
- On the *strategic* side a scheduled increase in arrival/departure slots seems feasible. Increased knowledge of vortex decay and environmental interaction could lead to small capacity gains from refined separation standards. Even a few slots per day at a busy airport would be of great value.

In all phases of research and development, the needs of the “customer” have to be considered. The past shows that it is a waste of time to develop the “final solution” before envisaging a feasible and operational implementation. Small applicable answers which build on each other are easier to develop and implement and they will steadily increase experience and confidence. The customer is a group of users, including aircraft manufacturers, ATC providers, airport service providers, airlines, and pilots. They sometimes have conflicting interests. Therefore, it is essential for the research institutions to involve all of them at a well defined but early stage and to keep them in the loop throughout the *RD&T* projects.

1.2 Definition and properties of wake vortices

Wake vortices shed by an aircraft are a natural consequence of its lift.

The wake flow behind an aircraft can be described by near field and far field characteristics. Just behind the trailing edge of the wing a strong downward motion (the “downwash”) prevails whereas the regions beyond both wing tips experience a weaker upward motion (the “upwash”). In the near field small vortices emerge from that vortex sheet at the wing tips and at the edges of the landing flaps. The governing physical processes are boundary–layer separation, roll-up of the vortex sheet, merging of co-rotating vortices, initiation of vortex instabilities, etc. These processes define the aircraft–induced characteristics of the wake for its development in the far field. Figure 1 exemplifies the early wake evolution behind an Airbus 340 model in high–lift configuration up to 6.4 spans.

After roll-up the wake generally consists of two coherent counter-rotating swirling flows, like horizontal tornadoes, of about equal strength: the aircraft wake vortices. Each vortex possesses a strong circulation, which is proportional to the weight of the aircraft, and a significant size in the order of half the wing span.

The far field is defined as the region where the impact of the atmosphere on the wake vortices becomes dominant, culminating in trajectory and structural changes and circulation decay. Under favourable atmospheric conditions, cooperative instabilities such as the long–wave Crow instability lead to reconnection and subsequent vortex decay. Properly disturbed counter-rotating vortices in a four–vortex system may also develop cooperative instabilities at shorter wavelength which trigger the transition to turbulent and less coherent primary vortices.

In the past three decades the endeavour to investigate the wake flow behind an aircraft has culminated in a better understanding of the physics of wake vortices and, quite naturally, also put forth a serious of new questions and problems.

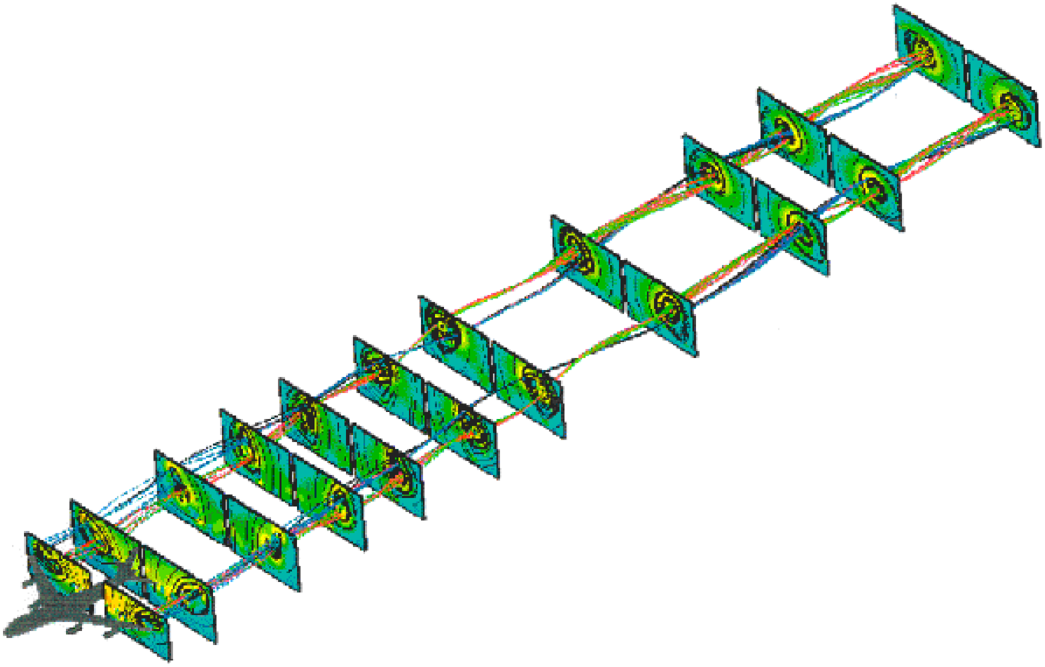

Figure 1: Wake roll-up from 0 to 6.4 spans behind an A340 high–lift model with lift coefficient of 1.76 in DNW wind tunnel; courtesy by K.&K. Hünecke, EADS-Airbus Germany.

1.3 Outline of problems

One question at issue is the appropriate definition of a quantity which can be used to characterize the potential hazard of a vortex and, at the same time, can be computed robustly enough from measured and simulated data. This requires a harmonization of data from all kind of sources like different models, aircraft, facilities and simulation efforts. The basis for a useful comparison of different investigations is a non-ambiguous measure for the respective vortex age. The circulation of a vortex may be assessed as one pertinent parameter which expresses the amount of vortex hazard. The decay in vortex circulation may be gradual but can also be accelerated by instabilities or catastrophic demise events such as vortex bursting or linking.

Another related question is how to best describe the decay process of wake vortices using such harmonized and properly normalized data. For instance, field measurements of vortices with ground-based lidar and laboratory measurements using particle-image velocimetry (PIV) showed a strong capability of such non–intrusive techniques. However, they also revealed that much effort must be put on the evaluation strategy of the data in order to yield robust results which may then allow not only to characterize reliably the wake vortex decay in the atmosphere but also to differentiate the evolutions of constructively modified wakes.

Recent research results pointed out that different strategies exist to produce and control less harmful wakes by wing–constructive means. These strategies, called the “low vorticity vortex approach” and the “quickly decaying vortex approach”, are based on different aspects of the evolution of the vortex circulation and, at a first glance, seem to exclude each other. In terms of technical implementation and control, they bear different levels of risk but they also bear different chances to effectively reduce vortex strength and hazard. Several facts indicate that in some aspects both approaches may be complementary rather than exclusive.

Solutions for new aircraft staggering procedures are sought which relax the current separations but do not lower todays safety levels. It is hoped that wake vortex warning systems will contribute to such a solution. For setting up a wake vortex warning system for an airport different approaches are discussed. One is to predict the decay and transport of wake vortices from individual aircraft or aircraft classes along the glide path and to stagger approaching aircraft according to the forecast. This requires a validated wake vortex transport and decay model together with high resolution meteorological input data. Aside from technical and financial issues, vertical profiles of wind, turbulent kinetic energy, and temperature are difficult to measure with high resolution in an operational environment where simplicity and robustness are important. The other approach is to establish weather dependent "wake vortex behaviour classes" which provoke a certain and known wake vortex evolution. Instead of predicting the development of the wake vortices, such a warning system would then predict or diagnose the wake vortex behaviour class, possibly resulting in simple, nevertheless useful, statements like "Rapid vortex decay and/or transport out of the glide path corridor for the next 20 min" or "Long living and/or stalling/rising vortices for the next 20 min".

However, neither is the safety level of the current standards properly known, nor do we have tools at hand to support and assess new developments in operational usage at busy airports. Therefore, a proposed wake vortex safety assessment model is introduced which evaluates the wake vortex hazard for aircraft under various operational and weather conditions in a probabilistic framework.

It is common practise among airlines to decrease separation on final approach when the predecessor can be seen by the pilot of the follower aircraft. The fact that severe vortex encounters occur so rarely justifies most of the reductions. On the other hand, most of the known wake–vortex encounter incidents have happened under such VFR conditions. Hence, it is obvious that reliable and on-time information in the cockpit on the existence and position of wake vortices in a safety corridor around the glide path would be very valuable. It is of secondary importance if the information stems from ground-based or airborne systems; in any case, it increases acceptance by pilots, replaces the human eye under IFR, and also gives more reliable vortex information under VFR. Recent ground-based tests demonstrated the capability of vortex detection by a Doppler-lidar system which has the capability to become an airborne system in the future.

Since encounters occur in daily practise and, probably, will never be avoided completely, wake vortex research needs to quantify the related risks. Accepted definitions of a hazard imposed by a vortex on an encountering aircraft, however, are still lacking. The difficulties in finding vortex hazard definitions partly result from the fact that the rating of an encounter as hazardous or harmless heavily depends on the height above ground of the encountering aircraft and also on the individual experience of the pilot. For evaluating the potential risk for an aircraft flying in or through wake vortices it is necessary to have a model that predicts the aerodynamic forces and moments induced by a wake disturbance flow field of given strength. With the upset aerodynamic forces and moments known, it is possible to assess the aircraft movements during a wake encounter and the related safety aspects, e.g. in a flight simulator. Aerodynamic models for wake encounter are also needed for parametric studies and in probabilistic wake encounter studies for assessing the main factors for safety.

The International Federation of Air Line Pilots' Associations (IFALPA) demands vortex *avoidance* as the target for any new reduced–aircraft–separation system. This pilot's point of view must be borne in mind when searching for technical solutions of the wake vortex issue.

1.4 Organization of the paper

The paper is devided into two major parts. Sections 2, 3, and 4 comprise the *methodological aspects* of data evaluation and interpretation, namely the description of wake ages (Section 2), the characterization of wake vortices (Section 3), and the correct set-up of field experiments and the evaluation of wake data from measurement and simulation (Section 4). Sections 5 through 9 collect the *state-of-knowledge* in the fields of vortex minimization (Section 5), prediction and monitoring of vortex decay (Section 6), vortex detection and warning (Section 7), vortex encounter modeling (Section 8), and wake vortex safety assessment (Section 9). Section 10 concludes the inventory.

2 How to describe the age of wake vortices

The evolution of the wake behind an aircraft is often described versus its distance x to the aircraft, normalized by the aircraft span B. Here we recommend, instead, to use the non-dimensional time, $t^* = t/t_0$ to characterize the evolution of a wake. The reference time t_0, as defined below, is better suited than a length scale, since it allows to compare various flight stages (cruise, landing, take-off), experimental approaches (wind tunnel, water tank, catapult facilities, or flight), and CFD simulations.

Table 2 lists the respective parameters and their definitions. The initial vortex spacing b_0 (after roll-up) always scales with the wing span B, where the parameter s is the spanwise load factor and depends on the local circulation $\Gamma(y)$,

$$s = \frac{2}{B}\int_0^{B/2} \frac{\Gamma(y)}{\Gamma_0}\, dy =: \frac{\overline{\Gamma}}{\Gamma_0}. \qquad (1)$$

From measurements it is straight forward to obtain b_0 when one vortex pair is present after roll-up. When more than one vortex behind each wing is considered, the reference length b_0 can be computed from the separation of the vortex centroïds (see Section 4). Alternatively, one can compute s and, thus, b_0 when the local circulation or the spanwise wing load

$$\Gamma(y) = 0.5 c_L(y)\, c(y)\, V \qquad (2)$$

is known. Often it is found that s is very close to $\pi/4$, the value for elliptically loaded wings, even if the wing is not elliptically loaded. However, for some investigations with, e.g., simplified wing geometries or high–lift configurated wings, s may deviate from $\pi/4$.

2.1 Reference time scale

The time scale t_0 describes the time in which the vortex pair, shed by the aircraft or aircraft model, propagates the distance of one initial vortex spacing downward. From the definitions in Table 2 we conclude that this time scale is given by

$$t_0 = 2\pi\,\frac{b_0^2}{\Gamma_0} = 2\pi\, s^2\, \frac{B^2}{\Gamma_0}. \qquad (3)$$

Table 2: Aircraft and wake parameters and their definition.

Mass of aircraft	M		[kg]
Wing span	B		[m]
Aircraft speed, free stream velocity in wind tunnel	V		[m/s]
Local chord	$c(y)$		[m]
Lift coefficient (local)	$c_L(y)$		[-]
Lift coefficient (global)	C_L		[-]
Wing aspect ratio	A_R		[-]
Gravitational acceleration	g		[m/s^2]
Air density	ρ		[kg/m^3]
Root circulation	Γ_0		[m^2/s]
Mean circulation	$\overline{\Gamma}$		[m^2/s]
Vortex core radius (maximum tangential velocity)	r_c		[m]
Reference length, initial vortex spacing	b_0	$= sB$	[m]
Reference velocity, descent speed of vortex pair	w_0	$= \Gamma_0/(2\pi\, b_0)$	[m/s]
Reference time	t_0	$= b_0/w_0$	[s]
Distance behind aircraft	x		[m]
Time after fly-by	t		[s]
Normalized length, usually used	x^*	$= x/B$	[-]
Normalized time, recommended	t^*	$= t/t_0$	[-]
Normalized velocity	v^*	$= V/w_0$	[-]

Since the equation includes vortex spacing (wing span) *and* circulation, this time comprises two major parameters of a given experimental or numerical set-up.

An airplane with velocity V, lift coefficient C_L, wing aspect ratio A_R and span B has a lift which is equal to the flux of vertical momentum of its rolled-up wake,

$$\frac{\rho C_L}{2 A_R} B^2 V^2 = \rho V b_0 \Gamma_0. \tag{4}$$

Hence, Γ_0 can be expressed in terms of aircraft flight parameters,

$$\Gamma_0 = \frac{C_L V B}{2s\, A_R}. \tag{5}$$

When the forces which act on the aircraft are in balance (as for really flying aircraft but, e.g., not in wind tunnels where the models are held by a strut), the aircraft lift and the flux of wake vertical momentum are also equal to the weight of the aircraft $M\, g$, and Γ_0 can then be obtained by

$$\Gamma_0 = \frac{M\, g}{\rho s B V}. \tag{6}$$

The "root circulation" Γ_0 represents the half-plane circulation of the far wake for a given real aircraft including fuselage, horizontal tail and so forth. With eqs. 3 and 5 the reference time scale now reads

$$t_0 = 4\pi s^3\, A_R\, \frac{B}{C_L\, V}. \tag{7}$$

With this equation it becomes evident that the scaling parameter s of the initial vortex spacing has a large influence on t_0.

2.2 Normalized time, length, and velocity

From eq. 7 and Table 2, we see that the reference velocity w_0 and the normalized velocity v^* of an experiment can be expressed by

$$w_0 = \frac{b_0}{t_0} = \frac{s\,B}{t_0} = \frac{C_L\, V}{4\pi s^2\, A_R} \tag{8}$$

and

$$v^* = V/w_0 = 4\pi s^2\, \frac{A_R}{C_L}. \tag{9}$$

In order to establish a relationship between time and distance, we finally assume constant flight or wind speed such that $t = x/V$. This converts into an equation for the normalized time t^* as

$$t^* := \frac{x}{V\, t_0} = \frac{x^*}{s\, v^*} = x^*\, \frac{C_L}{4\pi s^3\, A_R}, \tag{10}$$

making use of definitions in Table 2 and eq. 9.

Eq. 10 shows that the often used non-dimensional length $x^* = x/B$ only scales with the normalized age t^* if $C_L/(s^3 A_R)$ is constant. In other words, to determine the age of a vortex system, x^* can be used non-ambiguously between different experiments (especially in different facilities with different models) *only* when v^* is constant. For describing the age of aircraft wakes, we therefore recommend to use t^* instead of x^*. The use of t^* becomes prerequisite when data from different aircaft (and aircraft models) at different flight stages (cruise, landing, take-off) with different flight characteristics shall be compared.

2.3 Examples

Now we use flight parameters of an A340 and a B747 to exemplarily compare the resultant wake ages in terms of t^* and x^* in Table 3. For this comparison we set $s = \pi/4$ explicitly.

The reference time t_0 differs by a factor of 18 between the A340 model and the real A340 aircraft. However, at the same spanwise distances both wakes have the same ages t^* since C_L and A_R are kept the same. Comparing now the A340 with the B747, the smaller A340 has a larger normalized distance x^*. In landing configuration the A340 has a 22% lower circulation and a 12% higher reference time than the B747. Accordingly, the wake of the A340 is 4 to 5% younger in terms of t_0 at fixed distances of 2.5, 3, or 6 nautical miles. The Table finally shows that cruising aircraft have much younger wakes at fixed distances than landing aircraft due to their smaller lift coefficient.

Note that we used an elliptical scaling for vortex separation, $s = \pi/4$, for all examples. A reduction of s, i.e. a smaller vortex spacing than for elliptically loaded wings, would increase Γ_0 only linearly (eq. 5) but would decrease t_0 with s^3 (eq. 7). This is possibly a favourable effect since many data (e.g., Robins & Delisi 1999, Holzäpfel et al. 2001a) suggest that the wake circulation has decayed to 20 to 40% of its initial strength between 4 and 6 t_0, regardless of the value of t_0 (at least for civil transport aircraft). Thus, a smaller t_0 would automatically infer a higher age and, hence, a weaker vortex, at fixed distances. This hypothesis needs further proof in forthcoming measurement campaigns.

Table 3: Parameter and reference time for A340-300 and B747-400 aircraft with $s = \pi/4$. For the full scale aircraft, eq. 6 with max. landing weights and an air density of 0.35 kg/m^3 (1.2 kg/m^3) at cruise (airport) height has been used. For the A340 model, the separation is scaled by the span of the model, so x/B is constant for the A340 and the A340 model.

			A340 model	A340 landing	B747 cruise	B747 landing
	M	kg	–	187500	273000	273000
	B	m	2.0	60.3	64.4	64.4
	V	m/s	60.	75.	240.	80.
	A_R		9.26	9.26	7.	7.
	C_L		1.386	1.386	0.448	1.178
	Γ_0	m^2/s	11.4	431.	630.	552.
	t_0	s	1.36	32.7	25.4	29.1
	v^*	–	51.8	51.8	121.1	46.1
2.5 nm	x^*	–	77	77	72	72
=4630m	t^*	–	1.9	1.9	0.76	2.0
3 nm	x^*	–	92	92	86	86
=5556m	t^*	–	2.3	2.3	0.91	2.4
6 nm =	x^*	–	184	184	172	172
11112m	t^*	–	4.6	4.6	1.8	4.8

2.4 Maximum accessible wake ages in some facilities

In the light of forthcoming investigations in the EU project *C-Wake* and elsewhere, it is of interest to assess the wake ages (and in particular the maximum wake ages) which are accessible in the various wind tunnels, catapults and water tanks. Table 4 collects key parameters of various aircraft models to be used in *C-Wake*. Table 5 translates the measuring positions into normalized ages t^* for the wind tunnels and ONERA's catapults, using eqs. 9 and 10. Again, we use $s = \pi/4$.

The following table lists the dimensions of five water towing tanks at four institutions together with the height of ONERA's old and new catapult facilities (the latter will be operational in mid 2002).

Towing tank at	width	height h	length
WSG-DLR	1.1 m	1.1 m	18 m
TUD	4.2 m	2.5 m	142 m
HSVA 1	5.0 m	3.0 m	80 m
HSVA 2	18.0 m	6.0 m	300 m
INSEAN	13.5 m	6.5 m	454 m
old catapult	–	4 m	–
new catapult	–	14 m	–

The maximum wake ages t^*_{max} which are accessible in such towing tanks (or a catapult facility) are determined by

$$t^*_{max} = (h - f_1 B - f_2 s B)/sB, \tag{11}$$

where h is the height of the water surface in a facility. The term $f_1 B$ describes the minimum water–layer depth between model and water surface which is required to avoid disturbances at the surface when the model is towed. The term $f_2 sB$ is the minimum height of the vortices above ground without being in ground effect. Here we set $f_1 = f_2 = 1$ ($f_1 = 0$ for the catapults), hence we assume that the model is towed one span below the water surface and the wake is in ground effect when its height gets smaller than one initial vortex spacing $b_0 = sB$ (with $s = \pi/4$). Table 6 lists the values of t^*_{max} for the respective facilities.

As a result of that analysis one may conclude that the distances not only in the classical wind tunnels but also in the old catapult are too small, unfortunately, to allow the wake vortices to age significantly. We recall that in order to characterize the wake at the interesting distances of 3 to 6 nautical miles, we have to gain normalized wake ages of typically 2.5 to 5 in the facilities, see Table 3. Only in INSEAN's water towing tank (with small model 5) and ONERA's new catapult (with model 2) we expect to yield sufficiently high ages.

Table 4: Parameter of various aircraft models used in different facilities within *C-Wake*; $s = \pi/4$.
Model 1: DLR's F11 half model used in DNW-NWB and -LLF.
Model 2: Airbus' VLTA full model used in ONERA-F1 and ONERA's catapults.
Model 3: ONERA's VLTA half model used in ONERA-F2.
Model 4: NLR's SWIM model used in DNW-LST and -LLF; see Appendix A for details.
Model 5: DASA's A340-300 model used in watertanks TUD, HSVA, and INSEAN.

		Model 1 $f(V)$	Model 2	Model 3	Model 4 $f(\alpha)$	Model 5 high lift	Model 5 clean
B	m	2.8	2.28	1.6	0.60	1.2	1.2
V	m/s	45-90	21	50	60	3.0	3.0
A_R		9.22	8.16	8.16	8.0	9.26	9.26
C_L		1.55	1.55	1.55	0.94–1.77	1.76	0.6
s		$\pi/4$	$\pi/4$	$\pi/4$	0.68–0.76	$\pi/4$	$\pi/4$
Γ_0	m^2/s	13.5-27.0	5.8	9.7	3.1–5.2	0.436	0.148
t_0	s	2.3-1.1	3.5	1.0	0.34–0.25	12.8	37.7
v^*	–	46.1	40.8	40.8	49.5–32.8	40.8	120.

Table 5: Accessible wake ages t^* in the various wind tunnels.

x^*	Model 1 in NWB	Model 1 in LLF	Model 2 in F1	Model 2 in catap.	Model 3 in F2	Model4 in LST	Model 4 in LLF
0.5	0.014	0.014	0.016	—	0.016		
2.25	—	0.062	0.070	(0.070)	0.070		
3.5	—	0.097	0.11	0.11			
6.0	—	0.17	—	0.19	—		
13.3	—	—	—		—	0.40–0.53	
20.0	—	—	—	0.62	—	—	
30.0	—	—	—		—	—	0.89–1.20
40.0	—	—	—	1.25	—	—	—

Table 6: Accessible maximum wake ages t^*_{max} in the various towing water tanks with Model 5 (A340-300) and in the catapults with Model 2.

HIGH L. x^*	in TUD	in HSVA 1	in HSVA 2	in INSEAN	CLEAN x^*
12.2	0.38				35.8
29.2	—	0.91			85.8
148	—	—	4.1	4.6	436

x^*	old catapult	new catapult
40	1.2	
218	—	6.8

3 How to characterize wake vortices

For allowing comparison of data from different sources it is recommended to properly normalize the parameters which characterize the wake in terms of vortex strength, decay, or encounter. In the following, we list proposed parameters and propose respective normalizations.

3.1 Vortex parameters

Circulation $\Gamma(r)$ (r is the distance from the vortex centre) normalized by Γ_0: $\Gamma^*=\Gamma/\Gamma_0$.

Cross velocity components normal. by w_0: $v^*(y^*)=v(y/B)/w_0$, $w^*(z^*)=w(z/B)/w_0$.

Tangential velocity: $v_\theta = \sqrt{(v^2+w^2)}$, normalized by w_0: $v_\theta^* = v_\theta/w_0$.

Axial vorticity: $\omega_x = \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}$, normalized by t_0: $\omega_x^* = \omega_x t_0$.

Core radius r_c (when roll-up is completed), normalized by b_0: r_c/b_0.

Vortex separation b normal. by b_0: $b^* = b/b_0$.

Vortex Reynolds number $Re_\Gamma = \Gamma/\nu$.

3.2 Vortex models

One way of characterising a vortex is by its velocity profile. Here we list some formula for radial profiles of the tangential velocity, $v_\theta(r)$, which are frequently used to model a vortex in the rolled-up wake behind an aircraft (see also Hinton & Tatnall 1997). The trailing vortex pair is achieved by superimposing the induced flow of two modeled vortices with opposite circulation.

Rankine vortex

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r_c}\frac{r}{r_c} \quad \text{for} \quad r \le r_c,$$

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r} \quad \text{for} \quad r > r_c. \tag{12}$$

Lamb-Oseen vortex

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r}\{1-\exp(-1.2526(r/r_c)^2)\}. \tag{13}$$

Hallock-Burnham vortex

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r}\frac{r^2}{r^2+r_c^2}. \tag{14}$$

Adapted vortex (Proctor 1998)
For $r \le r_c$:

$$v_\theta(r) = 1.4\frac{\Gamma_0}{2\pi r}\{1-\exp(-10(r_c/B)^{0.75})\} \times\{1-\exp(-1.2526(r/r_c)^2)\},$$

for $r > r_c$:

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r}\{1-\exp(-10(r/B)^{0.75})\}. \tag{15}$$

Smooth blending vortex profile (Winckelmans et al. 2000)

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r} \times\left\{1-\exp\left(-\frac{\beta_i(\frac{r}{B})^2}{\{1+[\frac{\beta_i}{\beta_o}(\frac{r}{B})^{5/4}]^p\}^{1/p}}\right)\right\}, \tag{16}$$

with β_o, β_i, and $p = 10$, 500, and 3, respectively.

Multiple scale vortex (Jacquin et al. 2001)

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r_i}\frac{r}{(r_i r_o)^{1/2}} \quad \text{for} \quad r \le r_i$$

$$v_\theta(r) = \frac{\Gamma_0}{2\pi(r_o r)^{1/2}} \quad \text{for} \quad r_i \le r \le r_o$$

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r} \quad \text{for} \quad r \ge r_o \tag{17}$$

with $r_i \le 0.01B$ and $r_o \approx 0.1B$.

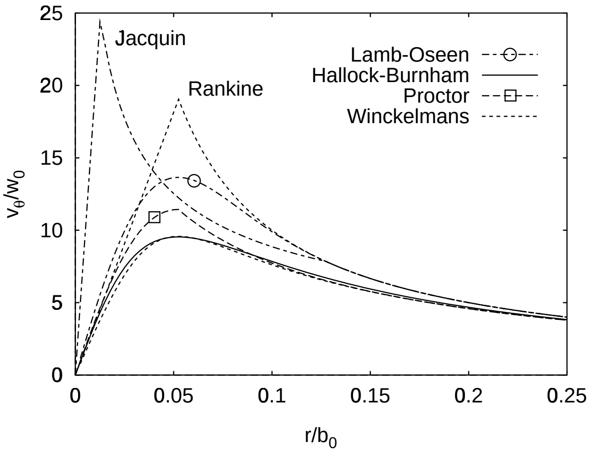

Figure 2: Normalized tangential velocity profiles $v_\theta(r)/w_0$ of mostly used and adapted vortex models; $r_c/b_0 = 0.052$ for all models except 17.

The multiscale model 17 is a fit of wind tunnel data and provides inner and outer core radii. In models 12 through 15 the core radius appears explicitly, hence the ratio r_c/b_0 is a free parameter. For comparing all models in Figure 2, we used the ratio $r_c/b_0 = 0.052$, which results implicitly from model 16, to scale all other models.

For a single and axisymmetric vortex the circulation is obtained from v_θ by

$$\Gamma(r) = 2\pi r v_\theta(r). \tag{18}$$

The Rankine vortex consists of a core flow which rotates like a solid body containing constant vorticity and an outer potential flow without vorticity. The Lamb-Oseen model blends the core region with the potential region of the Rankine vortex and decays with $1/r$ at $0.1b_0$ (roughly 2 r_c).

The multiple-scale vortex model results from the analysis of wind tunnel data gathered in a wake of a small transport aircraft (A300-type model). Jacquin et al. (2001) found that at 3, 5, and 9 spans downstream the trailing edge of the wing four regions can be distinguished around the center of the vortex shed by the high-lift wings of the model: The internal core where v_θ increases with r is very small, $r_i \leq 0.01B$, and is followed by a plateau region of width $0.03B$ where the tangential velocity is approximately constant. The plateau region has also been observed by Devenport et al. (1996). Beyond that plateau the tangential velocity decreases first with $r^{-0.5}$ before it follows the potential law r^{-1} at about $r = 0.1B$.

Proctor (1998) adapted his model to lidar field measurement data. This model has smoothly be blended by Winckelmans et al. (2000) and adjusted to a wind tunnel experiment with a rectangular wing (no flaps, no fuselage) and in two-dimensional vortex roll-up studies (using vortex methods). It is worth to emphasize that the model by Hallock and Burnham progresses very similar as Winckelman's proposition; their model also has been adapted from data of field measurement campaigns. Note that models 14, 15, and 16 meet the potential flow beyond $0.25b_0$ only, i.e., these vortices contain vorticity over a very large radius compared to the other vortex models.

Most of the evaluated data from real flights and laboratory tests (see also Brysov et al. 1999 and Soudakov 1999) seem to converge in the sense that a detailed description of the vortex in a aircraft wake requires at least a two-scale model with an inner and outer core (see also Spalart 1998 and Jacquin et al. 2001):

- The flow in the *viscous* or *inner* core with radius r_i is dominated by vorticity and viscosity owing to the very large transverse velocity gradients.
- The *vorticity* or *outer* core with $r_i < r < r_o$ is the result of the (basically inviscid) roll-up process of the vortex sheet and contains vorticity.
- The outer flow region where $r > r_o$ and $v_\theta \sim 1/r$ (potential flow) emerges from viscous diffusion and is free of vorticity.
- The maximum value of v_θ is at $r = r_c = r_i$. The outer core radius is the position where the total circulation Γ_0 is attained. The accurate sizes of these cores are, however, still uncertain.

Other radii are defined in Sections 4.2 and 8.1.

3.3 Parameters for vortex decay

Ratio of vortex core to spacing r_c/b.

Maximum axial flow u_{max}, normalized by maximum swirl: $u_{max}/v_{\theta max}$. Here, a normalization by w_0 is not appropriate, since the neighouring vortex is probably of secondary importance for decay mechanisms induced by axial flow.

Ambient turbulence in terms of turbulence velocity $q := \sqrt{u'^2 + v'^2 + w'^2}$, normalized by w_0: $q^* = q/w_0$, or in terms of turbulence energy dissipation rate ϵ, normalized by w_0 and b_0: $\epsilon^* = (\epsilon b_0)^{1/3}/w_0$. Further, a turbulence length scale, e.g., the integral length scale Λ which quantifies the average size of the turbulent eddies present in the turbulent flow field. The normalized length scale is $\Lambda^* = \Lambda/b_0$. The longitudinal integral length scale is given by

$$\Lambda_f = \int_0^\infty f(r)dr \tag{19}$$

with $f(r)$ as the longitudinal correlation function of the turbulence,

$$f(r) = \frac{Q_{11}(r,0,0,t)}{\overline{u'^2}} \quad \text{with} \tag{20}$$
$$Q_{ij}(\underline{r},t) = \overline{u'_i(\underline{x},t)u'_j(\underline{x}+\underline{r},t)}.$$

Aircraft induced turbulence $q^*_{ac} = q_{ac}/w_0$ or $\epsilon^*_{ac} = (\epsilon_{ac} b_0)^{1/3}/w_0$. Some hot-wire data from wind tunnel measurements (Devenport et al. 1996, Jacquin et al. 2001) and only a few samples for aircraft–induced turbulence from *in-situ* flight measurements (Baumann et al. 2000) are available in order to allow guesses of the intensity of the aircraft induced turbulence.

Ambient stratification in terms of the vertical gradient of the virtual potential temperature or Brunt-Väisälä frequency $N = \sqrt{g/\Theta_{v0}\, d\Theta_v/dz}$, normalized by t_0: $N^* = N\, t_0$.

Ambient shear in terms of the vertical gradient of horizontal cross wind (perpendicular to wake vortex axis) $S = du_c/dz$, normalized by t_0: $S^* = S\, t_0$.

Ambient cross wind u_c, normalized by w_0: $u^*_c = u_c/w_0$; u_c does not influence vortex decay but it transports the vortices laterally and, thus, is of major importance for safety corridor definitions.

Crow linking The Crow linking factor is defined as: $\beta(t) = \frac{b_{\max}-b_{\min}}{b_{\max}+b_{\min}}$, where $b_{\max}$ and b_{min} are the maximum and minimum lateral vortex separations. The vortex system is considered linked when the linking factor is greater than 0.85 and coherent ring-like structures are present.

Ground linking A ground linking factor can be defined similarly to the Crow linking factor as follows: $\beta(t) = \frac{z_{\max}-z_{\min}}{z_{\max}+z_{\min}}$, where $z_{\max}$ and $z_{\min}$ are the maximum and minimum altitude of one of the vortices. When the ground linking factor exceeds 0.85 the vortex can be considered linked with its ground image.

3.4 Parameters for wake encounter

The effect of a vortex encounter with possibly hazardous implications depends on

wake characteristics as wake strength, core radius, distance between vortices, ratio of wing spans of the generating and the following aircraft, B_g/B_f;

wake intercept route with intercept angle(s), intercept height (w.r.t. vortices), flight speed, height above ground;

properties of encountering aircraft as wing span, wing area and wing taper ratio, mass and roll moment of inertia (depends strongly on the weight, hence fuel, in the wing), location of horizontal and vertical fins, roll damping coefficient (depends mainly on taper ratio and wing sweep angle), available control power by size and location of horizontal and vertical fins and rudder size and locations;

experience of the pilot including his reaction time and properties of the auto-pilot.

The wake intercept route determines the duration of the wake encounter (exposure time) which is an important parameter for the magnitude of induced lateral and roll movements of the aircraft and for the ability to initiate effective counter-acting control.

Flight parameters which are mostly used to describe wake encounters are **bank angle**, **roll moment**, **roll rate and acceleration**, **pitch angle, pitch rate**, **(negative) lift**, **ratio of roll control to vortex induced roll**. Definitions are given in Section 8. Several threshold values to discriminate harmless from hazardous encounters are discussed in the literature but no common agreement has been achieved yet.

4 How to measure and evaluate wake data

In this section field measurement strategies and parameters for a unified description of wake vortex position, spacing, and circulation are suggested. The suggestions shall allow successful field trials and uniform comparisons of data from diverse sources including near field data and far field data of evolving vortices which usually decay turbulently.

4.1 Set-up of field trials

Further field measurement campaigns are planned which aim at vortex characterization and where lidars will be used to scan the vortex profiles. For the success of such campaigns and learning from past measurements, the following options and facilities are desirable, if not essential:

1. Combination and synchronization of 2 or 3 continuous–wave lidars which measure the same vortex from different positions, cross-plane but also parallel to flight direction.
2. Measurement of the relevant meteorological parameters (esp. profiles of wind and temperature) by pulsed lidar, wind profiler, radar, radiosondes.
3. Weather forecasting and nowcasting with numerical weather codes in a small area and of high resolution in order to plan flights carefully and to measure in the desired weather, e.g., in a calm atmosphere with weak turbulence and thermal stratification or in an atmosphere according to the wake–vortex behaviour classes (Frech et al. 2000 b).
4. Vortex visualization by smoke using smoke generators on the aircraft and at the ground.
5. Standardized data evaluation: mean circulation obtained by integrating over a range of radii (see Section 4.2).
6. Finally, vortex–noise measurements may be helpful for vortex detection and aircraft identification. This has to be demonstrated.

Of absolutely paramount importance for the success of any field trial is careful and appropriate selection of the precise sites for lidar operation (Greenwood & Vaughan 1998). The basic geometry of scanning a lidar beam in relation to the flight path of the aircraft (e.g. the glide slope on landing) becomes extremely complex in the presence of variable wind speed and direction. Factors include

- focal depth and range resolution of the available lidars,
- positions available on either side of the centre line,
- the likely sink rate of the vortices,
- height of aircraft passage overhead,
- prevailing wind and the local topography that may induce wind shear and turbulence,
- ground heating and convective activity (e.g. off tarmac road surfaces, roofs etc.).

The ideal site would have flat, featureless terrain for several km around, and would allow siting of the lidar(s) both directly underneath the glide slope and at distances up to several 100m to either side. At most existing commercial airports it is often very difficult to find positions that meet the required criteria.

It is also most important to be very clear as to the precise aims of a set of trials - which might range on the one hand from examining “ideal” long-lived vortices in conditions of low wind and turbulence, to on the other hand deliberately exploring the effects of various levels of turbulence, stratification and wind shear on vortex decay. In this regard it is worth noting the difficulties likely to be encountered in conditions of even light headwind directly down the glide slope. With typical short-term variation of wind direction of at least ±10°, and with a lidar sited underneath the glide slope, the vortex ribbons will be swept onto either side in an unpredictable and rapidly varying manner that inhibits precise measurements. In this regard, comparable variations in both speed and direction of a true crosswind are likely to be less damaging to the measurement process.

4.2 Data evaluation

To measure the vortex in real conditions, Doppler lidars can be used. As formally demonstrated by Constant et al. (1994), Doppler lidars evaluate the maximum velocity along the line of sight of the laser beam. Figure 3 exemplifies three scans through a vortex of a landing aircraft.

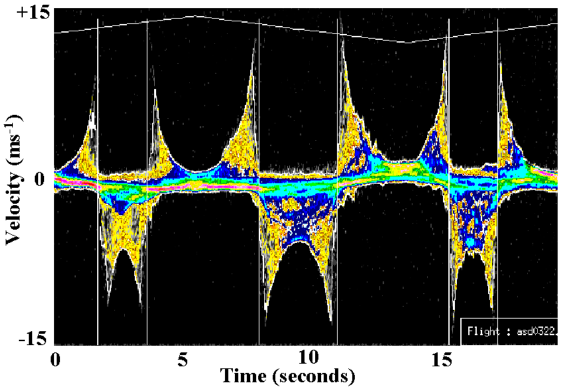

Figure 3: Lidar measurements of wake vortices. Line-of-sight velocity (positive values indicate motion away from the lidar) versus time (aircraft overhead at $t \approx 0$). The laser scan angle is indicated by the zigzag line on top. From Harris et al. 2000.

The evaluation of circulation from data scanned by lidar can be performed on arbitrary (large) radii according to eq. 18. However, when measuring close to the vortex core, the velocity errors may be small but the measured radii (being small) are likely to have large relative error. At large radii the velocity errors may be considerable since it is extremely difficult to discriminate the transition point from vortex-induced velocities to the ambient flow field. Therefore , the following technique has been widely used by DERA Malvern and is appropriate for a viewing geometry where the lidar is positioned underneath the glide slope close to the centre line: Evaluate the down-draught W at the mid-point between the two vortex cores $b_0/2$, averaged over an appropriate distance (usually several metres). The circulation is then given by

$$\Gamma(b_0/2) = \pi b_0 W/2. \qquad (21)$$

This approach has the attraction of simplicity and robustness; it does however limit flexibility for lidar positioning. Note that the summation of the contributions from the two vortices doubles the measured velocity, thus reducing the uncertainty. W lies typically in the range 4-8 m/s; the measurement uncertainty is of order 0.2 m/s, giving a likely uncertainty in Γ of order 3-5% in ideal atmospheric conditions. This could be reduced by some more sophisticated processing of the raw data.

Nonetheless, such a “single–point” measurement will suffer from the randomness of the turbulent fluctuations and the complex motion and deformation of the vortices as well as from uncertainties in b_0. The consequent scatter can best be reduced by averaging over as many measuring positions as possible. Alternatively, one can try to curve-fit the circulation by using a vortex pair defined with eq. 18. This however requires that one knows the distance between the vortices sB sufficiently accurate, what is difficult with a single Lidar when the height of the vortex pair is not known but what is feasible with two or more lidars by means of triangulation (Young 2001).

Therefore, it is also suggested to use Γ_{5-15} which is the averaged circulation obtained over radii from 5 m to 15 m. This definition unifies the following advantages: Small and large radii are excluded; the averaging of the data along a distance of ten meters reduces the scatter substantially; measurement errors due to the neighbouring vortex are less sensitive to the viewing angle (Campbell et al. 1997); and, particularly, Γ_{5-15} correlates well to effects of wake encounters (Hinton & Tatnall 1997). Therefore, Γ_{5-15} seems to be a good choice for investigations which aim at operational spacing reductions. If possible, both evaluation schemes should be used and compared to check their respective suitability.

Recently, wake data from 5-hole-pressure probe measurements in the wind tunnel behind an A321 half model and lidar measurements in full–scale field trials at Toulouse–Blagnac Airport have been compared (Harris et al. 2000). It is obvious that both techniques are complementary and, thus, both are required to obtain a full understanding of vortex behaviour. Moreover and although the differences in the measurement techniques and the experimental set-ups are very big, the tangent velocity profiles show good agreement for vortices of comparable age. This result increases confidence in the validity of both techniques and suggests that, at least in that case, the wind–tunnel results scale to the full size, despite the large difference in Reynolds number.

For instrumentations which deliver (at least) 2D data, like 5-hole-probes, PIV, CFD, and others, the vortex descent height and vortex spacing can be directly computed. However, in a spotty vorticity field the obtained scatter will be substantial. Worse, the calculation of the circulation based on an erroneous vortex centre will generally cause an underestimation. Therefore, it is suggested to determine the vortex circulation Γ and its position from the centroïds $\overline{y}$ and $\overline{z}$ over one half-plane of the wake by

$$\Gamma = \int_{-\infty}^{\infty}\int_{0}^{\infty} \omega_x \, dydz, \tag{22}$$

$$\overline{y} = \frac{1}{\Gamma}\int_{-\infty}^{\infty}\int_{0}^{\infty} y\,\omega_x \, dydz, \tag{23}$$

$$\overline{z} = \frac{1}{\Gamma}\int_{-\infty}^{\infty}\int_{0}^{\infty} z\,\omega_x \, dydz, \tag{24}$$

where ω_x denotes the axial vorticity. To account for distorted and bent vortex tubes especially at late flow stages, the coordinate system should be adjusted such that x always indicates the local axis of the vortex. All integrations are limited to one half-space cross-section behind the aircraft; when external forces are present (shear, buoyancy, ground) which produce counter-rotating vorticity around a vortex the integration domain must be adjusted accordingly.

A measure analogues to the core radius is constituted by the dispersion radius

$$r_d^2 = \frac{1}{\Gamma}\int_{-\infty}^{\infty}\int_{0}^{\infty} \left((y-\overline{y})^2 + (z-\overline{z})^2\right)\,\omega_x \, dydz. \tag{25}$$

The quantities 22 to 32 are also very useful in the near field where multiple vorticity patches exist during the roll-up phase. Jacquin et al. (2001) give an overview of the various length scales suitable in vortex flow dynamics.

To enable the comparison of circulation data from diverse investigations it is strongly recommended to compute also Γ_{5-15} as a standard vortex strength measure in all investigations where it is accessible.

5 Wake vortex strength reduction

This section deals with the requirements of the aircraft–manufacturing industry which wants to design and build new very large transport aircraft (VLTA) but has to avoid higher aircraft separations during approach and landing. VLTAs may, on one hand, help to ease the congestion on airports because of their higher capacity ("more passengers in less aircraft"). But, on the other hand, their larger weight can also cause stronger wake vortices which, in turn, may require larger separations between a VLTA and a follower aircraft. Hence, the benefit of larger capacity may be counterbalanced by increased separation.

The control of aircraft wake vortices by constructive means at wings and flaps (as flap setting, devices, jets) in order to ease their alleviation is still far from being resolved, despite an enormous effort in the past 30 years, in particular in Northamerica. A detailed overview over the research aktivities in the USA (esp. by NASA) can be found in Rossow (1999); that paper also contains a large list of references. Vyshinsky (1999) summarized the recent research efforts at the Central Aerohydrodynamic Institute (TsAGI) in Russia.

5.1 Facilities and instrumentation

The experimental tool for the *near and extended near field* (down to the order of 10 wing spans) is the classical windtunnel with 5-hole pressure probe (see Figure 1), hot-wire, LDA, and PIV instrumentation to survey the mean field and instantaneous fields as well as turbulence/meandering characteristics (Hünecke 1996, Devenport at al. 1996, Chow et al. 1997, Jacquin et al. 2001).

Starting from a measured plane close behind the trailing edge, CFD calculations of the roll-up process (within the near to extended near field) agree well with observations of the mean field (i.e. with 5-hole probe data), even in 2d, in spite of the facts that (i) in the near field the vortex filaments are not perpendicular to the measured and simulated planes, (ii) locally high axial velocities and radial gradients of axial velocities are observed, (iii) the vortex sheet around the wing is turbulent, and (iv) the vortices meander around their mean positions. Euler simulations of the flow around the aircraft also yield good results when compared to PIV data (Corjon et al. 1999, Stumpf et al. 2000). More realistic Navier-Stokes flow computations around rather simple aircraft geometries are just about to become feasible on now-a-days computers but will remain very expensive for a long time.

For *mid to far field* investigations under laboratory conditions it was thought to utilize the catapult and water towing tanks. In Section 2, we explained that only the water towing tank of INSEAN and the new catapult facility of ONERA have the proper (vertical) dimensions to reach far field wake ages (see Tables 5 and 6). Lately conducted smoke-visualization (Coton et al. 1998, Bezrodnov et al. 1999, de Bruin 2000a) and PIV measurements (Vollmers 2001) in the catapult yielded encouraging results for the data reproducibility from several launches of nominaly identical flights.

One has to keep in mind that both catapults and water towing tanks only allow gliding aircraft in a start configuration (flaps extended to about 22 degree) when flow separation along wing and flaps has to be avoided; higher flap settings are possible but with the risk of flow separation. Today it is not clear if this limits the significance of the measured far field wake characteristics, see Section 5.2. The water towing tanks still have to show their capabilities for such investigations. Problems may arise owing to sting disturbances, surface waves, reflections and cavitation problems.

Once established and validated, CFD tools can predict the *far field wake* characteristics in a given environment from near field data. However, owing to the huge spectrum of energy containing and interacting scales (e.g., scale of aircraft vortex vs. scale of atmospheric flow), this is still a very demanding issue. Vortex Reynolds numbers of real aircraft will not be accomplished in the near future. Advanced numerical methods and elaborated closure models have to fill the gap when the necessary resolution is not achievable.

In the real world, the continuous–wave lidar is the proper tool for wake vortex detection, monitoring and characterization through all wake stages from *the extended near field to the far field*. In the far field though, when the vortices are decaying in turbulent surroundings, the lidar has difficulties to discriminate the vortex from the ambient flow which limits the significance of such evaluations (see Section 4). Hope has been raised that a combination of several continuous–wave lidars will augment the data quality and knowledge on vortex decay. We have to keep in mind, though, that the lidar is a fair weather tool (no fog or heavy rain). This is certainly uncritical for field measurement campaigns aiming at characterizing wake decay but it may limit the applicability of lidars in a daily operational service at airports, cf. Section 6.

In-situ measurements in aircraft wakes can be conducted in the extended near field and in the far field. The measuring aircraft should not enter the mid field where the fully developed vortices have the maximum strength and would cause too large rolling and lifting moments, especially when the entering aircraft is smaller than the wake generator. But even repeatable measurements in the extended near field are difficult (Baumann et al. 2000). Capturing the core region is extremly difficult and is limited to very short crossing times such that no selective investigation of the turbulence structure of the cores is possible.

5.2 Facts and consequences

The following facts mark the lessons learned on vortex characterization and control.

1. It was proved in windtunnels and by CFD that flap/wing modifications and engine/flap positioning have an effect on vortex topology, peak vorticity, and core radius in the near to extended near field (Rossow 1999, Schell et al. 2000, Stumpf 2000). We do not know, though, if and how these near field modifications translate into the far field and if they result in a less harmful wake.
2. The flap setting influences the distribution of the vorticity among all shed vortices, e.g., a strong flap–tip vortex compared to the wing–tip vortex emerges when flaps are fully deployed. Pavlovets et al. (1999) showed that the inital wake intensity can be attenuated by increasing the loading on the outer wing sections. However, it has not been demonstrated comprehensively so far, if and how various initial circulation distributions in the vortex sheet show-up in the far field characteristics. On contrary, Sipp et al. (2000) showed that two-dimensional laminar vortex dipoles with various initial distributions of vorticity evolve towards a specific family of dipoles which is characterized by the ratio r_c/b.
3. Single vortices – even with low vorticity – have a very long lifetime except when they are exposed to strong ambient turbulence (Moet et al. 2000). The breakdown of a single vortex is favoured by strong axial velocity in the vortex core. The vortex bursting phenomenon, occasionally observed in aicraft wakes, is not yet well understood. A vortex characterized by a non-monotonic profile of circulation is unstable; the Rayleigh criterion suggests a centrifugal instability.
4. The decay of vortex strength (circulation) of a trailing vortex pair "can only result from the diffusion of vorticity across the centerline" (Donaldson & Bilanin 1975, p.8). The strength of wake vortices decays rapidly when instability mechanisms cause vorticity exchanges across the symmetry line. The onset of rapid decay can be triggered in a system of coherent vortices, e.g., by vortex dipoles (Rennich & Lele 1999, Crouch & Spalart 1999, Fabre & Jacquin 2000, Fabre et al. 2000).
5. In recent PIV measurements, performed in the frame of the EU project *WAVENC* in ONERA's catapult facility in Lille, a transition of the vorticity structure in the core region from a quasi-laminar state to a turbulent state was observed (Vollmers 2001, de Bruin 2000a). *In-situ* measurements behind cruising aircraft (Baumann et al. 2000) corroborate the turbulent structure of wake vortices throughout their lifespan. Temporal LES confirm the transition found in the catapult and elucidate that wake vortices with turbulent core regions may continue to descent relatively long times. Especially in quiescent and neutral surroundings Γ decays still rather slowly after the transition (Holzäpfel et al. 2001a). Consequently, this turbulent wake vortex regime defines a worst case scenario and should be investigated under safety aspects.
6. The decay of a counter-rotating vortex pair is faster as the ratio r_c/b becomes larger (Leweke & Williamson 1998, Laporte & Corjon 2000). Stretching of environmental vorticity in the wake–vortex induced velocity field generates azimuthal structures (Risso

et al. 1999) and vertical streaks of vorticity (Holzäpfel et al. 2001b) which, in turn, accelerate the decay of the vortex pair. An inhomogeneity of crosswind or vortices leads to reconnection with secondary vortices.

These facts among others led to two different strategies which have been developed to produce and control less harmful wakes. To present the two strategies, the following terms are defined:

Baseline configuration: The slat / wing / flap configuration of selected aircraft (models), e.g., A340, B747, VLTA, which produces **baseline wake vortices**. The respective data serve as reference data bases.

Completion of roll-up: The stage of the wake when the vorticity of the vortex sheet, shed by the trailing wing and flap edges, is concentrated in a "few", distinct, co-rotating, or counter-rotating vortices. The number of distinct vortices depends on the flight configuration (clean, high-lift) and the wing/flap modifications. The distinct vortices may continue to merge further downstream.

Low vorticity vortex, LVV: A wake vortex with significantly lower vorticity maximum and larger core radius than the baseline vortex after roll-up is completed. This is also a vortex with smaller swirl velocities at the core radius.

Quickly decaying vortex, QDV: A wake vortex system with significantly higher decay rate of circulation than the baseline vortex at a prescribed wake age.

Both aspects, LVV and QDV, define the strategies towards less harmful wakes. They both are thought to impose significantly smaller roll moments on follower aircraft than the baseline vortex.

5.3 Two possible strategies

The strategies are based on different aspects of the evolution of the vortex circulation. Figure 4 sketches the general decay behaviour of the circulation of a vortex in a trailing pair. The sketch summarizes the state of knowledge as obtained from several lidar measurements (Vaughan et al. 1996, Köpp 1999, Hannon 2000) and large-eddy simulations, LES (Jeanmart & Winckelmans 2000 a,b, Holzäpfel et al. 2001a, Proctor et al. 2000).

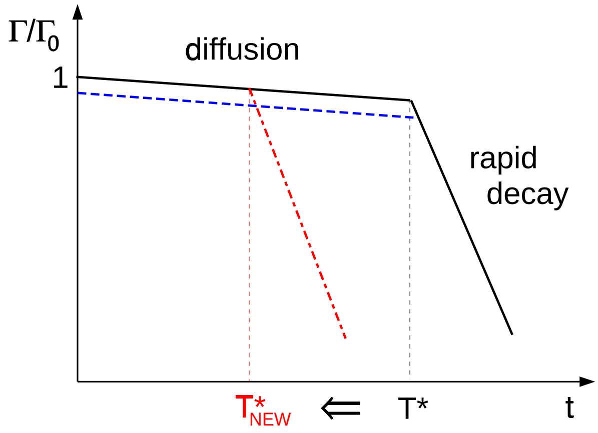

Figure 4: Sketch of vortex evolution in terms of circulation $\Gamma(t)$ normalized by root circulation Γ_0 versus time. Γ represents a mean value obtained over radii of 5 to 15 m, see Section 4.

Such data suggest that the circulation first decays at a relatively small rate, called the *(turbulent) diffusion regime*, followed by a rapid decay later on, the *rapid decay regime*. The onset of rapid decay occurs at a time T^* which sometimes is called the time of occurrence of a catastrophic event. This event occurs sooner or later in nature depending on the ambient atmospheric conditions. We observe an early onset at about 2 reference times ($2t_0$) and latest onset (under quiescent and neutral conditions) at about $6t_0$ (Holzäpfel et al. 2001a, Proctor et al. 2000). The onset is accompanied by a sudden and strong exchange of vorticity across the symmetry line in the vortex oval or with ambient vorticity which transfers the vortices from a quasi–laminar state into a turbulent state.

The **LVV strategy** now aims at producing vortices with larger cores and weaker vorticity, hence "older" vortices (in analogy to the single, plane, and decaying potential vortex) compared to the baseline vortex. Therefore it is expected that the value of Γ_{5-15} after roll-up is smaller than Γ_{5-15} of the baseline vortex. Since such measures operate in the diffusion regime we still expect a slowly decaying circulation in that regime. $\Gamma_{5-15}(t)$, thus, may follow parallel to but below the reference case, see dashed line in Fig. 4. This approach is then successfull when the wake of a new VLTA (whatever its state of decay is) is not stronger than the wake of largest civil aircraft on market, the B747.

The LVV strategy acts on single vortices by producing large and turbulent cores, by injecting turbulent jets (as an axial velocity in the core favours vortex breakdown), and by producing more than one "non-merging" vortex pair. Such measures can be addressed in the extended near field when roll-up is completed with classical wind tunnels and water towing tanks and with CFD and theoretical methods. Since Γ is expected to decay still rather slowly, the question of a hazardous vortex has to be addressed in that context.

The **QDV strategy** aims at shifting T^* to earlier wake ages (regardless of the environmental conditions) by means of triggering cooperative wake instabilities across the symmetry line, see dashed–dotted line in Fig. 4. For a certain phase of the wake flow, roughly from near to mid field, a system of coherent co-rotating or counter-rotating vortices is required to enforce short-wave and/or long-wave instabilities. Different from the LVV approach, additional turbulence production (by fences or the deployed landing gear) may be counter–productive here since turbulence may hinder the necessary secondary vortex pair to form stably. This has been observed during a flight test (Corsiglia & Dunham 1976).

The QDV strategy is targeted on one or more vortex pairs across the symmetry line by producing "non-merging" pairs of co–rotating or counter–rotating vortices (vortex dipoles). Either an unstable oscillation must be imposed on the pair with the smallest spacing or other vorticity disturbances have to be produced in directions perpendicular to the axis of the main vorticies in order to favour azimuthal and vertical structures of secondary vorticity. The respective flow could be initiated by active control surfaces on the wing (Crouch & Spalart 1999), by passive devices ("wake generators") mounted on proper positions below the wing, or by special flap and horizontal tail–plane settings (Soudakov et al. 1999, Stuff 2000). The QDV measures unfortunately can be addressed in the far field only (after onset of decay) with flight tests and CFD, possibly also in water towing tanks with small aircraft models or in larger catapult facilities. In the QDV approach the question of hazard is obsolete since the vortices decay very rapidly under realistic environmental flow conditions once their instability modes have been fomented.

At a first glance, both strategies seem to exclude each other. In terms of technical implementation and control they bear different levels of risk but they also bear different chances to effectively reduce vortex strength and hazard. Strong efforts in a tight interweavement of experimental, numerical, and analytical tools should be undertaken to come up with a modified wing design that possibly combines both strategies, i.e. that produces vortices with immediate low vorticity and quickly growing instability modes. This, indeed, may be feasible since, for example, multiple vortices on each side and a large ratio of vortex cores to vortex spacing, r_c/b, are helpful in both approches.

5.4 List of questions and forthcoming actions

1. How do constructive measures, which show effects in the near field, influence the far field decay ?
2. Is it possible to infer from near field data (vortex topology, spacing, relative strength distribution) to the behaviour in the far field ?
3. How do the results from laboratory and CFD investigations extrapolate to larger (real–world) Reynolds numbers ? Is it likely that there will be substantial differences ?
4. What are the relevant wing/aircraft parameters for the production and control of low vorticity vortices (LVV) or quickly decaying vortices (QDV) which then could be used by designers to build the right wing ?
5. Which final role do the instabilities, like short wave (Widnall) and long wave (Crow) or others, and the vortex meandering play ? Could they be customized (by, e.g., clever wing arrangements) for a controlled and quick vortex decay ?
6. How robust are all alleviation methods with respect to flight and environmental conditions ?
7. How much vortex alleviation is required ?
8. The rate of encountering trailing vortices on cruise flight recently increases because of vertically reduced aircraft separations. How to avoid/treat such encounters ? Are they hazardous ?

6 Wake vortex prediction and monitoring

This section focuses on the requirements and needs of the airport service providers and airspace controllers who observe that the continuous growth of air traffic increasingly congests airports (Urbatzka and Wilken 1997). The wake–vortex dictated separation standards between two aircraft approaching an airport (see Table 1 in Section 1.1) contribute significantly to the capacity constraints of many airports already today. From experience and research results gained during the past 30 years (Hallock et al. 1998, Spalart 1998), it became evident that the separation standards are too conservative for a variety of meteorological situations.

A forecasting model capable of accurately predicting the vortex positions and strengths in a given or forecasted atmospheric environment along the flight path might therefore permit air-traffic controllers to ease some of the regulations without loss of safety. The essential key towards such a model is the knowledge about the meteorological conditions and their impact on the wake vortex behaviour.

6.1 Atmospheric impact

The main atmospheric parameters that influence vortex transport and lifetime are ambient crosswind, turbulence, wind shear and thermal stratification. Crosswind may carry the vortices away from a security sector. Turbulence is the main atmospheric parameter that can affect vortex decay (Sarpkaya & Daly 1987, Liu 1992, Risso et al. 1999). Flight observations and CFD results clearly show that atmospheric turbulence in convective (thermally unstable) weather situations yields to strong deformation of the vortices and develops destructive structures of azimuthal and vertical vorticity with subsequent rapid decay of the wake (Corjon et al. 1997, Holzäpfel et al. 1999, 2000, Lin et al. 2000). LES of a single vortex and a vortex pair embedded in isotropic turbulence show the acceleration of vortex decay with the root-mean-square velocity of the turbulence and the strong vortex deformation induced by large turbulent integral length scales Λ (Moet et al. 2000).

Even thermally stable stratification conditions enhance the decay of vortices, also when parts of the wake may stall at or rise above flight level (Holzäpfel et al. 2001a, Switzer & Proctor 2000). Crosswind shear, on the other hand, is a candidate that may cause tilting of the vortex pair, accompanied by increased vortex separation (Robins & Delisi 1990, Proctor 1997, Hofbauer & Gerz 2000). Furthermore, vortices may rebound or stall in shear layers. It was shown that they can impressively rise back to the flight level without considerable loss of strength (Greenwood & Vaughan 1998, Hofbauer & Gerz 1999). Parametric investigations carried out with CFD tools have demonstrated that vortex trajectories are very sensitive to vortex and shear layer parameters (Darracq et al. 1999). All these situations and processes need to be considered in robust forecasting tools. Winckelmans et al. (2000) and Zheng & Lim (2000) recently published vortex-shear interaction models which they tested against LES and field measurement data.

In light winds, free of turbulence and up/down draughts, it is possible to make Doppler–lidar measurements of good precision that establish the characteristics of the vortex flow as generated by the aircraft in the early stages (typically 1-30 s). Depending on the atmospheric conditions these measurements may be extended to longer timescales, on occasion exceeding 60 s. In low crosswinds with some shear, vortices are likely to persist in the region of the glide slope. Such conditions of course potentially present the greatest hazard to following aircraft; clearly the behaviour of vortices, their movement and manner of decay etc. may readily be examined by lidar in these cases.

In stronger winds and more turbulent conditions detailed lidar studies become more difficult, particularly in variable wind conditions, and require careful siting of the lidar in relation to the expected paths to be taken by the vortices. Nevertheless it should be possible to examine vortex behaviour under the disruptive influence of atmospheric turbulence and to derive valuable information as to the manner of such decay. Lidar measurements in such conditions have clearly shown rapid decay of the vortex within 30 seconds of generation. It appears that the lidar techniques, although more difficult in stronger variable winds, appear to offer the only prospect of such investigations in the full-scale world of real atmospheric conditions.

6.2 Existing warning and approach systems

Some organizations have started to develop reduced separation systems (RSS) based on wake vortex warning and prediction or on alternative airport approaches. These systems should help the controllers and the airport authorities to increase traffic throughput but to maintain the level of safety. None of the systems are operational today for various reasons. We now briefly describe each system.

WSWS. The "**W**irbel**s**chleppen–**W**arn**s**ystem", initiated by DFS in the 1980s, has been developed for Frankfurt Airport (Gurke & Lafferton 1997, Frech et al. 2000a) where two too closely spaced parallel runways (518 m apart) cannot be operated independently because wake vortices may be advected to the adjacent runway. The WSWS uses data from a wind line, a statistical wind forecast, and a vortex decay and transport model to predict minimum non-hazard times for the two runways at appropriate winds in instrumented meteorological conditions (IMC).

SYAGE. The "**Sy**stème **A**nticipatif de **G**estion des **E**spacements" was developed by CERFACS and STNA and uses ground–based wind measurements and the wake vortex model VORTEX to predict reduced separations for single runway departure (Le Roux & Corjon 1997). The system is implemented for tests at Toulouse–Blagnac Airport.

AVOSS. The **A**ircraft **Vo**rtex **S**pacing **S**ystem is developed by NASA (Hinton et al. 1999, 2000) to produce weather dependent wake vortex spacing criteria in IMC for single runway approach. AVOSS provides current and predicted weather conditions and predicted wake vortex transport and decay. The functionality of the system was demonstrated in July 2000 at Dallas–Fort Worth Airport.

HALS/DTOP. The **H**igh **A**pproach **L**anding **S**ystem / **D**ual **T**hreshold **Op**eration has been developed for Frankfurt Airport by DFS and FAG (e.g., Frech 2000). Two aircraft, staggered by radar separation, approach the parallel runways along two glide paths which are separated 80 m vertically and 518 m laterally. The aircraft approaching along the higher path lands at a new runway threshold which is installed 1500 m behind the first threshold. The system will soon enter an operational test phase and is thought to work in CAT-1 with IMC conditions.

SOIA. The **S**imultaneous **O**ffset **I**nstrumented **A**pproach is developed by FAA for San Francisco Airport (Spitzer et al. 2000) where two runways separated by 225 m only prohibit independent operation under IMC. The system aims at simultaneous operations under IMC when the cloud ceiling is not lower than 1600 feet: Two aircraft approach non-staggered but safely separated by 3000 feet laterally until they reach the "missed approach point" at about 1000 feet height and 3.3 nautical miles before the threshold. The final aproach is then flown under VMC. Flight–simulator tests and trainings and wake–turbulence monitoring (Greene et al. 2001) have been performed.

A recent study has also highlighted the issue of vortex encounters for the simultaneous non-interfering operation of helicopters at major airports. There is potential for increasing airport capacity by use of vertical lift capable aircraft to a Final Approach and Take-Off (FATO) area which is separated from the primary runway. With the advent of tilt-wing and tilt-rotor technologies this may offer new avenues for increasing airport capacity. For FATO areas which are not located sufficiently far away from runways, further work is needed to understand the behaviour of vortices in close proximity to the ground as they transit from runway to the FATO area. Studies of a conventional helicopter operating near the FATO have shown that, if encountered, the response to such vortices can be significant.

6.3 Facts and requirements

We summarize now the state-of-knowledge on the properties and skills of a RSS and related technologies.

1. It is claimed by the IFALPA (1998a) and also generally accepted that in order to operate reduced aircraft separations during approach and landing, a RSS based on wake vortex

warning must *predict and monitor* the wake vortex evolution, i.e., its position, movement, and decay, along the glide path. Within given probability bounds, the wake vortices from the leading aircraft must either have irreversibly left the flight corridor or decayed to the level of ambient turbulence.

2. The RSS predictor contains two basic elements: a local weather forecast model and a vortex transport and decay model. The RSS monitor combines measuring instruments which observe the weather (esp. wind, turbulence, temperature and their respective gradients) and the wake vortices in the terminal area. The measured data provide input and quality checks for the predictions. Both, predictor and monitor must operate in real time.

3. Three-dimensional unsteady CFD codes are useful for idealistic studies to understand interaction processes of aircraft vortices with external flow conditions such as wind shear, turbulence, stratification and ground effects. They provide highly resolved three-dimensional and unsteady data to develop and improve parameterizations for real-time models. However, those CFD tools are computationally too expensive to be used for operational forecasting purposes.

4. To forecast vortex positions and decay in real time, relatively simple engineering models are needed and available (Greene 1986, Corjon & Poinsot 1996, Kantha 1998, Robins et al. 1998, 1999, Belotserkovsky 1999, Soudakov 1999, Winckelmans & Ploumhans 1999, Yaras 1999, Sarpkaya 2000, Holzäpfel & Schumann 2000, Zheng & Lim 2000). The physics enter such models via parametric assumptions which have been developed and improved from experimental and/or numerical data bases. Important are robust and conservative predictive capabilities.

5. Local meteorological data are often limited and dedicated measurement campaigns are complex and expensive. Existing data bases as such from Dallas–Fort Worth (Hinton et al. 2000), Memphis (Dasey et al. 1997), the Frankfurt wind–line (Frech et al. 2000a, Hallock et al. 2000), and the Toulouse SYAGE (Le Roux & Corjon 1997) should be used to check and improve CFD codes and real–time models.

6. Appropriate ground-based instruments for weather monitoring are pulsed lidars, wind and temperature profilers (e.g., sodar, RASS), (bistatic) radar, radiosondes, etc. Some of these instruments are still research tools or under development for operational application.

7. Another possibility to improve the meteorological database along the glidepath is the use of onboard systems of arriving/departing aircraft. By means of a suitable algorithm (e.g., Swolinsky & Krauspe 1984) wind and turbulence information can be calculated from the raw data of the inertial, GPS, and air data systems with sufficient accuracy. Important meteorological parameters for the prediction of the behaviour of wake vortices like stratification and wind gradients can be determined.

8. Vortices can be monitored by lidars. In discussion of a routine and reliable monitoring system it may be worth considering a combination of several lidars placed at appropriate separations underneath the glide slope or sideways from the runway threshold looking back along the glide slope (see also Section 7.1). The lidar settings could be arranged to scan suitably selected “windows” in various planes around the glide slope. Such lidars would thus monitor the presence, passage and departure of vortices from the window following the transit of the aircraft.

9. Owing to the large variability of almost all parameters, including operational aspects and weather factors, the prediction of vortex location and decay cannot be based on purely deterministic calculations but requires statistical approaches and climatologies.

10. One possible approach is to forecast mean vortex strength and trajectories plus security bounds for each individual aircraft (or groups of aircraft) for a given (forecasted) weather situation. This procedure is very demanding with respect to weather and vortex forecasting skills as well as to monitoring instrumentation.

11. A more simple approach is the collection of all relevant combinations of vortex behaviours in weather situations which results in wake–vortex behaviour classes with fixed aircraft separations (Frech et al. 2000 b). The classes must be designed such that they can

be forecasted from standard output data of the weather services. Since dense meteorological measurements typically will not be available at most of the European airports in the near future, this approach may be considered as an intermediate step towards individual wake-vortex forecasting.

6.4 List of questions and forthcoming actions

1. Where/when is a wake vortex innocuous ? Which are the proper safety requirements (see Section 9) ? How to define appropriate statistical safety bounds ?
2. There is a conflict between capacity-increase requirements and safety constraints. When do the security bounds nullify any capacity increase ?
3. Are approaches as the individual forecast approach or the vortex–behaviour classes approach or a combination of both feasible ?
4. How to monitor the entire glide path with respect to weather and vortices ? What is a “minimum” and a “optimum” instrumentation for an airport (cost–benefit analysis) ? How to design automated and operational instruments and how to implement them and the data streams in an airport environment (ATC interface) ? Specific technical solutions for each airport must be found.
5. The wake–vortex physics in all meteorological conditions has to be understood. CFD is the proper tool for such investigations. However, the CFD codes have to be validated for high Reynolds numbers. Is it likely that the wake decays differently when the Reynolds number is large ?
6. The parameterizations for the real–time models must be improved. What are the essentials of the complex wake–vortex behaviour in the atmosphere which have to be reproduced with simple models ?

At the end of all those endeavours, the reliability and robustness of all subsystem of a RSS and their interweavement must be tested, proven, and demonstrated to the user.

7 Wake vortex detection and warning

This section addresses the needs of the pilots and airlines. Pilots easily accept and even ask for a reduced separation under VFR conditions but they decline reduced separations under IFR conditions. Hence, seeing the preceding aircraft (note: not its vortices!) provides a sense of safety which may or may not be justified. The fact that severe vortex encounters occur so rarely justifies most of the reductions. On the other hand, it is communicated that most of the known wake-vortex encounter incidents (and certainly all of the vortex–related accidents) happend under VFR conditions. Hence, it is obvious that a wake-vortex detection instrument would be very valuable since it not only replaces the human eye under IFR but also gives more reliable vortex information under VFR.

IFALPA (1998a) believes that "there is a need to develop airborne [or ground-based] wake vortex detection and indication systems to enable pilots to make credible wake turbulence avoidance decisions". An investigation by IFALPA (1998b) showed that such a system would increase the acceptance by pilots to fly new wake–related aircraft separations.

7.1 Detection instruments

Vortices can be detected by ground-based or on–board pulsed lidars. The radar acoustic wake vortex sensor (Rubin 2000) may also be capable to detect vortex wakes.

It is widely considered that pulsed lidars operating at ranges of potentially up to 4–5 km could provide a technique for routine monitoring of vortices in the vicinity of the glide slope that might present a hazard. Much work has been undertaken in the USA with pulsed systems for detection of vortices (Hannon & Thomson 1994, Hannon 2000). The autonomous pulsed lidar system by CTI Inc., USA, has been used for vortex detection and characterization from ground at Dallas Fort Worth Airport during the AVOSS demonstration phase in July 2000. The laser beam scanned the vortex perpendicular to the flight direction.

Within the EU project *MFLAME* a pulsed Doppler lidar was developed to emulate a future airborne vortex detection system (Combe et al. 2000, Darracq et al. 2000). Tests performed at Toulouse–Blagnac airport in early 2000 achieved very promising results.

1. The ground-based measurement configuration, which was designed to emulate an on-board detection from a follower aircraft, demonstrated the feasibility and efficiency of a future airborne equipment.

2. The system is able to detect wake vortices at distances from 800 to 2350 m before the aircraft. This corresponds to an alert time for landing aircraft of approximately 30 s.

3. The best wake signatures are obtained with the velocity width (which is the width of the velocity fluctuations within a pulse volume of the laser) instead of velocity or backscatter signals.

4. Measurements, simulations and vortex detection algorithms show that the decaying vortex develops axial flow components of a spotty and turbulent character even if there was no axial flow initially. These axial flow fluctuations can be detected by the lidar.

5. The boundary layer of the atmosphere is most of the time in a turbulent state. Hence, there is high probability that aircraft vortices twist and that strong swirl components can also be detected by the lidar.

7.2 Situation awarness systems

NLR and partners develop a cockpit system which informs the pilots on the situation of the aircraft and the environment through which it flies (Rouwhorst 2000). Besides displaying the terrain and the surrounding traffic, the integrated situation awarness system (ISAS) also informs the pilots on potentially hazardous air disturbances as wind shear and wake vortices. Emphasis is put on an integrated approach where all information is gathered and ranked into a hierachy of potential dangers. Only the most severe situation which requires immediate action is displayed to the pilots and, thus, reduces their workload.

7.3 Detection, warning, avoidance

If a pilot receives a warning of a possibly dangerous vortex along his flight path, his possible reactions and manoeuvres may have to be approved by the air traffic controllers (in particular when the avoidance manoeuvre would not be small and brief). Proposals of operation for the sequence of detection, warning and avoidance (DWA) have to be acquired for ATC and the pilots to prevent accidents and minimize the impact of the jinks for the other air traffic.

Individual operation solutions may be necessary, depending on the runway system (single, parallel, crossing runways) of the airport. Other parameters for the establishment of a DWA sequence are the traffic mix, approach modes (VFR, IFR, VMC, IMC) and approach areas, wake vortex strength, and the quality of the warning.

7.4 List of questions and forthcoming actions

1. Can the wake vortex signal detected by lidar always non-ambiguously be differentiated from ambient turbulence ? Is it possible to discriminate hazardous and non-hazardous vortices from the signal ?
2. To improve vortex detection further, is it meaningful to combine the signals of velocity width, velocity and backscatter ?
3. Which is the necessary detection range of the lidar to enable avoidance operations ? The detection range for the approach mode used in *MFLAME* has been approved by end-users (Airbus Industries), but this must be confirmed by avoidance manoeuvre experiments in a flight simulator, taking into account ATM constraints.
4. How far can lidar as a fair weather tool assist the pilot under IFR ?
5. The step from the ground system to an airborne system is still ahead.
6. What is to do with the warning ? How much safety is gained when a pilot is aware of the upcoming encounter ? The purpose of the warning is to avoid, not to prepare. Nevertheless, there would be the side benefit that if a pilot couldn't get out of the way, he might not overreact as he knows what had hit the aircraft.
7. What is the proper ATM procedure in the DWA (detection, warning, avoidance) cycle ?

8 Wake vortex encounter

The overall hazard level will depend on flight conditions, particularly the height above the ground, and whether the aircraft suffers the maximum effects of the vortices by passing through the centre of a vortex or a much reduced effect when passing close to the vortex but not through the centre. It is useful to consider separately the potential severity of an encounter, which is a measure of the size of disturbances and is largely independent of height above ground, and the potential risk, where height above ground can be a crucial factor.

Mathematical or piloted simulations of encounters are difficult for many reasons, particularly the sensitivity of the severity of an encounter to the initial location and closure rates of an aircraft relative to the centres of vortices. Also an encounter of a vortex with a wing will possibly affect the subsequent vortex trajectory relative to the fin/tailplane and the strength remaining in the vortex. The subsequent encounter with the fin/tailplane will significantly influence initial yaw and pitch motion which are important factors during recovery from the encounter. There are also significant uncertainties in the knowledge of aircraft characteristics such as inertia, roll control power and many other key characteristics, particularly for executive, older and smaller aircraft that do not have a validated simulation definition package.

The present section will give a brief review of wake encounter modeling, mainly based on the work done in the EU projects *WAVENC* and recently in *S-Wake* and in the USA in connection with the AVOSS project and further in the UK in respect of helicopter encounters with wake vortices.

8.1 Aerodynamic encounter response models

Wake induced aerodynamic forces and moments are usually computed with an incremental model. Mostly, rather simple modeling strategies are applied, especially if the models have to be used in a real-time flight simulation environment. In *WAVENC* (de Bruin 2000a), both simple, like lifting–line, strip theory, and vortex lattice methods, and more advanced, like panel and Euler methods, have been compared with results from a wake encounter experiment in the large DNW-LLF wind tunnel. A satisfactory agreement between computed and measured results was observed. Simple methods can thus be used, provided a proper value for the gradient of the lift coefficient $C_{L\alpha}$ is known, see below and Rossow (1999). Therefore, the strip theory method from ONERA (Escande and Aurenche 1999) was implemented in the flight simulators of NLR and EADS in France.

The wake vortex induced change in lift ΔL and roll moment R experienced by a follower aircraft are defined as (see Table 2 for definitions)

$$\Delta L = \frac{\rho}{2} V^2 \int_{-\frac{B}{2}}^{\frac{B}{2}} c(y)\, c_L(y)\, dy \tag{26}$$

and

$$R = \frac{\rho}{2} V^2 \int_{-\frac{B}{2}}^{\frac{B}{2}} c(y)\, c_L(y)\, y\, dy. \tag{27}$$

The local lift coefficient is replaced by $c_L(y) = C_{L\alpha}\ \Delta\alpha(y)$, where $\Delta\alpha(y) = \arctan(W(y)/V) \approx W(y)/V$ is the change of the local angle of attack due to a vortex velocity component $W(y)$ normal to the wing plane at distance y from the wing root. Lift change and roll moment induced by the wake vortex then become

$$\Delta L = \frac{\rho}{2} V\, C_{L\alpha} \int_{-\frac{B}{2}}^{\frac{B}{2}} c(y)\, W(y)\, dy \tag{28}$$

and

$$R = \frac{\rho}{2} V\, C_{L\alpha} \int_{-\frac{B}{2}}^{\frac{B}{2}} c(y)\, W(y)\, y\, dy. \tag{29}$$

The roll moment coefficient induced by the wake vortex is given by

$$C_R = \frac{2R}{\rho V^2 S\, B} = \frac{C_{L\alpha}}{V\, S\, B} \int_{-\frac{B}{2}}^{\frac{B}{2}} c(y)\, W(y)\, y\, dy, \tag{30}$$

where $S = B^2/A_R$ is the projected wing surface of the wake encountering aircraft. We note that eqs. 28, 29, and 30 solely measure the response of the wake encountering aircraft in terms of the aircraft velocity, the lift–coefficient gradient, and the local chord as aircraft parameters and the local wing–normal velocity component of the wake vortex. The flying speed also influences the duration of an encounter. Automatic roll damping and any controlled reactions are not considered. ΔL and R do not provide definitions of “acceptable encounters”, since the acceptability of an encounter also depends on aircraft motion of inertia, roll control authority, pilot response delays, and aircraft altitude at the encounter (Hinton and Tatnall 1997 and Section 3.4). A more advanced approach, including roll damping and roll control, is given in the next section.

The ratio between wing spans of the generating and the following aircraft B_g/B_f determines which part of the wake is "felt" by the encountering aircraft. Studies with a model by Tatnall (1995) show that variations of B_g/B_f by a factor of 3 resulted in maximum lift and roll moment coefficients of -0.5 and 0.1 for a horizontal encounter, respectively (de Bruin 2000b). Small aircraft sense the wake vortex only in a very small region around the vortex core, whereas larger aircraft experience the disturbing effect (albeit with a lower amplitude) in a much larger region. (The same results are obtained for a vertical crossing of the vortex core.) Hence, the chance of a maximum severe wake encounter is relatively low for small aircraft because it has to hit the narrow region around the vortex core.

The local chord $c(y)$ can be expressed in terms of the wing taper ratio λ and root chord c_{root},

$$c(y) = c_{root}\left(1 - \frac{2|y|(1-\lambda)}{B}\right). \tag{31}$$

A taper ratio of 0.3 is typical for larger commercial airplanes. Smaller aircraft tend to have a larger taper ratio and calculations show that this leads to somewhat (up to 20%) larger roll moments.

The shape of the wake vortex velocity field has an influence on the magnitude of the aerodynamic forces and moments. Assumptions made for the vortex core size and for the shape of the velocity profile (see Section 3.2) will have an effect on the magnitude of the force coefficients when the aircraft enters the core region. Of course, small aircraft placed in the vortex core are more influenced by these assumptions than larger aircraft.

Jacquin et al. (2001) introduce a "rolling moment radius" defined by

$$r_{roll} = \frac{1}{\Gamma}\int_{-\infty}^{\infty}\int_{0}^{\infty}\omega_x\sqrt{(y-\overline{y})^2+(z-\overline{z})^2}\,dydz, \tag{32}$$

where $\overline{y}$ and $\overline{z}$ are the vortex centroïds defined in equations 23 and 24 in Section 4.2. This radius takes into account that an encountered vortex is not a point vortex but has a finite extension. It allows to quantify on how much the experienced roll moment is reduced when the vortex core has diffused to larger radii.

Elsenaar (2001) attempts, solely for the purpose of wake encounter studies, to define an average but constant level of tangential velocity v_θ in the vorticity core (named the "flat vortex") that is derived from the induced drag. When the so derived average velocity in the core is inserted in eq. 29, a good correspondence is found with the roll moment derived from velocity distributions as directly measured in the windtunnel.

8.2 Induced aircraft motions

The actual movements of an aircraft encountering a wake and the total and local loads experienced by the aircraft depend on the temporal evolution of the aerodynamic forces and moments during the encounter (e.g. on the wake intercept route). The wake induced forces cause accelerations and the moments cause angular accelerations. Induced roll and lateral accelerations may cause structural damage. Large accelerations may occur with short intense encounters, e.g., large gust–type loading when a wake vortex pair is crossed at large angles (Kuznetsov et al. 1996). Large roll or bank angles are to be expected with relatively slow wake intercepts, especially if the strength of the vortices induces roll moments that cannot be fully counteracted with the roll controls. Aircraft mass and its moments of inertia are important parameters affecting the maximum displacements and angular movements of the aircraft during the encounter. Control inputs are limited by the maximum available control power (size of control surfaces and maximum deflection angles).

Wake induced roll is the most important effect of a wake encounter. With I_{xx} as the roll moment-of-inertia, the equations for roll acceleration $\dot{p}$ (in rad/s^2) and the bank angle Φ (in rad) read

$$\dot{p} = \frac{R}{I_{xx}} \quad \text{and} \quad \dot{\Phi} = p. \tag{33}$$

We use Tatnall's (1995) one-degree of freedom model for the roll moment,

$$R = \frac{1}{2}\rho V^2 SB\,\left(C_{Rp^*}p^* + C_{Rv} - C_{Rc}\right), \tag{34}$$

to illustrate the main influencing factors. The dimensional and non-dimensional roll rates are denoted by p [rad/s] and $p^* = (pB)/(2V)$. The three coefficients in brackets represent the roll moment due to damping ($C_{Rp^*} < 0$), the vortex induced roll moment, and a counteracting roll moment from the roll controls. $C_{Rp^*} \approx -0.5$, depending on wing taper ratio and wing sweep angle. According to Roskam (1991), general commercial aircraft designs tend to attain $p^* = 0.07$ at maximum roll–control input. With $\dot{p} = 0$, we estimate $C_{Rc} = 0.07|C_{Rp^*}|$ for the maximum roll control input. It should be noted that this estimate is not very precise, but actual data for individual aircraft are rarely published.

Assuming that an aircraft suddenly experiences a constant wake induced roll moment C_{Rvm} at $t = 0$ and that maximum available (auto-) pilot reaction is given after some time delay t_c, we obtain for the roll acceleration

$$\dot{p} = K_2 p + K_1 \left(C_{Rvm} - C_{Rc}\, H(t - t_c) \right). \qquad (35)$$

$H(t-t_c)$ is the unit–step function, which returns a value of 1 if $t > t_c$ and 0 elsewhere. Further, $K_1 = 0.5\rho V^2 B^3/(A_R\, I_{xx})$ and $K_2 = 0.5 K_1 C_{Rp^*} B/V$. Note that with a constant disturbing roll moment the aircraft will attain a constant maximum roll-rate after a certain time. This roll rate is given by

$$p_{end} = \frac{K_1}{K_2} C_{Rvm} = \frac{2VC_{Rvm}}{C_{Rp^*}B}. \qquad (36)$$

The ratio between the exposed roll moment and the maximum available roll control is an important parameter for the potential roll controllability of the aircraft during encounter. The ratio is defined by

$$\Re_c := \frac{C_{Rvm}}{C_{Rc}} \approx \frac{C_{Rvm}}{0.07|C_{Rp^*}|}. \qquad (37)$$

A suddenly occuring roll moment will induce a large roll acceleration initially. Roll accelerations are important for the structural loads. The acceleration of the wing tip induces a wing tip load factor n_{tip} that is proportional to $\dot{p}$. For a suddenly applied roll moment the wing tip load factor becomes

$$n_{tip} = \frac{\dot{p}(0)B/2}{g} = \frac{K_1 C_{Rvm} B/2}{g} \qquad (38)$$

with g=9.81 m/s^2. It should be noted that in practice the aircraft will more gradually experience a wake induced roll moment and actual roll induced load factors will probably be much lower.

In a study of helicopter response by Padfield & Turner (1999) a fully non-linear flight mechanics model of a conventional helicopter has shown that flight near the vortex core can result in significant attitude transients in both pitch and roll. Outside the core there is a significant response in heave only. Using existing handling qualities criteria for helicopters following system failures it has been concluded that the observed attitude transients can be potentially hazardous but only when the helicopter and vortex core are in direct collision. The use of handling qualities metrics in this way is seen as a good framework worthy of further development.

8.3 An example

The equation for roll motion has been solved for the range of aircraft in Hinton and Tatnall (1997), using the airplane data collection from Stuever (1995). The following (simplifying and worst–case) assumptions were made:

- the generating aircraft is a B747-400 in maximum landing weight, flying along ILS path;
- wake circulation strength is computed from flying speed and weight, the Hallock-Burnham model (eq. 14) is used for the wake induced velocities with $r_c = 0.05B$ and no wake decay is assumed;
- the following aircraft fly at their normal ILS speed in (most severe) minimum landing weight conditions;
- at time $t = 0$ a sudden roll moment is assumed with an amplitude equal to the maximum roll moment for the pertaining aircraft combination.

With the sketched procedure the predicted roll accelerations are very large initially but decrease rapidly and approach zero asymptotically due to the roll damping. The roll rate is initially zero but increases rapidly until it attains a constant value (e.g., about 60° /s for a B737-500), when the assumed vortex induced roll moment is fully balanced by the roll damping roll moment.

The roll control ratio $\Re_c$ for different aircraft, sizing from an ATR-72 up to a B747-400, which encounter the vortex core of a B747 for 1 s, are shown in Figure 5. The simple analysis shows that all of these aircraft are unable to stay in the vortex core but will roll despite the maximum roll control inputs. When they fly faster (at maximum landing weights), $\Re_c$ becomes somewhat smaller. Hence, heavier aircraft, in principle, have higher controlability in a given wake.

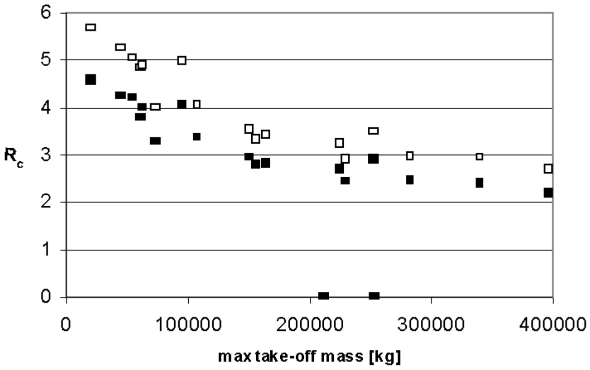

Figure 5: The ratio between the wake–induced roll moment and the maximum available roll control moment $\Re_c$ for aircraft of different sizes flying 1 sec in the vortex core of a B747-400 at maximum landing weight; open (closed) symbols: the encountering aircraft is at minimum (maximum) landing weight.

Note that this is by all means a worst–case example. Moreover, model encounter studies show that maximum disturbances only occur over a narrow range of initial position and closure rates relative to the position of the vortices. Disturbance levels rapidly reduce for encounters only a small distance outside this critical range of conditions. This is confirmed by the wide variation in disturbance levels and rare occurrence of maximum disturbances in piloted simulations.

For a more accurate prediction of the aircraft movement in the wake it is necessary to solve a more extended set of flight mechanic equations. The solution will not only depend on the properties of the aircraft pair, but also on the initial conditions of the wake vortex intercept route, see Section 3.4. Several-degrees-of-freedom models are used to simulate this behaviour. A proper pilot control model will however be needed. Results of such a reduced model should be compared with that of more extended flight simulations (as planned in *S-Wake*).

8.4 Pilot simulation training

It seems very doubtful that adding simulated training specifically for wake vortex encounters would improve safety. It is important to remember that pilots have little influence on the size of the initial roll disturbance if they encounter a strong vortex. Thus the most important training requirement is for speedy and safe recovery from unusual attitudes. General training in recovery from unusual attitudes is more important than the cause of that unusual attitude. Unusual attitudes can arise from engine, system, and instrument malfunctions, from severe wind shear, or from a wake vortex encounter.

Further, the unpredictability of the magnitude of disturbances in a simulated encounter with wake vortices makes it very difficult, if not impossible, to structure effective training or evaluation scenarios. Studies within *S-Wake* showed a randomness in the severity of encounters despite the fixed location of vortices relative to the nominal flight path. This made it impossible to conduct controlled parametric studies. However pilots found the simulations convincing, and simulation will be an important tool for evaluating operational procedures.

8.5 List of questions and problems

1. Is the often made assumption that local lift is a linear function of the local angle of attack valid if locally very large flow angles occur (e.g. close to the vortex core) ? Then, the locally predicted lift can very well exceed the maximum lift coefficient of the local airfoil section.

2. Simple methods such as the strip method require an assumption for $C_{L\alpha}$. There is no real consensus in literature which value should be used for this parameter (Rossow 1999). It is also not clear if the same value should be used for calculating the wake-induced lift. The approach chosen by Escande and Aurenche (1999) with an elliptic loading correction near the wing tips and the particular definition for $C_{L\alpha}$ seems to work well. For simple methods $C_{L\alpha}$ is basically a tuning parameter.

3. For rapid wake encounters under large intercept angles, it is not certain that the quasi-steady methods used to compute the disturb-

ing forces and moments are really appropriate. This should be checked with simple unsteady aerodynamic methods.

4. The evaluation of aircraft movements during wake encounter requires proper estimates for the moments of inertia, the (roll) damping coefficient(s) and the available (roll) control power of the particular aircraft. These parameters are generally not constant. The roll moment of inertia, for example, depends strongly on the amount of fuel in the wings. The roll-damping will depend on the setting of the high lift devices, and the available roll control power may depend on the auto-pilot settings (mode). With pilot in command the available roll control power is usually larger than with auto-pilot. Accurate values for these parameters seem hard to obtain, but are essential for a proper analysis, e.g., in a probabilistic approach.

9 Wake vortex safety assessment

Pilots and passengers rightly consider that any risk that is significant and can be identified must be avoided. It is essential to note that vortices are not expected to have disappeared, but only to have become insignificant. That is, vortices are insignificant for the follower aircraft when they have left the flight corridor or decayed to moderate turbulence. Aircraft are designed to operate safely in moderately turbulent and mild wind shear conditions. Other typical situations where aircraft operate safely in less than ideal situations include poor visibility, and system or even engine failures. Thus it is reasonable to expect an aircraft to operate safely in the presence of wake vortices that will not cause disturbances greater than those regularly encountered during moderate turbulence.

Although the current separation minima have 'proven to be sufficiently safe', the current safety level is unclear and there is a deficiency of validated tools to support new developments in operational usage at busy airports. Speijker et al. (2000a) and Kos et al. (2000) propose a probabilistic model to assess safety, and to evaluate the relation between wake vortex induced risk and aircraft separation distances. To evaluate wake vortex safety of different ATM concepts or procedures, operational requirements, procedural aspects, and human involvement (ATC and pilots) are important elements to be taken into consideration, in addition to the physical evolution of wake vortices.

To support the development of validated safety assessment models and tools, and for the purpose of incident and accident investigation, it is also important to gather and analyze incident/accident hazard data, e.g. through pilot reports on roll upsets attributed to wake vortex encounters. Such voluntary reports have been collected in the UK since 1972. However, it is not known how close the reported rate of encounters is to the actual rate of encounters, nor whether the reporting rate varies from year to year. The EU project *S-Wake* aims to address this issue through the development of an algorithm to detect and analyse vortex encounters from Flight Data Recorders (FDR). The algorithm will then be applied to large numbers of FDRs in order to validate the safety assessment models and tools.

9.1 Risk–based policy making

A safety management approach to regulate and control wake vortex induced risk can best be based on an assessment of accident risk probabilities, followed by a comparison with risk criteria. This requires the development of a probabilistic relation between the occurrence of wake vortex encounter severity and risk metrics that are related to the severity of accidents, incidents and related conditions.

For incident and accident investigation purposes, ICAO definitions are accident, serious incident, non-serious incident, and non-determined incidents (ICAO 1998, 1994). For safety assessment purposes, JAA has defined severity classes for adverse conditions: catastrophic, hazardous, major, and minor (JAR-25 1994). The above two classification schemes can be combined into a classification of wake vortex induced risk events (Speijker et al. 2000a, Kos et al. 2000):

1. *Catastrophic accident*: the aircraft encountering a wake vortex hits the ground, resulting in loss of life.
2. *Hazardous accident*: the wake vortex encounter results in one or more on-board fatalities or serious injuries (but no crash into the ground).
3. *Major incident*: the wake vortex encounter results in one or more non-serious injuries, but no fatality, on-board the encountering aircraft.
4. *Minor incident*: the wake encounter results in inconvenience to occupants or an increase in crew workload.

The next step is to introduce for each of these four classes suitable risk metrics to regulate and control wake vortex induced risk, such as risk event probability per movement and per year. Guidelines for the selection of risk metrics and the assessment of safety requirements are being developed by FAA/Eurocontrol Action Plan 3 and Eurocontrol (2000a,b) and listed in Speijkers et al. (2000b) and Mason & Kershaw (2000). Interest groups (regulators, pilots, controllers, safety analysts) shall be involved and gain acceptance of a risk criteria framework to be used within risk based policy making.

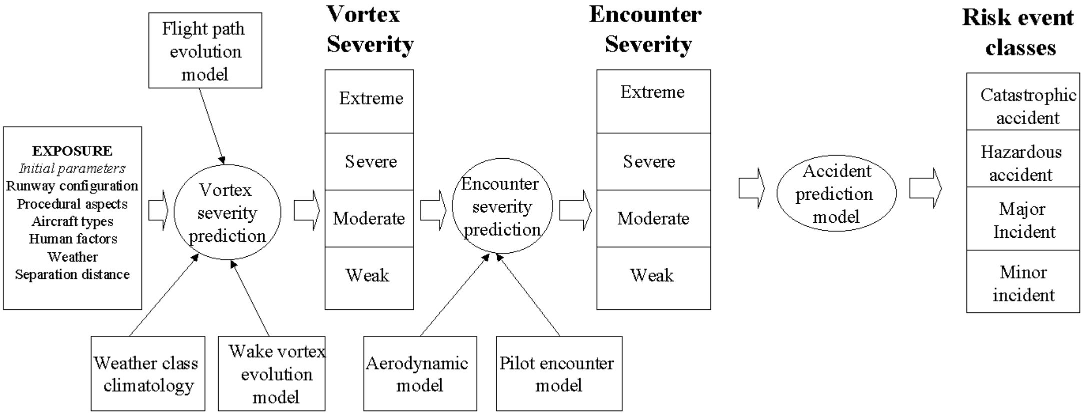

Figure 6: Safety modeling relations.

Figure 6 depicts safety modeling relations where classes of vortex severity are related to the wake–encounter severities which further on are mapped on the risk event classes.

9.2 Probabilistic safety assessment

Speijker et al. (2000a) and Kos et al. (2000) propose a probabilistic approach for the evaluation of wake vortex safety under various operational and weather conditions. It includes probabilistic sub-models for all uncertain phenomena as wake evolution, wake encounter, and flight path evolution. It allows evaluation of current practice flight regulations and new concepts (e.g., new operational improvements, aerodynamic aircraft designs, or weather based separation distances).

This probabilistic approach supports two commonly accepted rationales for acceptance of a newly proposed ATM concept by involved interest groups (i.e., pilots, controllers, regulators) by showing that the number of wake vortex induced risk events

- does not exceed some pre-defined and agreed safety requirements and
- does not increase with the introduction of a new ATM procedure.

The proposed model is based on publicly available wake vortex evolution models (Corjon & Poinsot 1996) and wake encounter models (Kuzmin 1997, Woodfield 1995) and extended with probabilistic wind field models including the impact of wind in the lateral and vertical direction.

9.3 Safety assessment with FDR data

An algorithm to detect and classify vortex encounters from Flight Data Recorder is under development within the *S-Wake* project. This algorithm will then be applied to FDRs from arrivals of a major British airline at London over the period of one year. Up to 80,000 flights will be analysed, and parameters from all the flights (such as aircraft type, landing weight, separation from leading aircraft, meteorological conditions) will be collected (Kershaw & Mason 2000).

The data will be analysed for relationships between the frequency/severity of encounters and other parameters such as the meterological conditions (e.g., wind speed/direction) or separation at encounter. The analysis is intended to give empirical information on minimum safe separations, for example in different weather conditions.

The information will also be used to validate the safety assessment models and tools developed within other parts of *S-Wake*. For example, the numbers and frequency of vortex encounters found empirically will be used to validate those predicted from the probabilistic approach.

9.4 Model validation with encounter data

To assess the probability of occurrence of each risk event, a probabilistic relation between encounter metrics and risk events is under development. An advantage of such an approach is that it allows the validation of the modeling relations with encounter data from, for example, the collection and analysis of large amounts of FDR data (Kershaw & Mason 2000, Haverdings 2000). Several encounter metrics can be used, see Section 3.4. To classify the possible encounter events and risk events, see Figure 6, numerical boundary values that separate the classes need to be defined and agreed.

As the encounter severity metric, such a probabilistic relation needs to include factors as height above threshold, pilot behaviour (both reactive and anticipative), autopilot behaviour and roll control capabilities of the involved aircraft. Further factors are weather at the time of occurrence and the degree of ambient turbulence before the encounter.

9.5 List of questions and actions

Research is continuing in the following key areas that deserve significant modeling effort:

- probabilistic modeling of navigation performance and long landing models under different navigation modes and various wind conditions;
- modeling of auto-pilot reactions to wake roll upset, and missed approaches initiated by pilots as a reaction to experiencing a roll upset during the ILS approach;
- modeling performance and anticipation of humans (pilots and ATC) to wake vortices;
- modeling of wake vortices bursting and linking under different weather conditions;
- weather conditions, in particular wind fields, turbulence, stable stratification and wind shear.

Further specific questions comprise:

1. Which parameters should be used to express the severity of a wake encounter ? What is the relation of these parameters to encounter data ?
2. How can the boundary values be defined that distinguish encounter severity classes ?
3. How to assess safety requirements for the risk event classes ?
4. How can the probabilistic relation between the wake encounter severity classes and the risk event classes be determined ?
5. How can the encounter severity classes be related to rating scales that can be used by pilots to express their subjective opinion on the consequences of an encounter ?
6. How to define pilot encounter reports such that the results can be fed back into the safety assessment of an ATM procedure ?
7. How to use safety assessment feedback results to establish ATM procedures ?

10 Conclusion

Since several years now, research in Europe on aircraft wake vortices is being supported by public funds of several nations and the European Union, and by (potential) purchasers as aircraft manufacturers, airspace controllers and airport service providers. The research areas cover prediction, monitoring, detection, characterization, and safety assessment of wake vortices.

The primary objective is to avoid potentially hazardous wake encounters for aircaft, especially on final approach towards an airport. Diminishing aircraft separation distances (even for VLTA) under most meteorological conditions, whilst keeping or even increasing the safety level, is the ultimate goal. Reduced time delays and increased airport capacity will be the benefits of these joint and ambitious ventures.

Remarkable progress has been achieved through the programmes:

- The experimental facilities, measurement techniques, and the methods in computational fluid dynamics for vortex flows have been improved.
- The vortex physics, in particular the roll-up process and the dynamic instabilities of vortex pairs, is much better understood. This is a major step towards wake characterization and control. Different concepts to achieve wake alleviation in the far field have been developed.
- The impact of the atmosphere on wake vortex transport and decay is largely understood when the ambient influences are treated separately. Real-time engineering models are developed and partly improved to predict the vortex behaviour in the terminal area of an airport.
- It has been demonstrated that the aircraft vortices can be detected along the glide path with ground based coherent laser radar (lidar). Based on this system, airborne detection seems practicable.
- The aerodynamic effects on an aircraft encountering a wake vortex have been investigated with flight simulators, wind tunnels, mathematical models and in full–scale flight.
- The development of a wake vortex safety assessment for new approach procedures is underway. Owing to the large variations in weather and operational issues, such an assessment will be based on probabilistic and statistical grounds.

Despite these advances, there are still open issues of crucial importance. A few are listed below:

- A proved method to characterize and control wake vortices from the near field to the far field is not available.
- Operational wake vortex forecast and monitoring in the terminal area are not yet feasible at reasonable costs.
- An elaborated sequence of detection, warning and avoidance (DWA) for the wake–vortex problem is necessary for the daily air traffic management. Work just started here.
- A valid and agreed definition of a hazardous vortex encounter is still lacking.

The ongoing research in the various European and national wake vortex programmes and future projects will certainly close some of these gaps in the next three to five years.

Acknowledgement. We gratefully acknowledge the discussions with many personalities, mostly during the four WakeNet workshops. We are especially indepted to Gerry Elphick and Chris Hume (AUK), Alex Fisher (British Airways), Florent Laporte and Henri Moet (CERFACS), Graham Turner and Rob Young (DERA), Michael Frech, Thomas Hofbauer, and Friedrich Köpp (DLR), Olivier Atinault and Klaus and Karen Hünecke (EADS-Airbus), Stefan Wolf (IFALPA), Andy Kershaw and Simon Mason (NATS), Henk Blom and Henk Haverdings (NLR), Hubert Combe (Thales-Sextant), and Gregoire Winckelmans (UCL) for their recurrent help to shape the idea of the position paper.

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12 Glossary

ATM/ATC Air Traffic Management / Control
AUK Airbus United Kingdom
AVOSS Aircraft VOrtex Spacing System
CFD Computational Fluid Dynamics
CTI Coherent Technology Inc.
CERFACS Centre Européen de Recherche et Formation Avancées en Calcul Scientifique
DERA Defence Evaluation and Research Agency
DFS Deutsche Flugsicherung GmbH
DLR Deutsches Zentrum für Luft– und Raumfahrt
DNW Deutsch–Niederländische Windkanäle
DWA Detection Warning Avoidance
EADS European Aeronautic Defence and Space Company
FAA Federal Aviation Administration
FAG Flughafengesellschaft Frankfurt am Main
FDR Flight Data Recorder
HALS/DTOP High Approach Landing System / Dual Threshold Operation
HSVA Hamburger Schiffs–Versuchs–Anstalt
ICAO International Civil Aviation Organization
IFALPA International Federation of Air Line Pilots' Associations
IFR Instrumented Flight Rules
ILS Instrumented Landing System
IMC Instrumented Meteorological Conditions
INSEAN Istituto Nationale per Studi ed Esperienze di Architettura Navale
JAA Joint Aviation Authorities
LAD Laser Doppler Anemometry
LBA Luftfahrt–Bundesamt
LES Large Eddy Simulation
LVV Low Vorticity Vortex
NATS National Air Traffic Services Ltd.
NLR Nationaal Lucht– en Ruimtevaartlaboratorium
ONERA Office National d'Etudes et de Recherches Aérospatiale
PIV Particle Image Velocimetry
QDV Quickly Decaying Vortex
RASS Radio Acoustic Sounding System
RSS Reduced Separation System
SOIA Simultaneous Offset Instrumented Approach
SWIM Simple Wall Interference Model
STNA Service Technique de la Navigation Aerienne
SYAGE SYstème Anticipatif de Gestion des Espacements
TUD Technical University of Delft
UCL Université Catholique de Louvain
VLTA Very Large Transport Aircraft
VFR Visual Flight Rules
VMC Visual Meteorological Conditions
WSG WasserSchleppkanal Göttingen
WSWS WirbelSchleppenWarnSystem