PERGAMON

Progress in Aerospace Sciences 38 (2002) 181–208

PROGRESS IN AEROSPACE SCIENCES

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Commercial aircraft wake vortices

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Abstract

This paper discusses the problem of wake vortices shed by commercial aircraft. It presents a consolidated European view on the current status of knowledge of the nature and characteristics of aircraft wakes and of 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 aircraft. Shortened aircraft separations under appropriate 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 and services. © 2002 Published by Elsevier Science Ltd.

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0376-0421/02/$ - see front matter © 2002 Published by Elsevier Science Ltd.
PII: S0376-0421(02)00004-0

Glossary

European research projects on aircraft wake vortices

ATC-Wake: Project on Integrated Air Traffic Control Wake-vortex Safety and Capacity System, co-funded by the European Commission under Project Number IST-2001-34729 from 2002 to 2005.

C-Wake: Project on Wake-vortex Characterisation and Control, co-funded by the European Commission under Project Number GRD1-1999-10332 from 2000 to 2002.

EUROWAKE: Project on Wake-vortex Formation of Transport Aircraft, co-funded by the European Commission under Project Number BE95-1085 from 1996 to 1999.

I-Wake: Project on Instrumentation Systems for on-board Wake-Vortex and other Hazards Detection Warning and Avoidance, co-funded by the European Commission under Project Number GRD1-2001-40176 from 2002 to 2005.

MFLAME: Project on Multi-Function Future Laser Atmospheric Measurement Equipment, co-funded by the European Commission under Contract Number BRPR-CT96-182 from 1996 to 2000.

S-Wake: Project on Assessment of Wake-Vortex Safety, co-funded by the European Commission under Project Number GRD1-1999-10695 from 2000 to 2002.

WakeNet: Thematic Network on Aircraft Wake Vortices, funded by the European Commission under Contract Number BRRT-CT98-5050 from 1998 to 2002.

WakeNet II: Thematic Network on Aircraft Vortices II, funded by the European Commission from 2002 to 2005.

WAVENC: Project on Wake-Vortex Evolution and Encounter, co-funded by the European Commission under Contract Number BRPR-CT97-0593 from 1998 to 1999.

Other abbreviations

ATC/ATM: Air Traffic Control/Management
AVOSS: Aircraft VOrtex Spacing System by NASA
CFD: Computational fluid dynamics

CTI:	Coherent Technology Inc., USA
CERFACS:	Centre Européen de Recherche et Formation Avancée en Calcul Scientifique, France
DFS:	Deutsche Flugsicherung GmbH, Germany
DLR:	Deutsches Zentrum für Luft—und Raumfahrt e.V., Germany
DNW:	Deutsch–Niederländische Windkanäle
DWA:	Detection warning avoidance
FAA:	Federal Aviation Administration, USA
FAG:	Flughafengesellschaft Frankfurt am Main, Germany
FDR:	Flight data recorder
HALS/DTOP:	High Approach Landing System/Dual Threshold Operation
HSVA:	Hamburger Schiffs–Versuchs–Anstalt, Germany
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, Italy
JAA:	Joint Aviation Authorities
LAD:	Laser Doppler Anemometry
LES:	Large eddy simulation
LVV:	Low vorticity vortex
NATS:	National Air Traffic Services Ltd., Great Britain
NLR:	Nationaal Lucht—en Ruimtevaartlaboratorium, The Netherlands
ONERA:	Office National d'Etudes et de Recherches Aérospatiale, France
PIV:	Particle image velocimetry
QDV:	Quickly decaying vortex
QinetiQ:	Formerly the Defence Evaluation and Research Agency (DERA), Great Britain
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 Aérienne, France
SYAGE:	SYstème Anticipatif de Gestion des Espacements
TUD:	Technical University of Delft, The Netherlands
UCL:	Université Catholique de Louvain, Belgium
VFR:	Visual flight rules
VMC:	Visual meteorological conditions
WSG:	WasserSchleppkanal Göttingen
WSWS:	WirbelSchleppen WarnSystem

1. Introduction

The purpose of this paper is to summarize the present day 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.

This text manifests a revised and condensed version of the position paper on aircraft wake vortices which has been initiated within the European Thematic Network *WakeNet*. That network comprises partners from research and industry to collocate the wide spread efforts and to guide ongoing and future work in R&D for aircraft wake vortices, see Glossary for a list of related European projects.

1.1. Motivation

Wake turbulence is one of the main reasons for capacity problems in the air-transportation 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. 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) divided 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 in the present. In view of the strong growth of air traffic, increasing demands on the capacity and safety of international airports have to be faced [119]. 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.

Table 1
ICAO aircraft separation distances to avoid wake vortex encounter

Leader aircraft (max. take-off weight)	Follower aircraft	Separation (nautical miles)	Time delay (s) (approach speed 70 m/s)
Heavy ($\geqslant$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 s) or 2.5 NM (66 s) applies.

- 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 not fully adequate.
- Airport capacity is ultimately limited by the separation standards.

In order to increase airport capacities whilst at least maintaining safety levels, the knowledge of wake-vortex behaviour under varying meteorological conditions achieves utmost 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 signifies a great challenge to fluid mechanics research and aircraft design. Better knowledge of the wake-vortex behaviour in typical atmospheric environments could lead to two types of improvement which may be classified as *tactical* or *strategic* [121]:

- On the *tactical* side we expect considerable scope for local hour-by-hour air traffic 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 all project phases.

1.2. Definition and properties of wake vortices

Wake vortices shed by an aircraft are a natural consequence of its lift, see, e.g., Donaldson and Bilanin [26]. 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 the 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. Fig. 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 has a strong circulation, which is proportional to the weight of the aircraft, and a significant size in the order of 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 [20] lead to connection, pinching of vortex rings and subsequent decay. Properly disturbed counter-rotating vortices in a four-vortex system may also develop cooperative instabilities at

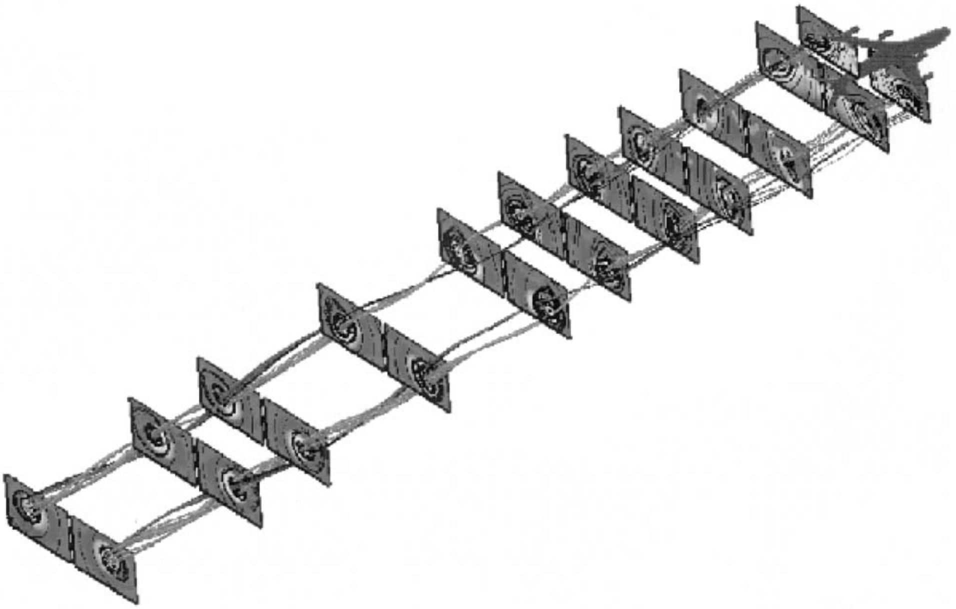

Fig. 1. Wake roll-up from 0 to 6.4 spans behind an A340 high-lift model with lift coefficient of 1.76 in DNW wind tunnel; courtesy by K.&C. Hünecke, Airbus Deutschland.

shorter wavelength which trigger the transition to turbulent and less coherent primary vortices.

In the past 3 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 series of new questions and problems. A detailed overview (with many references) over the research activities in the USA has been carried out by Rossow [97]. Hinton et al. [52] describe the efforts to design an aircraft vortex spacing system for airport capacity improvement. Vyshinsky [123] summarized the recent research efforts at the Central Aerohydrodynamic Institute (TsAGI) in Russia.

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-instrusive 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 dissipation rate, 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 wake-vortex safety assessment approach 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 Pilot's 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 divided 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 5–9 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 $\Gamma(y)$:

$$s = \frac{2}{B}\int_0^{B/2} \frac{\Gamma(y)}{\Gamma_0}\,\mathrm{d}y. \tag{1}$$

From measurements it is straight forward to obtain b_0 when one vortex pair is present after roll-up. When more

Table 2
Aircraft and wake parameters

Mass of aircraft	M (kg)
Wing span	B (m)
Wing area	A (m^2)
Aircraft speed, free stream velocity in wind tunnel	V (m/s)
Local chord	$c(y)$ (m)
Lift coefficient (local)	$c_{\mathrm{L}}(y)$ (–)
Lift coefficient (global)	C_{L} (–)
Wing aspect ratio	$A_{\mathrm{R}} = B^2/A$ (–)
Spanwise load factor	s see Eq. (1) (–)
Gravitational acceleration	g (m/s^2)
Air density	ρ (kg/m^3)
Root circulation	Γ_0 (m^2/s)
Vortex core radius (maximum tangential velocity)	r_{c} (m)
Reference length, initial vortex spacing	$b_0 = sB$ (m)
Reference velocity, descend 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 length	$x^* = x/b_0 = x'/s$ (–)
Normalized time, recommended	$t^* = t/t_0$ (–)
Normalized velocity	$v^* = V/w_0$ (–)

than one vortex behind each wing is considered, the reference length b_0 can be computed from the separation of the vortex centroids, see Eqs. (13) and (14). Alternatively, one can compute s and, thus, b_0 when the local circulation or the spanwise wing load

$$\Gamma(y) = 0.5 c_{\mathrm{L}}(y) c(y) V \tag{2}$$

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 as for example in high-lift configurations. It seems that the effect of non-elliptically loaded high-lift wings on s is compensated by the (opposite) circulation which is introduced by the horizontal tail plane. 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

$$t_0 = 2\pi \frac{b_0^2}{\Gamma_0} = 2\pi s^2 \frac{B^2}{\Gamma_0}. \tag{3}$$

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 momentum of its rolled-up wake,

$$\frac{\rho C_{\mathrm{L}}}{2A_{\mathrm{R}}} B^2 V^2 = \rho V b_0 \Gamma_0. \tag{4}$$

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

$$\Gamma_0 = \frac{C_{\mathrm{L}} V B}{2 s A_{\mathrm{R}}}. \tag{5}$$

When the forces which act on the aircraft are in balance (as for real flying aircraft but, e.g., not necessarily in wing 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 Mg, and Γ_0 can then be obtained by

$$\Gamma_0 = \frac{Mg}{\rho s B V}. \tag{6}$$

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 as

$$t_0 = 4\pi s^3 A_{\mathrm{R}} \frac{B}{C_{\mathrm{L}} V}. \tag{7}$$

With this formula for t_0 it becomes evident that the spanwise load factor s of the initial vortex spacing has a large influence on the reference time scale.

2.2. Normalized time, length, and velocity

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

$$w_0 = \frac{b_0}{t_0} = \frac{sB}{t_0} = \frac{C_{\mathrm{L}} V}{4\pi s^2 A_{\mathrm{R}}} \tag{8}$$

and

$$v^* = V/w_0 = 4\pi s^2 \frac{A_{\mathrm{R}}}{C_{\mathrm{L}}}. \tag{9}$$

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

$$t^* = \frac{x}{V t_0} = \frac{x^*}{v^*} = \frac{x'}{s v^*} = x^* \frac{C_{\mathrm{L}}}{4\pi s^2 A_{\mathrm{R}}}, \tag{10}$$

making use of definitions in Table 2 and Eq. (9). Eq. (10) shows that the relation of the non-dimensional length $x^* = x/b_0$ to the normalized age t^* depends on the factor v^*. In other words, to determine the age of a vortex system, the often used normalized length $x' = x/B = sx^*$ can be used non-ambiguously between different experiments (especially in different facilities with different models) *only* when $s^3 A_R/C_L$ 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 aircraft (and aircraft models) at different flight stages (cruise, landing, take-off) with different flight characteristics are compared.

Recently, doubts have been raised whether this scaling is also appropriate for aircraft configurations that deviate substantially from configurations of commercial aircraft for which the aspect ratios range from 7 to 9. For example, extremely long living vortices have been observed behind fighter aircraft with a typical aspect ratio of 3 [70].

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 (accordingly scaled) 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 dimensional distances translate for the smaller A340 to 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 4–5% 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 [94,96,58] suggest that the wake circulation has decayed to 20–40% of its initial strength between $4t_0$ and $6t_0$, regardless of the value of t_0 (at least for civil transport aircraft with large wing aspect ratios). 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.

We recall that in order to characterize the wake at the interesting distances of 3–6 nautical miles, we have to gain normalized wake ages t^* of typically 2.5–5 in the various facilities like wind tunnels, catapults, and water tanks, see Table 3. Assuming an aircraft model with a span of 1.2 m, these ages cannot be achieved in classical wind tunnels and small water tanks. Only at large water towing tanks or catapult facilities with a depth/height of around 6 m or more, we expect to achieve sufficiently high ages. A detailed analysis is given in Ref. [39].

Table 3
Parameter and reference time for A340-300 and B747-400 aircraft with $s = \pi/4$

		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)	60.0	75.0	240.0	80.0
	A_R	9.26	9.26	7.0	7.0
	C_L	1.386	1.386	0.448	1.178
	Γ_0 (m^2/s)	11.4	431.0	630.0	552.0
	t_0 (s)	1.36	32.7	25.4	29.1
	v^* (–)	51.8	51.8	121.1	46.1
2.5 nm = 4630 m	x' (–)	77[a]	77	72	72
	t^* (–)	1.9	1.9	0.76	2.0
3 nm = 5556 m	x' (–)	92[a]	92	86	86
	t^* (–)	2.3	2.3	0.91	2.4
6 nm = 11112 m	x' (–)	184[a]	184	172	172
	t^* (–)	4.6	4.6	1.8	4.8

[a] 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. 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.

3. How to characterize wake vortices

To allow for the comparison of data from different sources it is recommended to properly choose and 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. We define a coordinate system with origin in the centre of gravity of the aircraft and x, y, z defining the axes of flight, span, and height, respectively.

3.1. Vortex parameters

Tangential velocity $v_\theta = \sqrt{(v^2 + w^2)}$, normalized by w_0: $v_\theta^* = v_\theta / w_0$, is the most obvious feature of a swirling flow.

Axial vorticity $\omega_x = \partial w/\partial y - \partial v/\partial z$, normalized by t_0: $\omega_x^* = \omega_x t_0$, describes the vorticity of a straight (young) vortex. 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.

Circulation $\Gamma(r)$ (where r is the distance from the vortex centre), normalized by Γ_0: $\Gamma^* = \Gamma/\Gamma_0$, is one pertinent parameter of a coherent vortex and also expresses the amount of vortex hazard. The circulation is defined by

$$\Gamma = \oint v_\theta \, \mathrm{d}s = \int_{-\infty}^{\infty} \int_0^{\infty} \omega_x \, \mathrm{d}y \, \mathrm{d}z. \tag{11}$$

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

$$\Gamma(r) = 2\pi r v_\theta(r). \tag{12}$$

Vortex core position can be determined by searching the position of the maximum vorticity magnitude (or similar measures) or from computing the centroids $\bar{y}$ and $\bar{z}$ over one half-plane of the wake by

$$\bar{y} = \frac{1}{\Gamma} \int_{-\infty}^{\infty} \int_0^{\infty} y \omega_x \, \mathrm{d}y \, \mathrm{d}z, \tag{13}$$

$$\bar{z} = \frac{1}{\Gamma} \int_{-\infty}^{\infty} \int_0^{\infty} z \omega_x \, \mathrm{d}y \, \mathrm{d}z. \tag{14}$$

Core radius r_c (when roll-up is completed), normalized by b_0: $r_\mathrm{c}^* = r_\mathrm{c}/b_0$, defines the distance from the vortex centre where v_θ is maximum.

Dispersion radius r_d, normalized by b_0: $r_\mathrm{d}^* = r_\mathrm{d}/b_0$, provides a measure for the dispersion of axial vorticity in the (y, z)-plane:

$$r_\mathrm{d}^2 = \frac{1}{\Gamma} \int_{-\infty}^{\infty} \int_0^{\infty} ((y - \bar{y})^2 + (z - \bar{z})^2) \omega_x \, \mathrm{d}y \, \mathrm{d}z. \tag{15}$$

Vortex separation b, normalized by b_0: $b^* = b/b_0$, describes the local distance between the centres of both vortices. For undisturbed wakes, b is parallel to the y-axis.

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

The integrations (11), (13), (14) and (15) are limited to one half-space cross-section behind the aircraft; when external forces are present (shear, buoyancy, ground), which produce additional background vorticity around a vortex, the integration domain must be adjusted accordingly.

3.2. Vortex models

Here we list some fomulae 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 [50]). The velocity field induced by a trailing vortex pair is achieved by superimposing the flow of two modelled vortices with opposite circulation.

Rankine vortex

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r_\mathrm{c}} \frac{r}{r_\mathrm{c}} \quad \text{for } r \leqslant r_\mathrm{c},$$
$$v_\theta(r) = \frac{\Gamma_0}{2\pi r} \quad \text{for } r > r_\mathrm{c}. \tag{16}$$

Lamb–Oseen vortex [75]

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r} \{1 - \exp(-1.2526 (r/r_\mathrm{c})^2)\}. \tag{17}$$

Hallock–Burnham vortex [7]

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r} \frac{r^2}{r^2 + r_\mathrm{c}^2}. \tag{18}$$

Adapted vortex (Proctor [87])

$$\begin{aligned} v_\theta(r) &= 1.4 \frac{\Gamma_0}{2\pi r} \{1 - \exp(-10 (r_\mathrm{c}/B)^{0.75})\} \\ &\quad \times \{1 - \exp(-1.2526 (r/r_\mathrm{c})^2)\} \quad \text{for } r \leqslant r_\mathrm{c}, \\ v_\theta(r) &= \frac{\Gamma_0}{2\pi r} \{1 - \exp(-10 (r/B)^{0.75})\} \quad \text{for } r > r_\mathrm{c}. \end{aligned} \tag{19}$$

Smooth blending vortex profile (Winckelmans et al. [124])

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r} \left\{ 1 - \exp\left(- \frac{\beta_\mathrm{i} (r/B)^2}{\{1 + [(\beta_\mathrm{i}/\beta_\mathrm{o})(r/B)^{5/4}]^p\}^{1/p}} \right) \right\}, \tag{20}$$

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

Multiple scale vortex (Jacquin et al. [65])

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r_\mathrm{i}} \frac{r}{(r_\mathrm{i} r_\mathrm{o})^{1/2}} \quad \text{for } r \leqslant r_\mathrm{i}$$
$$v_\theta(r) = \frac{\Gamma_0}{2\pi (r_\mathrm{o} r)^{1/2}} \quad \text{for } r_\mathrm{i} \leqslant r \leqslant r_\mathrm{o}$$
$$v_\theta(r) = \frac{\Gamma_0}{2\pi r} \quad \text{for } r \geqslant r_\mathrm{o} \tag{21}$$

with $r_\mathrm{i} \leqslant 0.01B$ and $r_\mathrm{o} \approx 0.1B$.

The multiscale model (21) is a fit of wind tunnel data and provides inner and outer core radii. In models

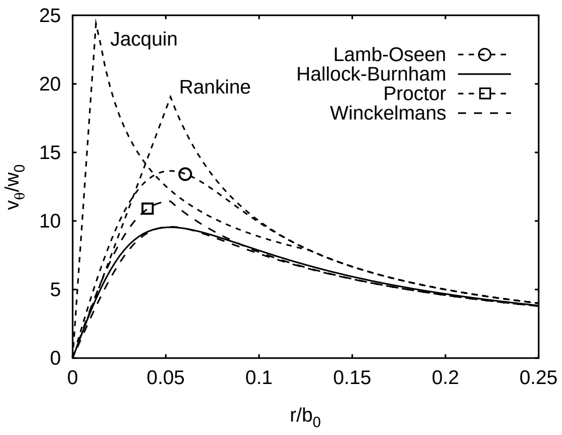

Fig. 2. Normalized tangential velocity profiles $v_\theta(r)/w_0$ of mostly used and adapted vortex models; $r_c/b_0 = 0.052$ for all models except Jacquin's model, see Eq. (21).

(16)–(19) the core radius appears explicitly, hence the ratio r_c/b_0 is a free parameter. For comparing all models in Fig. 2, we used the ratio $r_c/b_0 = 0.052$, which results implicitly from model (20), to scale all other models.

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 roughly $2r_c$ or $0.1b_0$.

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) at 3, 5, and 9 spans downstream the trailing edge of the wing [65]. Three regions can be distinguished around the centre of the vortex shed by the high-lift wings of the model: the internal core where v_θ increases with r is very small, $r_i \leqslant 0.01B$; for radii larger than r_i the tangential velocity decreases first with $r^{-0.5}$ before it follows the potential law r^{-1} at about $r = 0.1B$. Jacquin et al. [65] found further a plateau region for $0.01B \leqslant r_i \leqslant 0.03B$ where the tangential velocity is approximately constant. The plateau region has also been observed by Devenport et al. [25].

Proctor [87] adapted his model to lidar field measurement data. This model has been smoothly blended by Winckelmans et al. [124] 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 similarly to Winckelman's proposition; their model also has been adapted from data of field measurement campaigns. Note that models (18)–(20) meet the potential flow beyond $0.25b_0$ $(5r_c)$ 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 [6,104] seem to converge in the sense that a detailed description of the vortex in an aircraft wake requires at least a two-scale model with an inner and outer core (see also [107,65]):

- The flow in the *viscous core* or *inner core* with radius r_i is dominated by vorticity and viscosity owing to the very large transverse velocity gradients.
- The *vorticity core* 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.

3.3. Parameters for vortex decay

Ratio of vortex core to spacing, r_c/b, controls the evolution of short-wave instabilities, see Section 5.2.

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 neighbouring vortex is probably of secondary importance for decay mechanisms induced by axial flow.

Ambient turbulence in terms of turbulence velocity $q = \sqrt{u'^2 + v'^2 + w'^2}$ (where the primes denote velocity fluctuations around a properly derived mean value), normalized by w_0: $q^* = q/w_0$, or in terms of turbulence energy dissipation rate ε, normalized by w_0 and b_0: $\varepsilon^* = (\varepsilon b_0)^{1/3}/w_0$, has the strongest effect on a quick vortex decay. The latter scaling is especially appropriate when the wake-relevant scales of the ambient turbulent flow lie in the inertial subrange of turbulence. In this case, no additional information on the length scale of turbulence is required.

Aircraft induced turbulence $q^*_{ac} = q_{ac}/w_0$ or $\varepsilon^*_{ac} = (\varepsilon_{ac} b_0)^{1/3}/w_0$ stems from the turbine jets and the boundary-layer separation around wings and body of the aircraft. This amount of turbulence constitutes the minimum turbulence level always present in the wake behind the aircraft even if the atmosphere is absolutely calm. Some hot-wire data from tunnel measurements [25,65] and only a few samples for aircraft-induced turbulence from in situ flight measurements [1,58] are available in order to allow guesses of the intensity of the aircraft induced turbulence [36,37].

Ambient stratification in terms of the vertical gradient of the virtual potential temperature or Brunt–Väisälä frequency $N = \sqrt{g/\Theta_{v0}\, \mathrm{d}\Theta_v/\mathrm{d}z}$, normalized by

t_0: $N^* = Nt_0$, also accelerates the decay of a downward trailing vortex pair.

Ambient shear in terms of the vertical gradient of horizontal cross wind (perpendicular to wake-vortex axis) $S = \mathrm{d}v/\mathrm{d}z$, normalized by t_0: $S^* = St_0$, may cause the vortices to stall, rebound and separate and is, therefore, a crucial parameter for safety-corridor considerations.

Ambient cross wind v does not influence vortex decay but it transports the vortices laterally and, thus, is of major importance for safety-corridor definitions.

Crow linking factor is defined as [20]: $\beta(t) = (b_{\max} - b_{\min})/(b_{\max} + b_{\min})$, 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 >0.85 and coherent ring-like structures are present.

Ground linking Proctor et al. [89] suggested defining a ground linking factor similarly to the Crow linking factor as follows: $\beta(t) = (z_{\max} - z_{\min})/(z_{\max} + z_{\min})$, 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 radii, 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.

Jacquin et al. [65] introduce a "rolling moment radius" defined by

$$r_{\mathrm{roll}} = \frac{1}{\Gamma} \int_{-\infty}^{\infty} \int_{0}^{\infty} \omega_x \sqrt{(y - \bar{y})^2 + (z - \bar{z})^2}\, \mathrm{d}y\, \mathrm{d}z, \qquad (22)$$

where $\bar{y}$ and $\bar{z}$ are the vortex centroids defined in Eqs. (13) and (14). This radius takes into account that an encountered vortex is not a point vortex but has a finite extension. It allows to quantify how much the experienced roll moment is reduced when the vortex core has diffused to larger radii.

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, see Rossow [97] for definitions. Several threshold values to discriminate harmless from hazardous encounters are discussed in the literature but no common agreement has been achieved yet.

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).

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. These suggestions should allow successful field trials and uniform comparisons of data from diverse sources including near-field data and far-field data of evolving vortices which very often 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 and temperature profiler, radar, radiosondes.
3. Forecast of weather parameters (especially vertical profiles of (cross-) wind, temperature, and turbulence) with numerical weather codes in a small area with high spatial resolution and a forecasting horizont from 0.5 to 12 h in order to plan flights carefully.
4. Vortex visualization by smoke, using smoke generators on the aircraft and at the ground.

5. Standardized data evaluation: computing mean circulation by integrating over a range of radii or at the mid-point between two vortex cores (downdraught method).
6. Finally, vortex-noise (and aircraft-noise) measurements are helpful to detect both vortices at heights between 200 and 400 m above ground and to obtain informations on their axial topology and spacing variations (bent or straight vortices), as well as to identify the aircraft [2].

Of absolutely paramount importance for the success of any field trial is careful and appropriate selection of the precise sites for lidar operation [42]. The basis 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 kilometres around, and would allow siting of the lidar(s) both directly underneath the glide slope and at distances up to several 100 m 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 [127]. 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. On the other hand, crosswinds may prevent tracking of the vortices during their full life cycle because the vortices are advected out of the scan or focal region of a single lidar. Note that only little useful data is available that allows to study wake-vortex decay characteristics, especially after 3 or 4 reference time scales.

The field measurement campaign *WakeOP*, conducted at Oberpfaffenhofen (near Munich) in April and May 2001 [38], aimed at measuring wakes of a test aircraft at predicted and well-monitored weather conditions which were favourable to characterize the evolution of the wake according to weather and configuration impact. It has been shown that a combination of several continuous-wave lidars increases the range of observation, accuracy and statistical significance of the measured vortices.

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 and the lidar arrangements, 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(s) 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 s 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.

4.2. Data evaluation

To measure the vortex in read conditions, Doppler lidars can be used. As formally demonstrated by Constant et al. [11], Doppler lidars evaluate the maximum velocity along the line of sight of the laser beam. Fig. 3 exemplifies three scans through a vortex of a landing aircraft.

The evaluation of circulation from data scanned by lidar can be performed on arbitrary (large) radii according to Eq. (12). 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

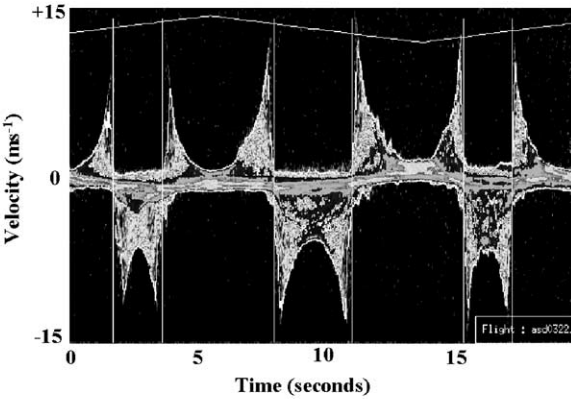

Fig. 3. Lidar measurements of wake vortices. Line-of-sight velocity (positive values indicate motion away from the lidar) versus time (aircraft overhead at $t \approx 0$). The laser scan angle is indicated by the zigzag line on top. From Ref. [49].

the transition point from vortex-induced velocities to the ambient flow field. The following technique is appropriate for a viewing geometry where the lidar is positioned underneath the glide slope close to the centre line: evaluate the down-draught velocity 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

$$\Gamma(b_0/2) = \pi b_0 W/2. \tag{23}$$

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 vortex spacing b. 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 by Eq. (12). This however requires that one knows the distance between the vortices 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 [127].

Therefore, it is also suggested to compute Γ_{5-15} which is the averaged circulation obtained over radii from 5 to 15 m. This is an appropriate averaging interval for upper medium and heavy aircraft. The calculation of Γ_{5-15} 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 [8]; and, particularly, Γ_{5-15} correlates well to effects of wake encounters [50]. 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 [49]. It is obvious that both techniques are complementary and, thus, both are required to obtain full understanding of vortex behaviour. Moreover and although the differences in the measurement techniques and the experimental set-ups are very large, 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 descend 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 centroids $\bar{y}$ and $\bar{z}$ over one half-plane of the wake by Eqs. (11)–(14). To enable the comparison of circulation data from diverse investigations it is 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 but has to avoid higher aircraft separations during approach and landing. Such large aircraft may, on the 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 to 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, active or passive control 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 North America [97].

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 Fig. 1), hot-wire, LDA, and PIV instrumentation to survey the mean field and instantaneous fields as well as turbulence/meandering characteristics [61,25,9,65].

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 radical 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 in high-lift configuration also yield good results when compared to PIV data despite the fact that the experimental target lift is recovered by adjusting the angle of attack [14,113,114]. 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, typically 30 millions of grid cells are required to compute accurately the viscous flow around a high-lift aircraft and its near-field trailing wake.

For *mid- to far-field* investigations under laboratory conditions it is thought to utilize large catapult facilities and water towing tanks. Lately conducted smoke-visualization [17,3,4] and PIV measurements [122] in the catapult as well as very recent PIV measurements in water-tank trials yielded encouraging results for the data reproducibility from several launches of nominally identical flights and for wake characteristics stemming from configuration changes.

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 versus 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, a combination of several time-synchronized continuous-wave lidars 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). We have further to keep in mind 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, in principle, be conducted in the extended near field, the mid-field, and in the far field. The measuring aircraft should enter the mid-field with utmost care, since there the fully developed vortices have the maximum strength and exert large rolling and lifting moments on the encountering aircraft. Repeatable measurements are extremely difficult when the vortex core is not marked by smoke or ice crystals [1]. However, when the vortices can be seen by the pilot of the chasing aircraft, controlled wake crossings can be flown, even in the mid-field [44]. Nevertheless, capturing the core region 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 [97,102,112]. 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. [86] showed that the initial 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. [103] showed that two-dimensional laminar vortex dipoles with various initial distributions of vorticity evolve towards a specific family of self similar dipoles which is characterized by the ratio r_c/b.

3. In a laminar environment, the decay of vortex strength (circulation) of a trailing vortex pair "can only result from the diffusion [or transport] of vorticity across the centerline" (Ref. [26, p. 8]).
4. In a turbulent environment, turbulent diffusion [83], deformation by atmospheric flow structures [13,57], and stretching of background vorticity in the wake-vortex induced velocity field, that generates azimuthal structures [92] and vertical streaks of vorticity, accelerate the decay of the vortex pair [24,59]. Furthermore, turbulence strongly promotes vortex instabilities.
5. 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 and four-vortex systems [18,91,29,30,19]. It has also been shown that the development of cooperative instabilities of a counter-rotating vortex pair is faster as the ratio r_c/b becomes larger [78,76].
6. In recent PIV measurements, a transition of the vorticity structure in the core region from a quasi-laminar state to a turbulent state was observed [122,4]. In situ measurements behind cruising aircraft [1] corroborate the turbulent structure of wake vortices throughout their lifespan. Temporal large-eddy simulations (LES) confirm the transition found in the catapult and elucidate that wake vortices with turbulent core regions may continue to descend relatively long times. Especially in quiescent and neutral surroundings, Γ decays still rather slowly after the transition [58]. Consequently, this flow regime, where the vortex pair evolves in a laminar and calm atmosphere and the turbulence only and unavoidably stems from the turbine jets and the boundary-layer separation around wings and body of the aircraft, defines a worst case scenario and should be investigated under safety aspects.
7. Single vortices—even with low vorticity—have a very long lifetime except when they are exposed to strong ambient turbulence [83]. The breakdown of a single vortex is favoured by strong axial velocity in the vortex core. The vortex bursting phenomenon, occasionally observed in aircraft 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.

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:

The baseline configuration is the slat/wing/flap configuration of selected aircraft (models), which produces *baseline wake vortices*. The respective data serve as reference data bases.

The completion of roll-up is 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.

The low vorticity vortex (*LVV*), is 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.

The quickly decaying vortex (*QDV*), is a wake-vortex system with significantly higher decay rate of circulation than the baseline vortex at a certain 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. Fig. 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 [120,71,48] and LES [35,15,68,58,90].

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

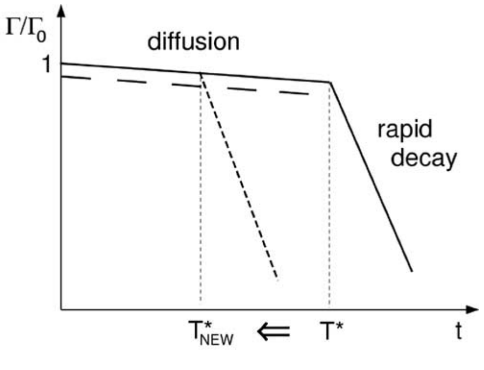

Fig. 4. Sketch of vortex evolution in terms of circulation $\Gamma(t)$ normalized by root circulation Γ_0 versus time. Γ represents a mean value obtained over radii of 5–15 m, see Section 4.

conditions. We observe an early onset at about 2 reference times ($2t_0$) and latest onset (under quiescent and neutral conditions) at about $6t_0$ [58,90]. 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. Γ_{5-15} (t), thus, may follow parallel to but below the reference case, see long-dashed line in Fig. 4.

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 short-dashed 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 (e.g., by 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 and Dunham [16]).

The QDV strategy is targeted on one or more vortex pairs 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 vortices in order to favour the production of secondary vorticity structures (spirals, streaks). The respective flow could be initiated by active control surfaces on the wing [19], by passive devices ("wake generators") mounted on proper positions below the wing, or by special flap and horizontal tail-plane settings [105,111]. The QDV measures unfortunately can be addressed in the far field only (after onset of rapid decay) with flight tests and CFD, possibly also in water towing tanks with small aircraft models or in the larger catapult facility B20 of ONERA. In the QDV approach the question of hazard is less critical 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 approaches.

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) 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 LVV or QDV which then could be used by designers to build the right wing?
5. Which final role do the instabilities, like short wave [118] and long wave [20] 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 has recently increased 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 growth of air traffic increasingly congests airports [119]. The wake-vortex dictated separation standards between two aircraft approaching an airport (Table 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. [45], Spalart [107]), it has become evident that the separation standards may be too conservative for a variety of meteorological situations.

A forecasting model capable of reliably predicting the vortex position and strength distributions 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 knowledge about the meteorological conditions and their impact on 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 affects vortex decay most efficiently [100,80,106,92]. Flight observations and CFD results clearly show that atmospheric turbulence in convective (thermally unstable) weather situations yields to strong deformation of the vortices and that destructive structures of azimuthal and vertical vorticity develop which cause subsequent rapid decay of the wake [13,56,57,79]. 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 strong vortex deformations induced by large turbulent eddies [83].

Even thermally stable stratification conditions enhance the decay of vortices, also when parts of the wake may stall at or rebound to the flight level [35,58,115]. Crosswind shear, on the other hand, is a candidate that may cause tilting of the vortex pair, accompanied by increased vortex separation [93,88,54]. 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 [42,53]. Parametric investigations carried out with CFD tools have demonstrated that vortex trajectories are very sensitive to vortex and shear layer parameters [21,55]. All these situations and processes need to be considered in robust forecasting tools. Vortex-shear interaction models tested against LES and field measurement data have been recently published [124,128,82].

6.2. Existing warning and approach systems

Some organizations have developed and advance 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 "Wirbelschleppen-Warnsystem", initiated by DFS in the 1980s, has been developed for Frankfurt Airport [43,32] 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 "Système Anticipatif de Gestion des Espacements" 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 [77]. The system is implemented for tests at Toulouse–Blagnac Airport.

AVOSS. The Aircraft Vortex Spacing System is developed by NASA [51,52] to produce weather dependent wake-vortex spacing criteria in IMC for single runway approach. AVOSS measures local weather conditions and uses them to predict wake-vortex transport and decay. The weather is also forecasted for a short-term range but that forecast is not yet used for wake predictions. The functionality of the system was demonstrated in July 2000 at Dallas-Fort Worth Airport.

HALS/DTOP. The High Approach Landing System/Dual Threshold Operation has been developed for Frankfurt Airport by DFS and FAG (e.g., Frech [31]). Two aircraft, staggered by radar separation, approach the parallel runways along two glide paths which are separated 80 m vertically and 518 m laterally. Medium and light aircraft approach along the higher path and land at a new runway threshold which is installed 1500 m behind the first threshold. The system has entered an operational test phase and is thought to work in CAT-1 with IMC conditions.

SOIA. The Simultaneous Offset Instrumented Approach is developed by FAA for San Francisco Airport [109] 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 approach with small lateral separation is then flown under VMC. Flight-simulator tests and trainings and wake-turbulence monitoring [41] have been performed.

6.3. Facts and requirements

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

1. It is claimed by the IFALPA [63] 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 basis 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 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 [38].
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 [40,12,69,95,96,104,101,128,84,85,66,60]. The physics enter such models via parametric approximations that are based on theoretical considerations as well as experimental and 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 [52], Memphis [23,129], the Frankfurt wind-line [32,46], and the Toulouse SYAGE [77] 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. The *WakeOP* campaign [38] made use of these instruments to gather weather data sets as complete as possible during the aircraft over-flights.
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., [116]) 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 Sections 4.1 and 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 [34,60] and climatologies [31].
10. One possible approach is to forecast mean vortex strength and trajectories plus security allowances 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 [33]. 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 allowances?

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 an "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 subsystems 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) happen 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 believes [63] 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 [64] 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 [99] 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 [47,48].

Within the EU project *MFLAME* a pulsed Doppler lidar was developed to emulate a future airborne vortex detection system [10,22]. 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 ranging 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 are triggered to twist and that also strong swirl components can be detected by lidar.

7.2. Situation awareness 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 [98]. Besides displaying the terrain and the surrounding traffic, the integrated situation awareness 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 runaway 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, [10]), 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 and the objective of the EU project *I-Wake*, starting in Spring 2002.
6. What 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 could not 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 most relevant parameters for wake encounter are listed in Section 3.4. The overall hazard level will depend on flight conditions, particularly the height above 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 its 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 *S-Wake* and in the USA in connection with the AVOSS project.

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* [4], 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 [97]. Therefore, the strip theory method from ONERA [28] was implemented in the flight simulators of NLR and Airbus.

As part of the AVOSS work in the USA [117,50], a set of equations has been derived based on strip theory approach that give the upset aerodynamic lift and roll moment coefficients in closed analytical form. This type of model is less general, complete, and versatile than the strip method of ONERA but could be useful for parametric studies or in Monte-Carlo type of simulations.

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)

$$\Delta L = \frac{\rho}{2} V^2 \int_{-B/2}^{B/2} c(y) c_{\mathrm{L}}(y)\,\mathrm{d}y \tag{24}$$

and

$$R = \frac{\rho}{2} V^2 \int_{-B/2}^{B/2} c(y) c_{\mathrm{L}}(y) y\,\mathrm{d}y. \tag{25}$$

The local lift coefficient is replaced by $c_{\mathrm{L}}(y) = C_{\mathrm{L}\alpha}\Delta\alpha(y)$, 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 centreline of the aircraft. Lift change and roll moment induced by the wake vortex then become

$$\Delta L = \frac{\rho}{2} V C_{\mathrm{L}\alpha} \int_{-B/2}^{B/2} c(y) W(y)\,\mathrm{d}y \tag{26}$$

and

$$R = \frac{\rho}{2} V C_{\mathrm{L}\alpha} \int_{-B/2}^{B/2} c(y) W(y) y\,\mathrm{d}y. \tag{27}$$

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

$$C_{\mathrm{R}} = \frac{2R}{\rho V^2 A B} = \frac{C_{\mathrm{L}\alpha}}{VAB} \int_{-B/2}^{B/2} c(y) W(y) y\,\mathrm{d}y. \tag{28}$$

We note that Eqs. (26)–(28) 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 [50].

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.

Elsenaar [27] 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. (27), 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 [74]. 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. Assuming that an aircraft experiences a constant wake induced roll moment the aircraft will attain a constant maximum roll-rate after a certain time. On the other hand, a suddenly occurring roll moment will induce a large roll acceleration which, in turn, has an impact on the structural loads.

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.

The ratio between wing spans of the generating and the following aircraft $B_{\mathrm{g}}/B_{\mathrm{f}}$ determines which part of the wake is "felt" by the encountering aircraft. Studies with a model by Tatnall [117] show that variations of $B_{\mathrm{g}}/B_{\mathrm{f}}$ from 1 to 3 changes the maximum lift and roll moment coefficients from -0.34 to -0.50 and from 0.06 to 0.10, respectively, for a horizontal encounter of a B747-400 wake when both, generator and follower, aircraft have the same speed [5]. 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.

8.3. An example

We consider the ratio between the exposed roll moment and the maximum available roll control, R_{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. The equation for roll motion has been solved for that range of aircraft [50] using the airplane data collection from Stuever [110]. The simplifying and *worst-case assumptions* are: (i) the generating aircraft is a B747-400 in maximum landing weight flying along ILS path; (ii) the vortex-velocity profile obeys the Hallock–Burnham model (Eq. (18) with $r_c = 0.05B$) without wake decay; (iii) the follower aircraft fly at their normal ILS speed in (most severe) minimum landing weight conditions; and (iv) at time $t = 0$ a sudden roll moment is assumed for 1 s with an amplitude equal to the maximum roll moment for the pertaining aircraft combination. 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 moment.

The resulting R_c values, depicted in Fig. 5, show that all of these aircraft—even the B747 encountering its own wake—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, R_c becomes somewhat smaller. Hence, heavier aircraft, in principle, have higher controlability in a given wake.

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. 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 are currently compared with that of extended flight simulations as performed in *S-Wake*.

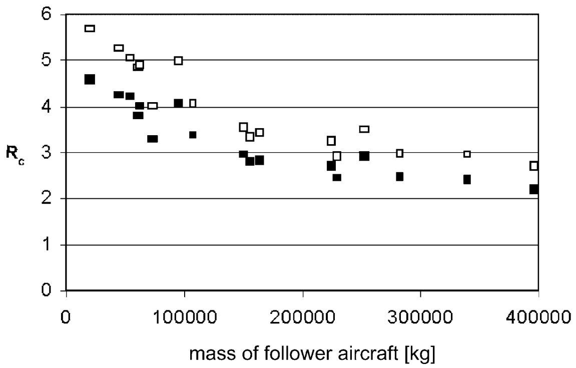

Fig. 5. The ratio between the wake-induced roll moment and the maximum available roll control moment R_c for aircraft of different sizes flying 1 s in the vortex core of a B747-400 at maximum landing weight; open (closed) symbols: the encountering aircraft is at minimum (maximum) landing weight.

It is important to remember that pilots have little influence on the size of the initial roll disturbances if they encounter a strong vortex. Thus the most important training requirement is for speedy and safe recovery from unusual attitudes. 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.

8.4. List of questions and problems

1. Is the often made assumption valid that local lift is a linear function of the local angle of attack if locally very large flow angles occur (e.g. close to the vortex core)? Are the assumptions valid made for the gradient of the lift coefficient $C_{L\alpha}$ in simple methods such as the strip theory?
2. For rapid wake encounters under large intercept angles, it is not certain that the quasi-steady methods used to compute the disturbing forces and moments are really appropriate. This should be checked with simple unsteady aerodynamic methods.
3. 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 for this purpose 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 [126]. 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. 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.

9.1. *Risk-based policy making*

For incident and accident investigation purposes, ICAO definitions are accident, serious incident, non-serious incident, and non-determined incidents (ICAO [62]). For safety assessment purposes, JAA has defined severity classes for adverse conditions: catastrophic, hazardous, major, and minor (JAR-25 [67]). The above two classification schemes can be combined into a classification of wake-vortex induced risk events [108,72]:

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.

9.2. *Probabilistic safety assessment*

A safety management approach to regulate and control wake-vortex induced risk can be based on an assessment of accident risk probabilities, e.g., risk event probability per movement and per year, 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. Guidelines for the selection of risk metrics and the assessment of safety requirements are being developed by FAA and Eurocontrol [81].

Fig. 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. To establish a relation between vortex severity and encounter severity, factors as height above ground, pilot behaviour (both reactive and anticipative), autopilot behaviour and roll control capabilities of the involved aircraft have to be included. Further factors are weather at the time of occurrence and the degree of ambient turbulence before the encounter.

A probabilistic approach for the evaluation of wake-vortex safety under various operational and weather conditions has been proposed [108,72]. It includes probabilistic sub-models for all phenomena which cannot be obtained deterministically 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

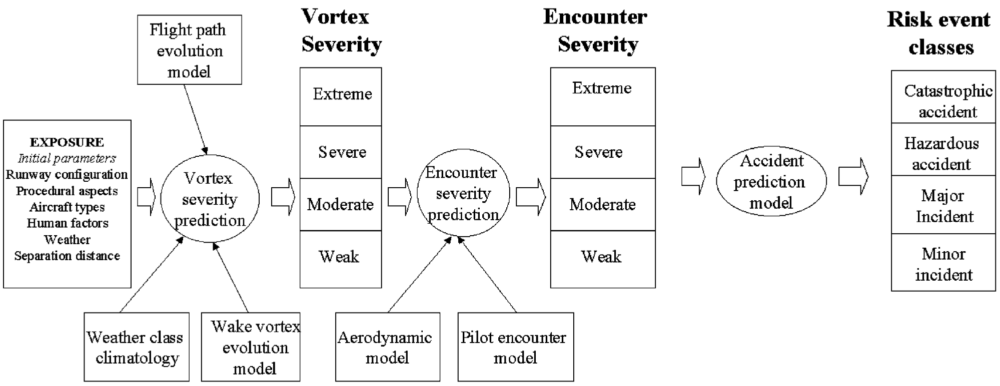

Fig. 6. Safety modeling relations. From ref. [108].

commonly accepted rationales for acceptance of a newly proposed ATM concept by involved interest groups (i.e., pilots, controllers, regulators) as it demonstrates that the number of wake-vortex induced risk events does neither exceed some pre-defined and agreed safety requirements nor increase with the introduction of a new ATM procedure. The proposed model is based on wake-vortex evolution models [12] and wake encounter models [73,125] and extended with probabilistic wind field models including the impact of wind in the lateral and vertical direction.

Besides for the purpose of incident and accident investigation, it is also helpful to gather and analyse incident/accident hazard data (e.g., through pilot reports on roll upsets attributed to wake-vortex encounters) to support the development of safety assessment models and tools. 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 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. Up to 80,000 arrivals of a major British airline at London over the period of 1 year will be analysed, and parameters from all the flights (such as aircraft type, landing weight, separation from leading aircraft, meteorological conditions) will be collected. The analysis is intended to give empirical information on minimum safe separations, for example in different weather conditions.

9.3. List of questions and actions

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 does a probabilistic relation between the wake encounter severity classes and the risk event classes read?
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. Conclusions

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 aircraft, especially on final approach towards an airport. Diminishing aircraft separation distances 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. However, the manifold of combinations of environmental factors is not fully covered yet. Real-time engineering models are developed and improved to predict vortex behaviour for approaching and departing aircraft.
- 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 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 and robust 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 will certainly close some of these gaps in the next 3–5 years.

Acknowledgements

This text manifests a revised and condensed version of the position paper on aircraft wake vortices [39] which has been initiated within the European Thematic Network *WakeNet* funded by the European Union under Contract Number BRRT-CT98-5050.

We are very grateful to Anton de Bruin, Abraham Elsenaar, and Lennaert Speijker from NLR, Mike Harris and Michael Vaughan from QinetiQ, and Alan A. Woodfield from Woodfield Aviation Research for their major contributions to the position paper.

We further acknowledge the discussions with many personalities and are especially indebted to Klaus and Caren Hünecke (Airbus Deutschland), Olivier Atinault (Airbus France), Gerry Elphick and Chris Hume (Airbus UK), Alex Fisher (British Airways), Florent Laporte and Henri Moet (CERFACS), Jens Konopka (DFS), Michael Frech, Thomas Hofbauer, and Friedrich Köpp (DLR), Stefan Wolf (IFALPA), Andy Kershaw and Simon Mason (NATS), Henk Blom and Henk Haverdings (NLR), Rob Young (QinetiQ), Hubert Combe (Thales Avionique), and Gregoire Winckelmans (UCL) for their recurrent help to shape the different facets of this challenging issue.

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