Department of Mechanical Engineering
Imperial College of Science, Technology and Medicine
Exhibition Road, London SW7 2BX

Conference on Capacity and Wake Vortices

11 to 14 September 2001

Abstracts of Presentations

Preface

This small volume contains abstracts of presentations. They are intended to provide a record of the topics, to require only modest effort from the presenters, and to facilitate maximum freedom of discussion. Further details of the content may be obtained from the authors.

It is appropriate to use this page to record thanks to presenters, chairmen and sponsors. The Conference would have been impossible without them and also without the secretarial assistance ably rendered by Ms. Serena Dalrymple. The main sponsors were the NASA Ames and Langley Research Centers, the U.S. Army's Aero-Flight Dynamics Directorate, the European Research Office of the U.S. Army Research Laboratory, and the U.S.I Air Force's European Office for Aerospace Research and Development. Essential discussions with Drs H McDonald, S. Sampath and C Raffoul of these organisations are gratefully acknowledged.

J H Whitelaw
August 2001

SESSION I:

CAPACITY AND STRATEGIES, 1

Chairman:

Chester Ekstrand, Boeing

THE EFFECT OF AIRCRAFT WAKE VORTEX SEPARATION ON AIR TRANSPORTATION CAPACITY

Dr. George L. Donohue

Department of Systems Engineering and Operations Research
George Mason University
Fairfax, Virginia 22030-4444
gdonohue@gmu.edu

The wake vortex separation problem has been known for over 30 years. The current system of static restrictions and approach separation criteria reduces the air transportation system capacity under IFR conditions. In the US, these static restrictions are frequently ignored under VMC conditions by assigning aircraft separation responsibility to the pilot once he has the airport runway in sight. The current system leads to 1) frequently imposing excessive separation under IMC and 2) infrequently allowing inadequate separation under VMC.

The recent NASA/FAA research on wake vortex separation has made significant progress on both theoretical understanding and empirical measurement of the aircraft wake vortex behavior interacting with the atmospheric boundary layer. The current state-of-the-art indicates that new sensors and vortex prediction and warning algorithms should be incorporated into FAA weather and ATM decision support system software in order to recover critical lost air transportation capacity while at the same time maintaining or increasing safety.

Runway wind directional variability is intrinsic to the random nature of the atmospheric turbulent boundary layer. This inherent uncertainty in wind vector presents challenges to accurately predicting runway wind direction out to 30 minutes. The predication time is required to begin the spacing of arriving aircraft approximately 200 miles from the airport due to the aircraft maneuver restrictions. The atmospheric turbulent boundary layer Turbulent Kinetic Energy (TKE) level or eddy dissipation level is a more stable scalar quantity and is more reliable in predicting the conditions for wake vortex breakup and accelerated circulation decay. Based upon both the experimental results observed in the NASA DFW experiments and theoretical considerations, it is recommended that the FAA Integrated Terminal Weather System (ITWS) be upgraded to initially provide a **WARNING** of wake vortex circulation intensity above background. It is suggested that this is a better criterion for any wake vortex ATC system, **NOT a PREDICTION** of wake vortex location relative to the runway centerline for initial system implementations. This system should work well under most windy conditions. Under low wind, stable IMC conditions, the wind conditions may be more predictable and wake centerline prediction may provide more additional capacity.

THE PILOTS VIEW ON WAKE VORTICES - CAPACITY VS. SAFETY

Stefan Wolf

German ALPA / IFALPA ADO -committee

0. OBJECTIVE

The presentation mainly addresses the following issues

- IFALPA structure / ADO committee
- Wake vortices as seen and encountered by pilots
- IFALPA´s activities / what's to be done

1. INTRODUCTION

Capacity-problems in terms of „movements per hour“ are becoming a major driver for the economical performance of airports, ATM systems and airlines.

The ICAO standard separation rules where developed in the early 70´s, when the phenomenon of wake vortices made people aware of the danger when entering the wakes of a preceding aircraft. Today the values of these standard separation are discussed whether they are still adequate or not in specific situations.

2. WAKE VORTICES

The dominant vortex hazard is the rolling moment induced on a directly following aircraft wing by the vortex motion. Because of the complexities of a vortex encounter, a simple parameter, the ratio of the maximum induced rolling moment to the maximum roll control authority of the aircraft, has generally been used to characterize the wake vortex hazard.

Another - but minor - concern is that wake turbulences might interfere with the laminar flow in the engine inlet thus causing engine stalls below optimum relight speed especially at smaller jet engines.

3. A/C MANUFACTURERS

It's more and more important to sell aircraft, that are “smooth operators“ thus meaning they are of a low specific vorticity.

The actual projects of a future VLTA (very large transport aircraft) are addressing the wake vortex problems during the whole design process as they want to prevent the birth of a „super heavy“ aircraft class thus neutralizing the capacity gain of large passenger decks by requiring additional track miles to separate the succeeding traffic.

4. AIRPORTS

All the major hubs in the world are facing restrictions in the approach traffic flow as the specific “traffic mix“ during peak hours strongly affects separation distances between aircraft and the optimised use of airspace.

All efforts by the scientists, the manufacturers and the ATM-providers are very welcome to solve the wake vortex problem thus increasing the movements per hour or stabilizing the values under different weather and “traffic-mix“ conditions.

5. THE PILOTS

Our main task is to follow the actual discussion regarding the capacity problems, the scientific research activities on the wake vortex topic and to observe the possible suggestions to design future a/c in terms of “vorticity“.

We have to stay in touch with the national research facilities and their representatives as well as the a/c manufacturers. Participation in field tests or even flight trials is strongly appreciated. Invitations by ATM-providers or e.g. manufacturers of LIDAR-systems have been received.

6. THE IFALPA "WAKE VORTEX POLICY"

Since 1998 the IFALPA Wake Vortex policy has been passed as a result from many inputs from the national ALPA´s.

The topics that are addressed herein are

.1 a general commitment to serious efforts allowing a safe reduction of the standard wake-turbulence separation minima

.2 support for the results of international research activities contributing the development of any wake vortex warning / avoidance system

.3 the demand for airborne wake vortex detection systems and

.4 the demand for ground based wake vortex advisory and warning systems

With this policy we have a very vital document that has already been presented to many of the above mentioned participants in the ongoing discussion of how to increase capacities, examine wake vortices and reduce standard ICAO separation criteria

CV The Author is flying for a major German Airline as a pilot on the Airbus 320-family. Before that he finished his engineering diploma at the Technische Universität Darmstadt As a member of the German ALPA "Vereinigung Cockpit e.V." he is working for the ADO(aircraft design &operation) and WSWS (Wirbelschleppenwarnsysteme) working groups.

He is delegate in the IFALPA ADO committee, and in this function officially representing IFALPA in the EU WakeNet program.

RUNWAY CAPACITY CONSTRAINTS AT HEATHROW AIRPORT

Neil May

Head of Safety Analysis for National Air Traffic Services Limited

The capacity of Heathrow Airport is constrained by the capacity of the two runways. In recent years, many steps have been taken to increase runway capacity but these have been able to produce only small, incremental increases rather than the large, step change increases demanded by the aviation industry. One of the major constraints on runway capacity is the separation required between successive arrivals or between successive departures. These separations are governed in part by the wake vortex separations necessary to ensure the safety of arriving and departing aircraft.

The presentation will describe the process used by NATS to declare runway capacity at Heathrow and will identify the factors that constrain increases to that capacity. Particular focus will be placed on one of these factors, namely the wake vortex separations between aircraft. Examples will be provided to illustrate the potential capacity gains that could be achieved from safely reducing the required separations between aircraft. There will also be discussion around the operational tactics employed by controllers at Heathrow to minimise the effects of wake vortex separations on runway capacity.

About the presenter:

Neil May holds a Bachelor of Science degree in Mathematics and Numerical Analysis from Dundee University. He started his career as an Operational Researcher for the UK Home Office before joining **National Air Traffic Services Ltd (NATS)** in 1990. He worked for a number of years as the senior cost benefit analyst for NATS before taking up roles investigating airspace system efficiency and the development of NATS' Operational Strategy up to the year 2015.

Neil was appointed the Head of Airport Studies in 1997 and was responsible for undertaking regular runway capacity assessments for 6 of the major UK airports. The results of these assessments are used to advise ATC, the airport operator, the airlines and the slot co-ordinator of the operational implications of the current capacity declaration. They are also used to identify the potential consequences associated with increases to that capacity. Neil was also responsible for managing analytical studies for a number of major UK airports for which NATS is the ATC service provider. The aims of such studies are generally to identify the benefits to NATS, the airlines and the airport operator of making changes to existing operating procedures and / or airport infrastructure. In particular, the studies usually aim to identify potential improvements to increase runway capacity, improve traffic throughput or deliver better ATC service quality at airports.

In April 2001, Neil was appointed the Head of Safety Analysis for NATS. He has responsibility for the on-going monitoring and reporting of operational safety performance in UK airspace, at UK airports controlled by NATS and in oceanic airspace controlled by NATS. In particular, Neil has responsibility for monitoring the performance of safety nets such as Short Term Conflict Alert (STCA) and the Traffic Alert and Collision Avoidance System (TCAS). He is also responsible for undertaking risk monitoring and safety analyses for all aspects of NATS' air traffic management activities, including wake vortex separations at airports. The work enables NATS to ensure that current operations continue to achieve "best-in-class" safety standards and that future developments aimed at meeting growing demand will meet NATS' safety objectives.

SESSION 2:

CAPACITY AND STRATEGIES, 2

Chairman:

Marc Maurel, Airbus

FAA'S RESEARCH STRATEGY

George C. Greene

FAA R&D Field Office, NASA Langley Research Center

Wake turbulence is an international concern that currently limits airport capacity and constrains the implementation of new technologies and procedures which might increase airport efficiency. Therefore, wake turbulence research must be a significant consideration in any plan addressing the capacity of the air traffic system.

Recently, both the FAA and the Boeing Co. released plans for significantly enhancing air traffic system capacity. This talk addresses the FAA's research strategy for ensuring that wake turbulence considerations do not limit the implementation of these planned enhancements. Specific topics include near term research on closely spaced parallel runway operations, evolution of NASA AVOSS technology for operational use, and international cooperation in wake turbulence research.

INCREASING CAPACITY BY WAKE TURBULENCE AVOIDANCE SYSTEMS AT FRANKFURT/MAIN AIRPORT

Jens Konopka

DFS Deutsche Flugsicherung GmbH, Research and Development
Paul-Ehrlich-Str. 37-39, 63225 Langen, Germany

Frankfurt/Main is among the10 largest airports in the world. It accommodates a traffic volume of 460.000 movement per year (2000) including a 30% fraction of heavy type aircraft like Airbus 340s or Boeing 747s. The runway system consists of two closely spaced parallel runways (25/07) plus a third runway (18) that is exclusively used for departures.

One of the most stringent capacity limiting factors are wake turbulence separation requirements due to leading heavy aircraft. German Air Navigation Services (DFS) together with Frankfurt Airport (FRAPORT) is developing systems and novel procedures that allow for safe reduction of wake turbulence separation minima for landing traffic on different but close spaced runways even in IMC conditions.

This paper gives an overview on the concept of the Wake Vortex Warning System (WVWS), its components, and how the system will be incorporated in a real Air Traffic Control environment.

While current ICAO provisions rely on wake decay, the novel procedure will ensure wake turbulence safety because the wake of the leading (heavy type) aircraft will be transported away from the flight corridor of the trailing (medium type) aircraft.

This shall be accomplished by accurate measurement of the prevailing meteorological conditions and subsequent forecast of the wake vortices' motion between the two glideslopes. Currently the WVWS covers a safety box of 80 m height, however as a next step a wind-temperature radar will supplement the system and provide necessary data to extend the prognosis along the entire final approach path.

Another alternative is presently tested in field trials: In the High Approach Landing System/Dual Threshold Operation (HALS/DTOP) project, FRAPORT and DFS have built an additional threshold (26L) on an existing runway (25L). The new threshold is displaced by 1500 m and thus ensures that aircraft approaching 26L will always stay 80 m above leading aircraft on 25R. Due to this 80 m shift the aircraft's flight corridor will be clear of wake turbulence.

IMPROVING AIRPORT CAPACITY USING VERTICAL FLIGHT

Eur Ing John W. Leverton, Ph.D, M.Sc, M.R.Ae.S, MIOA

Director Infrastructure Development*
AHS International
Alexandria, Virginia, USA

The airline industry is being subjected to an ever-increasing number of flight delays and cancellations of as a result of airport and airspace congestion and now this is becoming a common everyday occurrence. This is having a direct impact on the economic viability of the airlines and acceptance by the traveling public. The authorities and airlines are under increasing pressure to find a solution to what may now be described as an intolerable situation. Traffic growth continues and the demand for air travel increases, if for no other reason, as a result of the increase in population and the need by the public to fly for commercial and leisure purposes. Some improvements are possible by redefining operational procedures but major increases in airspace capacity in a traditional sense is not possible. The construction of new airports and the addition of new runways and terminal facilities at existing airports will also help. Increases in airport size are generally not acceptable to the general public largely on environmental grounds; moreover often such additions cannot be made at locations where the demand requires them. Even if such increases can take place they will only offset some of the problems in the short term and it will not be a major improvement since the complete aviation system is becoming saturated.

A new, innovative solution must therefore be developed and implemented which makes use of the parts of the airspace system and airport infrastructure that are currently either not used or under utilized. The use of vertical flight in the form of new generation advance technology rotorcraft, civil tiltrotor (CTR) aircraft offers this potential. These and other runway independent aircraft (RIA), using a ATC framework which allows simultaneous non-interfering (SNI) operations, would appear to be the only viable solution to the current problems if the needs of the traveling public and commerce are to be met. This is possible since significant portions of flights, particularly in the USA, are over ranges of 100 to 200 miles. These aircraft only carry a small portion of the total number of passengers but require the same airspace and runway slot as a large long distance aircraft. These operations could easily be replaced by advanced technology rotorcraft. With the advent of CTR and other RIA ranges of up to 400 to 600 miles could similarly be handled. These have the advantage of not requiring a valuable 'slot' and could easily make use of the unused airspace (airspace 'voids') on the side of most major airports. High reliability, all weather operations including flights in icing conditions to achieve true IFR operations, is essential. Operating costs are inherently higher than today's civil flights and the need to offset such costs, together with important aspects such as flight safety (included perceived safety) environmental impact and passenger acceptance are important. Advance technology rotorcraft CTR's and RIA's offer a solution in the short term of overcoming the airport/airspace capacity limitations and providing the basis of a valuable integrated aviation system based on today's civil aviation fleet supplemented with a vertical flight segment.

* Former Director Market Development, GKN Westland Inc./E.H.Industries Inc.

SESSION 3:

EXPERIMENTS WITH WAKE VORTICES, 1

Chairman:

Anton De Bruin, NLR

RECENT DEVELOPMENTS IN INDUSTRIAL WAKE VORTEX RESEARCH

Klaus Huenecke

EADS Airbus, Bremen, Germany

The capacity limitation of today's airspace and that of major airports is of increasing concern, in particular as air traffic continues to grow at the present rate of 5% per year. At some key airports, and at peak hours, more aircraft arrive than the approach paths are able to accommodate. In Europe this is regularly the case at the airports of London Heathrow, Frankfurt and Paris CDG. Airlines, airports and authorities therefore are searching for advanced solutions of how to accommodate the growing air traffic, without degrading the high standards of safety.

One of the most promising routes to increase capacity is to reduce separation distances between aircraft. Separation is necessary, both horizontally for landing and take-off, and vertically for particular en-route legs, to avoid the risk of encountering wakes from preceding aircraft. Hence, separations are vital to assure flight safety. Because the hazard from vortices increases with aircraft size, the wake vortex issue is becoming even more critical with the appearance of very-large transport aircraft (VLTA) from 2005 onward.

Indeed, "Wake vortex" is among the major issues that will affect the super airplane of the future, and growth of air traffic in general. Although numerous investigations were carried out worldwide in the past, it was realised that the available database was only of limited value for the industry. As a consequence dedicated research activities, both on a national and supra-national level, were launched by major European nations which focus on the characterization, and then on control, of vortex-dominated wakes.

European initiatives in wake vortex research

The scope of the wake vortex issue exceeds the resources of a single enterprise or even a single country. Hence, the European Union with its scientific resources is the ideal institution to support such efforts.

Some of the wake vortex topics were previously addressed within European projects like
- *Eurowake* (Wake Vortex Formation of Transport Aircraft)
- *MFLAME* (Multifunction Future Laser Atmospheric Measurement Equipment)
- *Europiv* (A cooperative action to apply particle image velocimetry to problems of industrial interest).

The "Eurowake" project focussed on wake formation, the initial part of a wake. The industrial interest in such efforts was emphasized by the three Airbus consortium members as major participants in the "Eurowake" project.

The main objective of the "MFLAME" project was to prove the viability of an airborne Lidar wake vortex detection system.

The "Europiv" project is looking into even more specific details of a wake by addressing the measurement technology for unsteady particle motion in a variety of industrial applications, which is of utmost importance in wake behavour.

A "*Thematic Network Wake Vortex*" was established by the EC as an effort to gain added value through cross-fertilisation of various projects which have a common goal.

VORTEX EVOLUTION AND CHARACTERIZATION

Donald P. Delisi and Robert E. Robins

NorthWest Research Associates, Inc., Bellevue, WA, USA

A major concern with airport capacity issues is the characterization and evolution of trailing wake vortices. These vortices can be studied with laboratory models, numerical simulations, and aircraft measurements. An issue with using laboratory studies is how the difference in Reynolds number affects the results and the interpretations of those results. The danger is that effects that are observed in low-Reynolds number flows may not be observed in high-Reynolds number aircraft flows. Consequently, care must be used in interpreting low-Reynolds number studies and extrapolating those results to the high-Reynolds number aircraft case.

For several years, we have been performing low-Reynolds number laboratory model studies and comparing those results to aircraft data and numerical simulations. Favorable comparisons of laboratory vortices with aircraft vortices and numerical simulations have included vortex migration, in both nonstratified and stratified environments, vortex core size with time after aircraft passage, vortex circulation as a function of time after aircraft passage, and the level of turbulence in the vortex cell. In addition, we have performed a number of laboratory studies with which we have no full-scale data for comparison. These studies include vortex separation with time and vortex lifetime in both quiescent and turbulent backgrounds.

Our laboratory studies will be reviewed and comparisons will be shown with aircraft measurements. Studies with which no comparison data are available will also be reviewed. The extrapolation of our results will be discussed with regard to airport capacity and related safety issues.

PIV-SURVEY OF THE VORTEX WAKE STRUCTURE BEHIND AN AIRBUS A340 IN A TOWING TANK

L.L.M. Veldhuis, K. van Wijk, F. Scarano

Delft Aerospace – Aerodynamics Group
Delft University of Technology
Kluyverweg 1, 2629 HS Delft, The Netherlands

To find detailed information about the vortex structure and its decay PIV measurements were performed in a 142 m long water tank behind an Airbus A340-300 model. The main objective of the experimental investigations is to demonstrate the applicability of the PIV technique for measuring the mid to far field behind aircraft in towing tank facilities. The collected data are used within the European research programme C-WAKE to arrive at a better understanding of the behavior of the vortex system at large distance behind the aircraft. The survey was performed at $2°, 4°$ and $8°$ angle of attack and towing speeds of $3\,m/s$ and $5\,m/s$. Two-dimensional PIV data were taken in a fixed plane perpendicular to the towing direction to measure the stream wise wake vorticity. To be able to track the down going vortices an underwater camera moving vertically with the vortices was used yielding high spatial resolution measurements. Recordings are acquired at an effective rate of $3.3\,Hz$ over a field of view of about $0.5 \times 1.2\,m^2$. The image analysis was performed with an iterative PIV processing technique with multigrid interrogation including a window distortion algorithm. The collected data on the vortex flow demonstrate that the PIV technique is very suitable for this type of experimental research. Moreover the application of the towing tank facility in conjunction with PIV diagnostics allows to obtain a longer time/space description of the vortex wake (up to 260 wingspans) in comparison with wind tunnel experiments and catapult facilities.

Introduction

The wake of a large aircraft is characterized by strong vortical structures mainly generated at the wing tips and the flaps ends. When aircraft fly in close proximity to each other, for example close to an airport, wake vortex encounter problems arise. A serious safety hazard exist when an aircraft enters the strong vortex wake generated by a large aircraft flying ahead of it. The trailing vorticity generated by the wings produce strong counter-rotating vortices that are approximately proportional to the aircraft's weight over span ratio.

Early solutions to this problem have been sought in avoidance of vortex encounters and prescribed large spacing between aircraft. The spacing requirements (especially for landing) however constraint the operational capacity of a growing number of congested commercial airports around the world. This means that for future large aircraft further costly delays may be expected between landings. To find other means of alleviating this problem by attacking the problem at its source there has been a growing interest in the fluid dynamics of vortex flows. Several studies are devoted to increase the knowledge of aircraft generated wakes from a theoretical, numerical and experimental standpoint as is summarized by Rossow [1999]. Also flight tests are considered to be the ultimate and most reliable extension of the latter approach. It is clear that the three dimensional wake flow field has a complex nature, further what makes it a challenging topic is the large spatial aspect ratio. The wake vortex at a fixed stream wise location is still contains considerable cross flow energy even after the aircraft has passed over some hundreds wingspans.

Although the vortices may be persistent in the first phase after creation viscous effects force the decay of the vortices when time progresses. Thus at some distance behind the aircraft the strength of the cross flow velocity diminishes. In fact three vortex regions can be distinguished :

- The roll up region or *near field* : 12-20 spans , 5 sec. flying time, 1 Km
- The vortex region or *mid field* : 300-500 spans, 1.5 minute flying time, 20 km
- The decay region or *far field* : > 500 spans

The *near field* is defined as the region where the vorticity shed from the wings organizes itself into a vortex pair system. Several wind tunnel investigations have been performed within this range mainly using 5-hole pressure probes and lately particle image velocimetry (Huenecke [2]).
The *mid field* is defined as the region where the vortex pair system is stable and persists, apparently as effective as it was at its formation, before entering the decay stage that occurs in the *far field.* Investigation of the *mid field* cannot be performed in wind tunnels and flight tests are often considered as the best method. Among ground based facilities capable of performing test in this range the only ones available are: free flight facilities (catapult) and water towing tanks.

Experiments

The present study describes PIV measurements in a towing tank on an aircraft model A340 (Fig. 1). Measurements of the instantaneous velocity field were performed in a plane perpendicular to the model flight direction at a rate of $3.3\,\mathrm{Hz}$. A specially designed underwater camera traversing system allows the field of view to move during the measurements. In this way the wake vortex is tracked in time and the PIV system is capable of describing its behavior at a high spatial resolution. Moreover the analysis of the digital recordings is performed with an enhanced multigrid image distortion correlation technique.
A PIV-system used from DANTEC is used, consisting of a sensitive, double-frame, PIV camera ($1280\times1024\,\mathrm{pixels}$, $12\,\mathrm{bits}$), and a double-cavity pulsed Nd:YAG laser ($400\,\mathrm{mJ/Pulse}$). A special underwater camera box with an internal rail and controlled motor was designed in order to allow the fine positioning and movement of the camera during a single experiment run. This choice is of crucial importance to achieve high spatial resolution without the need of clustering several cameras to be pointed along the vortex path. The typical distance of the camera from the measurement plane is $3\,\mathrm{m}$ and a laser sheet is formed of about $7\,\mathrm{mm}$ thickness. To diminish daylight background a narrow band green filter is used. The flow is seeded with *VESTOSINT®* particles of $56\pm2\,\mu\mathrm{m}$ diameter. The seeding mixture is injected into the flow with the help of an injection rake. The particles density of $1.016\,\mathrm{gr/cm^3}$ yields a settling velocity smaller than $1\,\mathrm{mm/s}$ in water at 15 C°. PIV measurements on the Airbus A340 vortex wake are performed in the towing tank of the TU Delft Marine Engineering Laboratories, with a length of $142\,\mathrm{m}$, a width of $4.2\,\mathrm{m}$ and a water depth of $2.4\,\mathrm{m}$.
The underwater camera system rests on the tank bottom and is stabilized with a clamp on the tank side. The laser sheet is inserted vertically into the water from the free surface as shown in Fig. 2. In order to prevent any sheet deformation due to surface waves a Plexiglas window is used as interface between the air and the water.

Before the model crosses the measuring section a magnetic trigger delivers a synchronization input signal to the PIV-measurement system and to the digital control of the camera movement motor. Due to hardware limitation of the acquisition system, the grabbing rate is of $3.3\,\mathrm{Hz}$. The co-ordinate system of the experiment places the model wing tip in the axes origin. The V_{tow} and z-axes lie in the measurement plane, while the x-axis is oriented along the stream wise direction. The aircraft model (designed and manufactured by EADS-D) represents an Airbus A340 at a scale of 1:48 and a resulting wingspan $b = 1.2\,\mathrm{m}$. The PIV-recordings are analyzed preliminarily with the built-in *DANTEC* software (*Flowmap*® [4]) although the off-line image processing is made with an advanced cross-correlation technique (Scarano and Riethmuller 2001). A typical data output of 78×62 (HxV) is obtained with interrogation regions of 41×41 pixels (61% overlap). The average valid data yield of the raw vector maps is 91%.

Results

Each experimental run returns a time sequence of the instantaneous velocity field that describes the evolution of the vortex wake at a fixed location with respect to the towing tank. Under the assumption that the vortex wake is steady with respect to an observer moving with the aircraft, it is possible to substitute the time variable into the stream wise coordinate. Given the towing speed as V_{tow} and the stream wise coordinate x, the non-dimensional time variable is obtained as $t' = x / V_{tow}$. This allows visualizing the data as a three-dimensional representation of the vortex field sliced at regular stream wise abscissas. Fig. 3 shows a typical measurement sequence obtained at $V_{tow} = 3\,\mathrm{m/s}$ and $\alpha = 2$ deg. The roll-up stage is characterized by the formation and merging of individual vortices from the engine nacelles the wing tip and the winglet respectively. Once these structures have merged an intense well-organized vortex is formed that persists over the entire observation time exhibiting an apparently low decay rate. Further image processing and data reduction will allow to extract relevant information on the vortex strength history as well its trajectory.

References

[1] Rossow, V. J.: Lift generated vortex wakes of subsonic transport aircraft. Progress in Aerospace sciences 35 507-660, 1999

[2] Huenecke K., Huenecke C.: Flow field visualization in aircraft wake vortex research. 19 th Int. Symposium on Flow Visualization, Edinburg (UK), 2000

[3] Stanislas, M., J. Kompenhans and J. Westerweel (ed.): Particle Image Velocimetry, progress towards industrial Application, Kluwer Academic Publishers, 2000

[4] Dantec MT: "FlowMap", Installation & User's guide, 4 th ed., Publication no. 904U3623, 1998

[5] F. Scarano and M. L. Riethmuller: Advances in iterative multigrid PIV image processing, Experiments in Fluids 29 7,
S051-S060, 2000

[6] Tukker J., Blok J.J., Kuiper G., Huijsmans R.H.M.: wake flow measurements in towing tanks with PIV. 19 th Int. Symposium on Flow Visualization, Edinburg (UK), 2000

EXPERIMENTAL CHARACTERISATION OF WAKES IN THE EXTENDED NEAR-FIELD BEHIND GENERIC-TYPE AND TRANSPORT AIRCRAFT-TYPE MODELS

Eric Coustols*, Philippe Geffroy and Laurent Jacquin****

ONERA Department Models for Aerodynamics and Energetics, 2 avenue Edouard Belin, 31055 Toulouse Cedex, France.

ONERA Department of Fundamental and Experimental Aerodynamics, 8 rue des Vertugadins, 92190 Meudon, France.

Aircraft trailing vortices are generated by the finite span lifting wings, equipped with moving flap surfaces. They are often referred to as wake turbulence and constitute one of the main concerns for air traffic growth limitation. Indeed, in order to avoid any vortex hazardous encounter, minimum separation distances are imposed to aircraft on airport approach, under instrument flight rules. The separation rules, established in the early 1970's, should be re-examined according to the present and on-going knowledge about wake vortex formation and development. Such distances are a major source for airport congestion and delay, which could be relieved by reducing wake vortex impact on the following aircraft without degrading today's high safety standards.

It is therefore mandatory to study aircraft wake vortex in order to understand their formation, development and far-field behaviour, to predict their decay and, then, to try to minimise their intensity, to disorganise or even destroy the vortices by suggesting approaches with potential to safely reduce the separation distances.

With respect to the above-cited objective and according to ONERA's involvement in past and present European projects, an experimental investigation has been defined and conducted in a low-speed research-type wind tunnel (F2 testing facility from ONERA Centre of Fauga-Mauzac). Depending upon model scale, the steady properties of the wake have been scrutinised to about five to nine wing spans downstream of the model, using complementary measurement techniques: laser sheet visualisations, hot-film, 5-hole probing and 3D Laser Doppler Velocimetry. The presentation will summarise wake vortex formation and evolution obtained for two specific sets of experiments, under the following conditions:

- A300 model, property of EADS-F; scale: 1/100, wing span, *b*: *0.448m* – two lifting wing configurations: clean case (lift coefficient, *Cl~0.7*) and high lift one (*Cl~1.7*) – Reynolds number based on the aerodynamical chord length *Rc~200,000* (*Eurowake* project);
- A rather simple generic SWIM model, property of NLR, *b: 0.60m* with 2/3 span flaps, in high lift conditions (*Cl~1.6*) at *Rc~300,000* (*C-Wake* project).

Mean and turbulent quantities, vorticity distributions in the wake as well as vortex trajectories will be provided and discussed in detail for the base line configurations. Furthermore, the outcome of first attempts to control the wake vortices, using either flap and wing tip devices for the A300 model or spoiler type add-on devices for the SWIM model, will be also briefly evoked. It is therefore desirable that the consistent data base, generated from these two experiments, could be devoted to validate CFD tools for wake vortex prediction, within the framework of European projects or outside of them.

SESSION 4:

CALCULATIONS OF WAKE VORTICES, 1

Chairman:

Alan Bilanin, Continuum Dynamics

WAKE VORTEX PREDICTION AND OBSERVATION IN THE ATMOSPHERE

Thomas Gerz

Institut für Physik der Atmosphäre, DLR Oberpfaffenhofen, D-82234 Wessling
Thomas.Gerz@dlr.de

Wake turbulence is one of the reasons why the air transport industry experiences capacity constraints. New wake--vortex related staggering procedures for approaching aircraft are sought which reduce the current separations and thereby relax airport capacity shortages but do not lower todays safety levels.

DLR launched the project "Wirbelschleppe" (German for wake vortex) to reduce the capacity bottlenecks at airports caused by wake vortex problems. The key feature of this development is a system that makes it possible to predict and observe aircraft wake vortices along the glideslopes of airports. Reduced aircraft separation distances seem feasable under most meteorological conditions, whilst keeping or even increasing the safety level.

The starting point for this work is a precise understanding of the laws under which these vortices are created and decay. Numeric simulations of the flow fields behind aircraft show that wake vortices behave in different ways. How long they remain in the air and where they drift to depend on atmospheric conditions as well as the condition of the ground.

Therefore, an effective prevention system will have to consist of two elements: a short-term, weather and wake forecast is necessary for the time and place of landing. In addition, the system will need to monitor the weather and the wakes and recognize particularly dangerous situations. This kind of concept would make it possible to adapt the landing distances to the weather conditions.

The short-term weather forecast is a difficult task by itself. A system developed for Frankfurt Airport at first considered only data for winds blowing across runways—not enough to make exact prognoses. The DLR developed the system further by also allowing for winds parallel to the landing runway for the wind forecast. This made it possible to improve the quality of the prognosis six-fold.

The paper presents results from the recent wake forecasting and measuring campaign *WakeOP*. During that campaign the trajectories and decay of the wake vortices of a particular aircraft flying with prescribed configurations have been predicted and measured under various meteorological conditions. High resolution weather forecasting and wake predictions are operationally possible in real-time.

WAKE VORTEX TRANSPORT AND DECAY FROM THE PERSPECTIVE OF PARALLEL RUNWAYS

Fred Proctor[+] and D.W. Hamilton

NASA Langley Research Center
Hampton, VA 23681-2199 USA
f.h.proctor@larc.nasa.gov /Fax +757-864-8858

For aircraft approaching/departing a single runway, safe aircraft separations may be determined from the time interval needed for a wake vortex to either dissipate or transport out of the flight corridor. For parallel runways, predictions for safe conditions are more complex since crosswinds can transport wake vortices into adjacent flight corridors. During instrument meteorological conditions (IMC), capacity is decreased for airports with parallel runways, since operations may be reduced or shut down along one of the runways due to the uncertain position of the laterally-drifting wakes. Potential encounters with wake vortices generated from adjacent corridors can be avoided by ensuring that runways are built with adequate lateral separation. However, since this is not always feasible and many parallel runways are in place, capacity improvements must benefit from predictions of wake vortex position and lifetime. Important environmental parameters for predicting wake vortex transport and demise for parallel runway systems are the vertical profile of ambient crosswind and intensity of ambient turbulence. A system designed to predict vortex spacing for parallel runways, at minimum, should be able to predict if wake vortices from adjacent runways can reach the flight corridor before vortex demise. This will require an understanding of how vortices interact with the ground, crosswind shear, and ambient turbulence. We are investigating these interactions with the LES Terminal Area Simulation System (TASS) and will present results at the conference. Our results show that for optimal conditions of strong crosswinds and weak ambient turbulence, wake vortices may drift laterally up to distances of 27 *bo* for out of ground effect and 17 *bo* for in ground effect.

[+] Presenter

NUMERICAL SIMULATIONS OF VORTEX EVOLUTION

Robert E. Robins and Donald P. Delisi

NorthWest Research Associates, Inc., Bellevue, WA, USA

If it were possible to determine when aircraft separation standards imposed by the hazard due to trailing vortices could safely be reduced, then airport capacity could be increased. An important step in being able to realize this possibility is the development of reliable methods for predicting the effect of realistic atmospheric conditions on the behavior of trailing vortices.

In this talk, we describe two prediction methods, one based on solving the equations describing fluid motion and the other based on solving equations derived from a heuristic analysis of vortex evolution. Predictions from both of these methods are compared with full-scale observations and the comparisons are shown to be favorable. We conclude that useful predictions of trailing vortex evolution are feasible and may be useful in the effort to increase airport capacity.

NUMERICAL SIMULATIONS OF LARGE AIRCRAFT TYPE WAKES

D. Darracq*, A. Benkenida† and F. Laporte‡

CERFACS, Toulouse, France

Numerical simulations may be used for the characterization of aircraft wake vortices in the near to extended near field, i.e. covering downstream distances corresponding to the completion of the roll-up process. Complete aircraft computations enable to predict the vortex generation mechanisms and the downstream evolution. On the one hand, such simulations appear as an alternative/complement to wind-tunnel experiments. On the other hand, accurate results in terms of vortex dynamics imply strong numerical requirements, such as high quality meshes (true for both structured and unstructured meshes) and high-order numerical schemes, that allow for steady Euler or Reynolds-averaged Navier Stokes computations (RaNS), but not for Large Eddy Simulations (LES) at the moment. Therefore, numerical simulations may usefully benefit from near-field wind-tunnel experiments, used as inlet data for Euler, RaNS or LES extended near-field computations. Both approaches corresponding to complete aircraft computations, and to the complementary experimental/numerical approach are presented.

The first approach is detailed considering inviscid computations of the flow around a large aircraft type in high-lift configuration by a structured Navier-Stokes solver. Preservation and transport of vorticity being the major concern of the computations, the numerical treatment is described in detail. The efficiency of the use of mesh refinement techniques like Patched Grids and Adaptive Mesh Refinement is demonstrated, showing low-dissipative results. This may be further improved by using suitable high-order schemes. Too dissipative simulations result mainly in too large vortex cores. This strongly affects the extended near field behavior (e.g. spurious or accelerated merging of the co-rotating vortices), as well as the far field dynamics (modification of the stability properties of the vortex system).

The second approach is devoted to steady and unsteady simulations of the extended near field of commercial aircraft type wakes from time-averaged experimental data. Comparing to the first method, the problems related to the meshing constraints are negligible, but the improvements brought by a high-order spatial discretization scheme are also demonstrated in this case, illustrating the difficult issue of reaching grid convergence. Steady RaNS simulations and LES are compared, confirming the widely-spread assumption of laminar vortex cores surrounded by turbulent fluctuations. The method has been validated against wind-tunnel measurements in the extended near field. Some configuration effects have been investigated, demonstrating the sensitivity of the vortex dynamics in the extended near field with respect to minor configuration changes.

Far field temporal or spatial and temporal simulations may be initialized from the outputs provided by any of the two approaches. These simulations allow the prediction of the flow evolution up to the regime of decay of the wake vortices under either atmospheric turbulence or instability mechanisms, potentially including the region of airplane-vortex encounter. Far field LES results based on the first approach are presented. The use of the overall numerical procedure form vortex generation to vortex decay appears as an efficient tool for vortex characterization, and can be further used to test vortex destruction mechanisms.

---

* Senior scientist, e-mail: darracq@cerfacs.fr

† Current position: researcher at the French Petroleum Institute (IFP)

‡ PhD student

SESSION 5:

REMOTE SENSING

Chairman:

Skip Fletcher, Ames Research Center

FIELD TRIAL MEASUREMENTS OF AIRCRAFT WAKES USING COHERENT LASER RADAR

Michael Harris

Sensors and Electronics Division
QinetiQ (formerly DERA) Malvern
Worcestershire WR14 3PS, U.K.

Coherent laser radar (or lidar) is a powerful technique for the detection and evaluation of full-scale aircraft wake vortices. The technique measures the Doppler shift of light scattered from atmospheric particles, and hence infers the line-of-sight flow velocity allowing a picture of vortex flow to be built up. Detection and monitoring of vortices at ranges exceeding a few hundred metres is best carried out using pulsed lidar; in contrast, detailed measurements at short range are better obtained with continuous-wave (CW) lidar.

This presentation will concentrate on characterisation of wake vortices by CW lidar measurements; the work has potential to aid low-vortex wing design, and for quantifying the vortex hazard from existing aircraft. Data will be presented from several trials conducted by DERA/QinetiQ at Heathrow, Toulouse and Munich. Analysis techniques will be outlined for obtaining vortex characteristics such as circulation and trajectory. The influence of atmospheric conditions and local topography on vortex measurements will be discussed.

DETECTION AND TRACKING OF WAKE VORTICES WITHIN APPROACH AND DEPARTURE CORRIDORS

Stephen M. Hannon

Coherent Technologies, Inc.
Lafayette, Colorado USA
(303) 604-2000, e-mail: steveh@ctilidar.com

Pulsed infrared Doppler radar (Doppler lidar) sensors provide a unique capability to generate high resolution, three-dimensional distributions of wind data. Appropriately processed, these data can be used in the airport terminal area to map hazardous wind shear and turbulence levels and to detect and track wake vortices. Within the past five years, continued rapid developments in the arena of solid-state infrared Doppler radar have yielded substantial advancements in terms of autonomous, stand-alone operation. Such developments have made possible the ability to deploy compact and robust systems that are unattended. For certain operational scenarios and procedures designed to improve capacity, the lidar can provide needed wake vortex detection and tracking observations within the approach and departure corridors. This presentation summarizes our autonomous pulsed lidar developments and reviews results from recent relevant deployments.

LONG-RANGE DETECTION OF AIRCRAFT WAKE VORTICES

Friedrich Koepp

DLR Institute of Atmospheric Physics
Oberpfaffenhofen, D-82230 Weßling

For the purpose of flight safety and airport capacity it is of growing importance to detect wake vortices and atmospheric hazards, like wind shear, downdraft and clear-air turbulence, well before a possible encounter of the aircraft. This can be achieved either by a forward-looking sensor being installed in the aircraft or by a ground-based sensor covering the approach area of highly-frequented airports. The most promising candidate for such sensors is the Doppler lidar in pulsed version.

A pulsed Doppler lidar system has been developed and tested in the frame of the EC Project MFLAME (Multifunction Laser Atmospheric Measuring Equipment). It is based on the laser transceiver unit MAG-1 from CLR Photonics with special features necessary for wake-vortex detection: the pulse repetition rate of 500 Hz allows to cover the field-of-view of 12° x 3° within few seconds with sufficient spatial resolution and the pulse length of 500 ns provides a range resolution well adapted to the size of the phenomenon. Following the transceiver, the laser beam is twenty-times expanded by an off-axis telescope and then deflected into the sensing area by a scanning device. This device is the combination of two separate units: a fast vertical scanner consisting of two counter-rotating prisms and an oscillating plane mirror providing the horizontal scan. In this way, one complete image is covered within 5 s by a sinusoidal scan pattern with 75 vertical lines. The detector signals from the atmospheric return and the pulse-monitor reference are digitized with 500 MHz sampling rate and stored by the data acquisition and quick-look unit. Links to the scanner device enable the localization of each line-of-sight within the field-of-view.

To demonstrate the feasibility of the pulsed lidar for wake-vortex detection, ground tests have been carried out at the airport Toulouse-Blagnac in February and March 2000. There, the lidar system was installed below the glide slope of runway 33L approximately 800 m in front of the threshold. The landing aircraft were flying towards the lidar system passing the sensing area at an altitude of 50 - 80 m. In this configuration, the angle between the vortex axes and the lidar line-of-sight, the so-called aspect angle, is rather small - similar to the airborne case. In this way, the detection of vortices generated by a large variety of aircraft has been successfully demonstrated up to ranges of more then 2 km. The next step will be the integration of the lidar system into an aircraft for the detection of wake vortices generated by preceding aircraft.

WAKE VORTEX MEASUREMENTS WITH A CW COHERENT LASER RADAR OF THE XV-15 TILTROTOR AIRCRAFT

R.M. Heinrichs, J.C. Libby, T.J. Dasey*
and B. Edwards**

M.I.T. Lincoln Laboratory
Bell Helicopter Textron

Lincoln Laboratory, in coordination with Bell Helicopter Textron, has conducted measurements of the wake vortex characteristics of the XV-15 tiltrotor aircraft. Vortices generated in different forward flight configurations were detected and tracked by our mobile continuous-wave coherent CO2 laser radar. This is the first time the wake of a tiltrotor aircraft has been measured using laser radar. The CW coherent laser radar was developed as part of the NASA AVOSS program. It has been employed over several measurement campaigns to collect wake-vortex data from fixed-wing landing aircraft while simultaneous measurements were performed to characterize the atmospheric state. The laser radar is described along with examples of wake-vortex measurements of landing fixed-wing aircraft under the AVOSS program. Measurements made in August 2000 at the Bell Helicopter Test Flight Facility in Arlington, Texas are then presented, along with an analysis of the vortex data.

SESSION 6:

CALCULATIONS OF WAKE VORTICES, 2

Chairman:

Ulrich Schumann, DLR

INSTABILITIES OF WAKE VORTEX MODELS IN THE NEAR AND FAR FIELDS

Florent Laporte*

CERFACS, Toulouse, France

Ensuring accelerated wake vortex decay under any kind of atmospheric conditions is one of the most promising approaches to the wake vortex problem. Enhanced decay might be obtained by acting on the potential instability mechanisms that are likely to develop in wake vortex systems. The knowledge of the stability properties of the vortex systems shed by aircraft is a necessary pre-requisite to the control of these flows.

The complexity of the flows under consideration has lead to study here the stability properties of simplified models of wake vortices (complete wake vortex characterization is still being a difficult issue, mainly with respect to the turbulence structure, the intrinsic unsteadiness properties, the far field measurements, ...). These model flows are nevertheless representative of a large class of civil transport aircraft in high-lift configuration (among which Airbus-type aircraft). Stability properties of both a model of near field and a model of far field wakes are studied by the means of Direct Numerical Simulations (DNS) and Large Eddy Simulations (LES). The intrinsic most unstable modes are temporally simulated by superimposing a white noise on the base flows so as to obtain perturbed initial conditions. The relevance of the flow models with respect to realistic aircraft wake flow conditions and the numerical treatments are discussed.

Near field flows (of downstream extension between 1 and 20 wingspans, orders of magnitude) are modeled by considering a single-flap wing shedding two co-rotating vortices, corresponding to the flap and tip vortices. The stable interaction between these vortices corresponds to the well-known merging phenomenon resulting in a single stable vortex. The simulations reveal also the possible development of a three-dimensional elliptic instability in these two vortices, confirming and extending the recent discovery of Meunier & Leweke in a low Reynolds number experiment. The instability would lead to an unstable merging resulting in a turbulent final vortex. The characteristics associated to the final vortex are found to be potentially significantly different with or without the instability.

Far field flows (of downstream extension larger than 10-20 wingspans) are modeled by considering the wake vortex system shed by an aircraft formed after completion of the roll-up process. For many aircraft types in the fleet, this results in a unique pair of counter-rotating vortices, which can be characterized by a single control parameter. The linear, non-linear and transitional regimes are simulated in the case of the development of the long-wavelength Crow instability, and in the case of the development of the short-wavelength elliptic instability. The influence of the control parameter on the dynamics is discussed, and the late stages of the flows are characterized in terms of hazard. Potential benefits and disadvantages brought by the use of these instability phenomena to accelerate the vortex decay are detailed. The optimal control conditions for an efficient wake destabilization using these mechanisms are interpretable in terms of wing design.

* PhD. Student, e-mail: flaporte@cerfacs.fr

FORCING THE BREAKUP OF AIRPLANE TRAILING VORTICES

J. D. Crouch

Boeing Commercial Airplanes

Reducing the airplane separation requirements imposed due to trailing vortices would help increase airport capacity. Unsafe trailing-vortex encounters can be prevented by avoiding the vortices, by enabling the encountering aircraft and crew to tolerate the vortices, or by alleviating or destroying the vortices. Efforts to avoid the vortices, while reducing airplane separations, often make use of local weather predictions to determine when alternative procedures can be imposed. This type approach has the advantage of providing immediate benefit once it is applied. A shortcoming of this approach is that the benefits are weather dependent and can not be fully exploited due to uncertainties in predictions. Also, procedural solutions are airport specific and may not be transferable to different locations. An alternative approach to improve airport capacity is to implement a system to destroy the vortices within a prescribed distance behind the lead aircraft. If successful, this has the advantages of being a predictable benefit and it is applicable to many airports. A disadvantage of this type approach is that the number of airplanes having the system limits the benefits.

Boeing is working to develop an active system to break up the trailing vortices within a prescribed distance that is less than some current airplane separation distances. Airplane control surfaces are used to force flaps-down vortex instabilities that lead to the breakup of the vortices into vortex rings. The concept has been tested in a towing tank using a simplified flaps-down model. Breakup into vortex rings was achieved with a moderate level of forcing at a distance of about 2.5 to 3 nmi. behind the airplane (when scaled to flight for a 747 airplane). The experimental results are in general agreement with numerical simulations. The performance of the active system depends on details of the airplane configuration (e.g., the flap system and horizontal tail loading). Ongoing efforts are aimed at determining a simple set of parameters that can be used to predict the effectiveness of the system for a given configuration.

Before such a system can be implemented, there are a number of issues that must be addressed. These issues can be grouped into active-airplane issues, following-airplane issues, and airport-environment issues. The most obvious issues for the active airplane are the potential impact on ride quality, dynamic-load effects on the structure, and the ability to maintain control authority during operation. In terms of the following airplane, the primary question is at what stage in the breakup can the vortices be considered benign. Airport-environment issues include determining how the breakup is affected when the vortices are near the ground, what are the effects of atmospheric stratification and shear winds, and how can the total system reliability be demonstrated to such a high level that rules can be changed.

Vortex avoidance would still be the norm when the active system is in operation. In the unusual event of a vortex encounter, the system would ensure that the vortices are sufficiently disorganized within the airplane-pair separation distance. The talk will provide an overview of the active system and a discussion of some of the implementation issues that have so far been considered.

THE EFFECTS OF THE ATMOSPHERIC TURBULENCE ON WAKE VORTICES

Henri Moet *

CERFACS, Toulouse, France

Wake vortices are strongly affected by ambient atmospheric parameters such as wind shear, stratification, and turbulence as well as by the proximity of the ground. The lifespan of wake vortices may be short in presence of strong turbulence but may also be of the order of several minutes in case of weak turbulence. The vortex lifespan is an essential aspect in the issue of wake vortex encounters. In this study we focus on the effect of three-dimensional ambient atmospheric turbulence on vortex decay using temporal large eddy simulations.

The effect of ambient atmospheric turbulence has been investigated by placing vortex systems in homogeneous isotropic turbulence, which is assumed to be either a good approximation of atmospheric turbulence as well as a suitable option for generic vortex/turbulence interaction studies. A large set of single vortex and vortex pair configurations has been considered in order to determine the quantitative and qualitative effects of ambient turbulence on the vortex dynamics. The different mechanisms that have been observed during the decay process are turbulent diffusion, the creation of azimuthal structures of vorticity, the concurrent exchange of vorticity between primary vortices and the surrounding turbulence, as well as occurrence of large deformation and the onset of instability processes. The circulation, which quantifies the strength of the vortex is significantly affected by the presence of turbulence, and an accompanying parameter study resulted in the identification of pertinent parameters governing the circulation decay.

Based on the numerical simulations, a simple turbulence decay model is proposed as a function of the parameters characterizing the ambient turbulence. The observations made during the analysis of the results showed the appearance of the different phenomena mentioned above that dominate the vortex decay. The relationship is assumed to model the circulation decay of vortices interacting with ambient turbulence, a neutrally stratified background with no wind shear and no ground effect.

A second three-dimensional large eddy simulation code is used to simulate the behavior of aircraft wake vortices in a more realistic atmosphere. In this case, both weak turbulence and stratification effects are studied. Stable stratification is here a consequence of the earth's boundary layer activity. A system of vortices in post roll-up phase placed in a suitable meteorological background form the initial conditions of a temporal simulation. Mesh refinement techniques enable the use of a large computational domain to capture the different scales of motion present in the atmospheric boundary layer as well as a sufficient resolution in the region where the vortices reside. Eventually, the decay processes identified in the homogeneous isotropic turbulence simulations and in the more realistic test case will be compared.

* PhD. Student, e-mail: moet@cerfacs.fr

THE VORTEX FORECAST SYSTEM (VFS): PREDICTION OF TRAJECTORIES AND DECAY FOR AIRCRAFT WAKE VORTICES IN AN OPERATIONAL ENVIRONMENT.

Gregoire S. Winckelmans

Centre for Systems Engineering and Applied Mechanics (CESAME),
Mechanical Engineering Department,
Division of Thermodynamics, Fluid Mechanics and Turbomachines,
Universite Catholique de Louvain, 1348 Louvain-la-Neuve, Belgium.
gsw@term.ucl.ac.be

The VFS is an operational wake vortex predictor system based on the Method of Discrete Vortices (MDV). It was developed under contract with Transport Canada and its Transportation Development Center, during 6 Phases (from 1993 to 2000), and by an international team: Prof. Sergei Belotserkovsky *et al.* (SABIGO Ltd., Moscow, Russia), Prof. Gregoire Winckelmans *et al.* (UCL, Louvain-la-Neuve, Belgium), Prof. Metin Yaras (Carleton University, Ottawa, Canada), Jim Harvey *et al.* (Oratel Telecomputing Inc., Carleton Place, Canada), Wayne Jackson *et al.* (Transport Canada and Transportation Development Centre, Ottawa), Gilles Fournier (Environment Canada). It was developped in close collaboration with the AVOSS program conducted by NASA LaRC.

The VFS is now a fairly sophisticated, validated and mature technology: one that can be used in real-time operational systems. It could nevertheless be further validated and improved. It handles: Creation of the initial near wake using either SABIGO's detailed Near Wake DataBase (NWDB) or the simplified Universal Near Wake (UNW) which then assumes the "universal'" circulation profile for aircraft wakes shortly after rollup; Modelling of wake transport, using the vortex-induced velocities and the cross-wind velocity profile; Modelling of the slow wake decay, using the atmospheric turbulence profile (either EDR decay model or TKE decay model) and of the fast decay time (time to demise as function of EDR); Modelling of inviscid near ground effects (by image discrete vortices) and of viscous in ground effects (by injection of secondary discrete vortices from the ground); Modelling of non-uniform wind shear effects (by additional vertical velocities acting on the discrete vortices); Modelling of stratification effects, using the atmospheric stratification profile (model implementation is ongoing). For simulations of landing, the VFS is run in multiple cross-plane "gates" (typically 5 gates, ranging from the intercept plane to the touchdown plane), so that a more realistic space-time vortex evolution is obtained. It can also be used for closely-spaced parallel runway applications.

Scoring of the latest VFS (version 5) was also conducted, in early 2001, by Bob Robbins of NorthWest Research Associates (NWRA), under NASA contract. The procedure was the same as that used for scoring the first VFS version in early 2000: It was run on 211 cases from the Memphis (MEM) database and 191 cases from the Dallas Fort Worth (DFW) database. The latest VFS scoring results compared well with those obtained with the other AVOSS predictor models. The specific VFS capabilities (e.g., modelling of ground effects and of non-uniform wind shear effects) were also recognized as valuable and worth pursuing.

A short VFS demonstration will be presented: the simulation of the wake from a B-727 that is produced at 150 m altitude, and experiences significant non-uniform wind shear + ground effects, due to a low level jet (MEM Case 1132).

The VFS project summary reference is: W. Jackson, M. Yaras, J. Harvey, G. Winckelmans, G. Fournier and A. Belotserkovsky, "Wake Vortex Prediction - An Overview", Phase 6 and Project Final Report prepared for Transportation Development Centre and Transport Canada, TP 13629E, March 2001 (www.tc.gc.ca/tdc/projects/air/9051.htm).

SESSION 7:

EXPERIMENTS WITH WAKE VORTICES, 2

Chairman:

Michael Vaughan, DERA

HOW CAN WE TRULY REDUCE THE WAKE-VORTEX HAZARD BY MODIFYING THE WING?

Philippe R. Spalart

Boeing Commercial Airplanes

The airframers wish to contribute to the combination of safety and airport capacity, in the context of wake turbulence. They are widely involved in the air-traffic system and design airplanes to recover from upsets due to wake- or other turbulence, up to some level. When viewing the airplane as the leader, the airframers are ready for limited compromises to make the wakes less troublesome. Characteristics that may be traded for this include: drag, lift, weight, complexity, control authority, pilot workload, or noise. The Airbus A380 is the first model for which such steps are, to our knowledge, being taken.

Here we attempt to concretely identify what could make a less troublesome wake.

A classic trade between wake properties involves the circulation Γ and the effective span b_0 of a single vortex pair. Given the weight and speed, $\Gamma x b_0$ is fixed. Lowering Γ makes a weaker wake, and encounters are less severe. However the wake descends more slowly, and its Crow instability grows more slowly; the wake lingers. Both effects increase the probability of an encounter. Thus, the preference between Γ and b_0 depends on the policy (avoidance or tolerance of encounters) and on factors such as the leader and follower sizes, actual in-trail separation, phase of flight, and weather. The trade is not simple.

Flow-control designs can be classified as active, when the configuration is varied cyclically to initiate an instability, or passive. Boeing's active system is discussed in this volume. The aim is *wake collapse*. Approaches such as tip turbines appear intermediate but are closer to passive systems, in that they divide and displace the vortices, and/or increase mixing.

Most passive designs use a static geometry, winglets for example. The trade between Γ and b_0 leaves little room. The known passive designs are presumed to produce "weaker" wakes, for the same Γ and b_0, making encounters less violent. The aim is *wake alleviation*. Common measures of a wake's threat include the peak vorticity, peak velocity, and kinetic energy. Useful changes to these will be very difficult to demonstrate. The first two concern small tubes of air, of the order of 1m in diameter. Reducing them has little effect on the rolling moment for a passenger plane. The kinetic energy reflects the velocity farther from the axis and does correlate with rolling moment, especially for a follower smaller than the leader. However, the kinetic energy cannot be reduced by a large factor without extensive changes to the wing. Within the lifting-line approximation, its initial value is proportional to the induced drag, which itself is bounded from below if the span is fixed (winglets reduce it slightly). The kinetic energy in the aging wake, miles downstream, would be lowered by strong turbulent dissipation; however free vortices are known to disable turbulence. Furthermore, the spin-down of a single vortex is arrested by the need to conserve angular momentum (this result is not exact for a pair). Thus any "weak vortex'" concept will need to counter some fundamental theorems before it is accepted. The theorems depend on approximations, but these approximations are robust. It appears that the design freedom for passive systems is very restricted.

For all wake-turbulence-oriented design features, testing and certification will pose extreme challenges. No testing programme will directly demonstrate accident probabilities in the 10^{-8} range, and the stochastic nature of the atmosphere is unavoidable.

WAKE ALLEVIATION THROUGH CONTROL VORTEX INSTABILITIES

Ömer Savaş, Jason M. Ortega, and Robert L. Bristol

Department of Mechanical Engineering
University of California at Berkeley
Berkeley, CA 94720-1740 USA

A series of experiments are carried out in the vortex wakes of wings with outboard flaps, which are used to generate control vortices. A rapidly growing instability is observed to develop between unequal strength, counter-rotating vortex pairs in the wakes of airfoils with outboard triangular flaps (figure). Unlike the wake of a simple rectangular airfoil, the wakes of the triangular-flapped airfoils become highly unsteady and complex as the result of this instability. The qualitative features of the instability, such as its wavelength and non-linear evolution, are examined by flow visualization measurements that are made in a towing tank at a chord-based Reynolds number of $O(10^5)$. This sinuous instability is seen to develop on the weaker flap vortices and have a wavelength of order one wingspan. Typically, the instability requires about 15 wingspans to become finite in amplitude. Planar velocity field measurements of the vortex wakes are made with a PIV technique, allowing the vortex structure, trajectories, kinetic energy, and distribution to be assessed up to several hundred wingspans downstream of the airfoils. For angles of attack ranging from -1. 0° to 2.0°, the circulation strength ratio of the flap and tip vortices ranges from -0.7 to -0.4. Additionally, the circulation-based Reynolds number is seen to be of $O(10^5)$. The PIV data indicate that the wake's two-dimensional kinetic energy decreases substantially as the instability transforms the two-dimensional nature of the wake into a three-dimensional one.

The wake alleviation properties of these wings are estimated using the PIV data, following Rossow (1976). The non-linear interactions between the vortices result in a wake that is highly three-dimensional and incoherent. These effects are reflected in large decreases in both the rolling moment and downwash on a simulated following wing. The results are compared to those of a rectangular wing. For all of the experimental runs, the wakes of the triangular-flapped wings have a maximum rolling moment and downwash that are substantially less than those of the rectangular wing. In particular, non-dimensional rolling moment and downwash are about 1/3 of those of a comparable rectangular wing. The results of this study indicate that the triangular-flapped wing design offers a possible solution to the wake hazard problem.

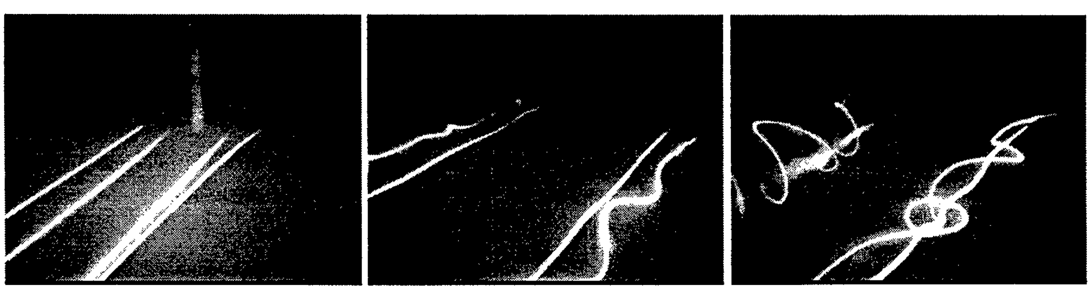


Figure: The instability in the wake of a triangular, outboard flapped wing. The vortices are marked by injecting dye at their cores.

EXPERIMENTS ON WAKE VORTEX CONTROL

Peter Bearman & Christine Hogan

Department of Aeronautics, Imperial College of Science, Technology and Medicine, London SW7 2BY, UK

The decay process for a pair of aircraft trailing vortices is influenced by the amplification of naturally occurring disturbances. This leads to a strong interaction between the vortices resulting in a mixing of vorticity closer to the aircraft than would occur solely through diffusion of the vortex cores. One way to control the breakdown distance is to introduce artificial disturbances into the vortices as they are formed. The type, amplitude and frequency of this disturbance play a critical role in determining how rapidly the vortices reduce in strength to a level that does not pose a hazard to following aircraft. Studies of the decay of trailing vortices are difficult because of the large spatial separation between the formation and decay regions and because the decay process is highly unsteady. This presentation is concerned with a laboratory investigation of trailing vortices and use is made of a water tank to visualise flow structure. Measurements of velocity and vorticity fields, at a series of downstream stations, are being made in a wind tunnel using PIV. The initial experiments have been performed using a delta wing with a 75° leading edge sweep, i.e. 30° apex angle. It is planned to move to a typical transport aircraft wing configuration in the near future. Disturbances are introduced in two ways: by adding a harmonic variation to the relative flow speed and by adding a sinusoidal perturbation to the wing incidence.

Flow visualisation is carried out in the water tank using fluorescent dye and a light beam from an argon ion laser. The beam passes through a set of optics to produce a near constant thickness sheet running the length of the tank. After the wing has traversed the tank the trailing vortices continue to interact and the flow is studied until the vortex structure has apparently broken down. Some caution has to be observed because dye is being viewed and not vorticity. In some experiments one trailing vortex was visualised with green dye and the other with red dye in order to obtain a clearer picture of the interaction process. Some video sequences of the flow visualisation will be shown. Initially the short wavelength instability is clearly visible but as the flow evolves the well-known Crow[1], or long wavelength, instability develops. The time to the point where one vortex appears to wrap around the other is termed the breakdown point. This time is then transformed into an equivalent distance behind the wing, which in the present case is about 110 wing spans downstream. For a 75° delta wing the wavelength of the Crow instability, as shown in previous studies[2], is around 4.6b, where b is the initial distance between the trailing vortices. If the flow speed is perturbed at this wavelength then the trailing vortices are found to breakdown closer to the wing. However, if the wavelength is smaller or larger than the Crow value by some critical amount the breakdown point moves further downstream and the imposed disturbance decays before the Crow instability develops. It is clear, therefore, that if artificial disturbances are to be introduced it is important that the wavelength is carefully controlled. Further results using incidence variation will be shown, together with PIV measurements.

1. S.C.Crow. Stability theory for a pair of trailing vortices. AIAA Journal, 8(12), pp 2172-2179, 1970.
2. C.H.K.Williamson, T.Leweke and G.D.Miller. Fundamental instabilities in spatially-developing wing wakes and temporally-developing vortex pairs. ASME Fluids Engineering Division Summer Meeting, paper FEDSM98-4993, June 1998.

A NEW FACILITY TO STUDY NEAR TO FAR VORTEX FIELDS

Patricia Coton

ONERA/DCSD

With the aim of studying aircraft behaviour in the low-speed domain and demonstrating the performances of new concepts the Department for System Control and Flight Dynamics of ONERA (ONERA/DCSD) has developed over many years a specific experimental method based on flight tests of scaled models performed in a laboratory. To take off the model is propelled by means of a catapult whose height and slope angle have been previously adjusted. Once the model is launched, it flies freely without any wall or mounting interference and is recovered in a volume of plastic foam.

The experimental method has the peculiarity to allow the observation and the analysis of the wakes emitted in the ground based reference frame contrary to the experiments carried out in a wind tunnel. The access to the far field is then possible, which is a very significant asset for this type of facility compared with wind tunnels where the observations are limited to some wing spans.

In the former facility called B10, this analysis could be led until a maximum distance approximately 100 wing spans downstream from the model. In the new facility B20, considering its larger dimensions in length but also in height, and taking into account the descent speed of the wake, this observation could potentially be carried out on a distance approximately 200 spans before the effect of the ground proximity influences the dynamics of the wake. As an example this distance represents 8.5 nautical miles behind a A3XX, which largely covers the current separation distances between the planes during the approach and landing phase.

The use of this laboratory, which enables to gather, under the best operating conditions, aerodynamic data which are inaccessible in a wind tunnel, requires for this type of study the implementation of specific measurement equipment. The laser tomoscopy is one of this equipment which makes it possible to obtain images of the flow patterns and to identify according to time the sizes and positions of the emitted vortices. Then knowing the trajectories of these vortices, precise and quantitative measurements of the velocity fields of the sown flow can be carried out by means of the PIV technique (Particle Image Velocimetry). The data thus obtained are of major importance to study and understand the mechanisms which govern the development and the evolution of the wakes. The LIDAR technique, which was adapted to the characteristics of model flight tests by the department DOTA of ONERA, enables to use the same tools as during full-scale flight tests. A direct link can thus be established between the observations carried out in the laboratory and the results of flight tests of the plane.

As for low-speed wind tunnel tests the main limitation relative to the exploitation of the data collected in flight on a reduced scale model can come from the conditions of the Reynolds's similarity related to flow separation on the wing, in particular. Performing experiments with a Reynolds number appreciably lower than in reality requires beforehand to check, in a wind tunnel or by calculation, the respect of the aerodynamic similarity for the test conditions in the flight analysis laboratory. For the flights with high values of CL, in particular, it is necessary to be ensured of the similarity of flow separations on the lifting surfaces.

SESSION 8:

ROTORCRAFT EXPERIMENTS, 1

Chairman:

Andy Kerr, US Army

HELICOPTERS AND VORTICES

Gerd E.A.Meier

DLR Institute of Aerodynamics and Flow Technology, Göttingen

Helicopters and vortices have a special relation. Vortices are generating in an interaction with the rotor blades a major part of the noise of a helicopter. In a lot of research activities it was found, the interaction of the blade tip vortices with the following a blade is generating the slap noise of helicopters heard in special directions.

There is a certain directivity of the noise, because the location of the major interaction areas and the orientation of blades and wind speed, preference depending on the flight situation special directions.

In case of fast rotation of the rotor also shock waves generated by supersonic tip speed can contribute to the noise. But since modern helicopters prefer low speed multiblate rotors this supersonic shock noise is not the most important noise source any more.

We focus our considerations in this paper on the mechanisms of noise generation by vortex blade encounters and on the observation and measurement techniques for locating the vortices in the wake of the rotor.

The first part is therefore dealing with experiments and numerical calculations showing a two dimensional vortex interaction with a two dimensional airfoil section. The sound generation is clearly visible in the results and documents two different mechanisms of sound generation. The first one is a kind of bow shock which is radiated because the approaching vortex increases the incoming wind speed and the blade is producing a kind of bow shock this way. A second mechanism of generating steep sound waves is due to an increase of flow velocity on the surface of the airfoil. Here a supersonic flow pocket can be generated and the closing shock wave is radiated as a sound wave later when the vortex has passed the airfoil section.

The rotor experiments with the flying helicopter have been made possible by an new optical technique, which is called BOS (Background Oriented Schlieren). This technique enables field recordings of density gradients in unlimited viewing fields. This way the interaction areas and of a rotor flow field can be recorded. Results for two different helicopters have been achieved and show the generated vortices but also some spectacular vortex vortex interactions.

INVESTIGATIONS OF SHIPBOARD ROTORCRAFT INTERACTIONAL AERODYNAMICS

Kurt Long

Naval Air Warfare Center Aircraft Division, Patuxent River, MD, USA

Since 1943, the US Navy has conducted Dynamic Interface (DI) shipboard flight tests to evaluate all aspects of shipboard rotorcraft compatibility, and to develop shipboard rotorcraft operating envelopes. The shipboard environment poses unique challenges to routine fleet operations and test operations alike. Since the mid-1990s, the US Navy has increasingly focused on developing improved analytic techniques that would facilitate more efficient and cost effective shipboard rotorcraft flight test programs. This paper summarizes recent USN investigations, which include wind tunnel, CFD and other analytic efforts, conducted at NASA Ames Research Center, which are designed to investigate shipboard rotorcraft interactional aerodynamics, thereby allowing the USN to optimize and improve shipboard rotorcraft compatibility.

The paper and accompanying brief summarize a variety of wind tunnel efforts, which were conducted to investigate and characterize the complicated flow fields that exist aboard various USN ship classes, for use in improving USN shipboard flight test programs. The efforts included investigations of the wake flow around simplified and complicated three-dimensional ship structures, with and without model rotorcraft (both conventional and tiltrotor) imposed into the flow. These investigations included a variety of quantitative and qualitative measurement techniques, including surface oil and wake smoke flow visualization, a seven-hole probe, hot wire anemometry, particle image velocimetry surface pressure taps, pressure sensitive paint, and shear-sensitive liquid crystals. The wind tunnel results are compared with calculations and with full-scale shipboard flight test data.

This briefing considers flow similarity of complicated ship geometries and simpler three-dimensional shapes, the potential airwake impact of small changes in shipboard geometry, the variation of shipboard wake flow patterns with wind direction, and the fascinating interactions of aerodynamic effects associated with a spinning rotor system in close proximity to complicated structures like ships. Other issues include flow similarity requirements, wind tunnel blockage effects, limitations to the existing program, and an overview of USN shipboard rotorcraft flight operations. The paper also draws conclusions concerning the implications associated with civilian rotorcraft operations in the vicinity of buildings and other structures. It summarizes the status of a joint NASA/USN program, which is devoted to acquiring more complete understanding of shipboard rotorcraft interactional aerodynamics. The presentation will include still and video photography.

Information: Kurt Long is a USN shipboard rotorcraft flight test engineer, who has conducted over 70 shipboard rotorcraft Dynamic Interface flight test programs. Since 1997, Mr. Long has been involved in the conduct of wind tunnel, CFD, and other analytic shipboard rotorcraft compatibility optimization efforts at NASA Ames Research Center.

ROTORCRAFT WAKES IN THE CONTEXT OF AIRPORT OPERATIONS

Leo Dadone

Senior Technical Fellow, Boeing-Philadelphia

Helicopters and tiltrotor aircraft are designed for high performance, and low vibration characteristics. Low noise becomes a requirement for civil operation close to urban areas. Rotor wakes play a key role in the flow environment of rotorcraft. The modeling of the interaction between wake and blades is at the core of all rotor aerodynamics and aeroacoustics analysis methods – whether they involve explicit models of the rotor wake, or rely on harmonic representations of rotor inflow characteristics.

The structure of rotor wakes is so complex that most of the detailed understanding, and modeling, has been focused on the 'design' flight conditions - namely, hover (requiring axisymmetric wake modeling) and high-speed / high-thrust (limited to periodic conditions in 'straight-line flight'). But low speed wake models are becoming increasing practical, and progress continues in extending the rotor wake models to maneuver flight and to the prediction of a wide range of interactional aerodynamic conditions.

Dealing with airport environments requires addressing conditions that fall outside of the wake modeling employed in rotor design. Typically, when more rigorous analytical modeling is not possible, empirical data are used to complement the analytical predictions. Progress continues to be made in the modeling of complex flow fields by means of Computational Fluid Dynamics (CFD). Advanced methods are also being investigated to couple flow field information with blade aerodynamics and dynamics effects. This includes, or can potentially include, rotor downwash, ground proximity effects, the interaction of rotorcraft with the wake of large structures and other aircraft, and even blade sailing effects during start-up/shut-down.

This presentation will review current rotorcraft analysis methods with emphasis on rotor wake modeling, by both CFD and vortex element methods, addressing what has been done and could be done to deal with flow field issues relevant to airport operations when rotorcraft and fixed-wing aircraft share the space.

HELICOPTER ENCOUNTERS WITH AIRCRAFT VORTEX WAKES

Gareth D Padfield

Bibby Professor of Aerospace Engineering
The University of Liverpool

Results are presented from a study concerning the risks associated with locating a helicopter Final Approach and Take-Off area (FATO) alongside an active runway at a busy international airport. Specifically the problem of a helicopter encountering the shed wing tip vortex from a large transport aircraft is addressed. Data derived from measurements of tip vortices taken using a coherent laser radar located under the final approach path are used to validate a model of the distribution of the flow velocities occurring in the shed vortices. The data has also provided an opportunity to examine the length of time these vortices can retain an appreciable strength. A 'worst case' scenario is defined in which the shed wing tip vortices from a Boeing 747 are encountered by a hovering 5000 kg helicopter located at 250 m from the line of the main runway. No significant decay in vortex strength is assumed in the time taken for the vortex to travel from source aircraft to the helicopter.

The simulations show, for a range of flight conditions, that the helicopter can experience transient attitude changes of up to 40 degrees and accumulated descent rates of 1500 ft/min during the encounter, assuming no pilot intervention. Established handling qualities metrics relating to attitude quickness (related to time to change attitude) and transient response following system failures have been applied to the problem and suggest that these responses may produce handling difficulties. The worst transient attitude response occurs when the helicopter encounters the inner core of the vortex. The sensitivity of the response to offsets between helicopter and vortex centre during near misses is shown to be fairly high, resulting in a decrease in the probability of the worst case actually occurring. In the study, the simulations were expanded to consider the influence of various helicopter design parameters on the magnitude of response and the effects of considering shed vortices from source aircraft other than the Boeing 747.

The study concludes that under particular circumstances a helicopter can experience significant transient motions on encountering a shed wing tip vortex, although no attempt has been made to estimate the probability of this occurrence. The proposed transient response criteria provide a sound basis for assessing hazard severity and probability.

SESSION 9:

ROTORCRAFT CALCULATIONS

Chairman:

Marco Borri, Politecnico Milano

RECENT ADVANCES IN COMPUTING AND VISUALIZATION RELEVANT TO AIRPORT CAPACITY

Lyle N. Long

The Pennsylvania State University, University Park, PA 16802 USA
http://www.personal.psu.edu/lnl/lnl@psu.edu

The National Aeronautics and Space Administration (NASA) predicts that by the year 2022, three times as many people will travel by air as they do today. To keep the number of new airports and runways to a minimum, there is an urgent need to increase their efficiency while reducing the aircraft accident rate. This paper will describe a number of roles that computing and visualization can play in helping to meet future airport capacity issues. In particular, runway independent aircraft (primarily rotorcraft) promise to ease congestion by moving passengers through the airports without utilizing traditional runways. It will be essential to use computers to help design future rotorcraft that are quiet, efficient, cost effective, and reliable. In addition, computer visualization will be very valuable in future air traffic control systems.

Moore's law states that computers will double in performance every 18 months, while cost remains constant. If this trend continues, in the year 2022 computers will be roughly 10,000 times faster than today. This rate of change is difficult to comprehend, but it is essential that we use this increased computational power in solving the airport capacity crisis. These computers will be needed to help design better aircraft, better air traffic control systems, and better onboard systems. Similar advances are expected in networking and visualization. In fact, Kurzweil predicts that by 2020 inexpensive computers will be more intelligent than humans (and there could be millions of them).

While the power of individual computers grows exponentially, it is also fairly commonplace to use computers in parallel, yielding up to 10,000 times the power of a single computer. Parallel computer simulations are playing an increasingly important role in all areas of science and engineering. In addition, virtually all parallel computers are now made from commodity processors, which means the cost is quite reasonable. Homemade parallel computers (Beowulfs) are also quite common now. With the tremendous growth in the speed and memory of parallel computers, it is possible to run many simulations in real-time. The combination of advanced parallel computers and virtual reality visualization provides one of the most realistic and powerful simulation tools available to the scientific community.

In the area of computing, large-scale simulations will be needed to help design quieter, more efficient, and more reliable transportation systems. In particular, aeroacoustics, aerodynamics, and structural dynamics can benefit from more robust and accurate simulations. While computational fluid dynamics (CFD) has advanced considerably in the last few decades, it still has a long way to go. While we can solve a few problems well, there are many more that are beyond our reach. While we can solve for the time-averaged turbulent flow over very streamlined bodies, flows that involve phenomena such as separation, unsteadiness, complex body motions, reactions, multiple phases, or rarefaction are still major research areas. Unfortunately several of these complex phenomena are found on rotorcraft, which is why we are not able to completely simulate the details of the aerodynamics of these vehicles today.

The final paper will present results from aeroacoustics, helicopter fuselage flowfields, rotor simulations, and ship airwakes; as examples of important unsolved computational flow problems. Effectively modeling turbulence is crucial. Using parallel computers for multiple serial jobs will also be discussed, which allows for rapid trade studies.

Computer visualization will also be discussed. In particular, the rapidly expanding field of virtual reality, and the less well known field of augmented reality (AR), will be discussed. This technology offers to be very useful in air traffic control and in cockpits. The most common virtual reality system is a CAVE, which is basically a room and each wall is a projection screen. And the projections are done using stereo graphics, so the user must where shutter glasses to see the 3-D images. Just as supercomputers used to cost millions of dollars, CAVE's also cost millions of dollars. However, due to the rapid growth in computing power, virtual reality systems are becoming quite cost effective. There are now "Beowulf" type virtual reality systems based on high-end PC's, inexpensive stereographics cards, and Linux. This will allow the proliferation of virtual reality systems.

Several examples of research efforts in VR in the U.S.A. will be presented, as well as some additional areas where VR/AR can help solve the capacity problems. One of our research efforts attempts to create a general software system to integrate Virtual Reality with real-time numerical simulations for visualizing aircraft wakes near and around airports. Specifically, this work aims at creating a wake-vortex hazard avoidance system by realistically simulating an airport with real-time visualization of the predicted wake-vortices generated by the moving aircraft. The dangers (and unknowns) associated with aircraft flying through wake-vortices is a dominant limiting factor in airport throughput. If implemented, such a system has the potential to greatly increase the utilization of airports while reducing the risks of possible accidents. Since the wake-vortex prediction for an entire fleet of aircraft taking-off and landing at a busy airport is a computationally intensive problem, a parallel solution is proposed. The output from the parallel code will then be sent to the VR system via a computational steering framework.

RECENT IMPROVEMENTS TO MODELING ROTOR WAKES IN HOVER AND FORWARD FLIGHT

Lakshmi N. Sankar and Zhong Yang

School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, GA 30332-0150

The goal of this study is to develop an efficient solution methodology that will accurately predict the aerodynamic loads on a rotor in forward flight. The model should simulate the complex blade dynamic motion in forward flight, include a trim process, have a self-consistent wake model, and account for the aeroelastic deformations of the blade.

A hybrid method is used in this study, and is demonstrated to be an appropriate phenomenological methodology for capturing the unsteady flow phenomena over the rotor in different flow regions. A Navier-Stokes analysis is used for modeling the viscous flow and near wake in a small region surrounding the single rotor blade. A finite volume form of the Navier-Stokes equations is solved using Roe's approximate Riemann solver with third order or fifth order spatial accuracy. In the outer zones of the computational domain, a potential flow analysis is used to solve the inviscid isentropic flow and carry the acoustic and pressure waves generated by the blade to the far field. A velocity decomposition approach is implemented that consists of a superposition of the freestream velocity, disturbance potential velocity, and induced velocity caused by the far wake. The grid velocity terms in the viscous and inviscid zones are implemented in a general form to take into account the fact that the cell faces are moving with respect to an inertial observer, and are deforming as a result of aeroelastic effects in forward flight. A Langragean wake approach is implemented to capture the effects of the tip vortex once it leaves the viscous zone, and convect it without diffusion in the inviscid zone and the far field. The present approach is complete in that there is no need to link the analysis to an external rotor wake simulation code in order to include the far wake effects. This transonic, potential-based method with a Lagrangean wake model can convect the wake vorticity in the far field without numerical dissipation. This strategy also permits the use of a fairly sparse grid in the far wake.

Calculations are done by marching in time. At the end of each rotor revolution, the computed loads are used to adjust the trim settings so that the specified thrust setting and tip path plane angle are achieved. The calculations converge to a periodic solution after two or three blade revolutions.

A two-bladed AH-1G rotor at a low advance ratio has been studied, and the results compared with flight test data and experimental data. The computed surface pressure fields as well as the azimuthal variations of the sectional loads are in good agreement with the measurements. It is found that the present Lagrangean wake model can capture the blade-vortex-interaction (BVI) phenomenon with good accuracy. Flow over a model UH-60A rotor in high speed forward flight has also been studied. In this case, it was found that the present method yields good results only if the elastic deformations of the blade are accounted for in the analysis. The results are in good agreement over the first three quadrants of the rotor disk. Additional work is needed to improve the three-dimensional dynamic stall effects in the fourth quadrant.

Additional details of the simulations may be found in the second author's Ph. D. dissertation, found at http://www.ae.gatech.edu/~lsankar/CERT .

ADVANCES IN ROTORCRAFT WAKE AERODYNAMICS

F.X. Caradonna*, J. Ortega, O. Savas**, W. Dietz*****

* Army Aeroflighdynamic Directorate,
Army/NASA Rotorcraft Division, Ames Research Center,
** Univ. of California, Berkeley, ***Flow Analysis Inc.

Subsonic aerodynamics encompasses a wide array of problems. Of these, it may be that rotorcraft aerodynamics is the most varied and complex, a major cause for difficulty being the dominance of wake flows. While such flows have been the subject of both experimental and computational studies for many years, the field of study is far from being exhausted. Indeed, the need and opportunity for new studies and new ideas seems to be as great as ever. This presentation is intended to illustrate this point with a number of computational and experimental developments under recent or current development at or with the U.S. Army Aeroflightdynamics Directorate (AFDD).

Wakes have probably constituted the largest single area of experimental rotor study over the years. And yet new phenomena are always being discovered. For instance, a vortex-pairing phenomenon was discovered by several different researchers fairly recently using stroboscopic smoke flow visualization and shadowgraph. This phenomena and others have now been seen at a much smaller scale using a new flow visualization method being developed jointly by at U. of California Berkeley and AFDD. In this approach, small rotor models are operated at low RPM in a large water tank. Water permits various types of visualization including tip dye injection (analogous to smoke in air) and air bubbles. The latter is interesting because buoyancy traps bubbles in tip vortices and permits an unusually clear tracking of vortex events until these become chaotic and dissipate. Particle Image Velocimetry (PIV) has been shown to be particularly useful in a water facility. The small rotor scale combined with the use of PIV permits a visualization and measurement of an entire rotor wake flow, clearly showing the convection and dissipation of the starting vortex, blade tip vortices and shed vorticity sheets. These underwater visualization techniques are also being developed for use in forward flight testing by means of operating the rotor(s) in a model ship tow tank.

The prediction of such wake flows using CFD is a very difficult matter because of the grid sizes that are required to avoid numerical dissipation. Two new efficient schemes, designed to counteract the effects of this dissipation, will be described. The first, an Eulerian-Lagrangian scheme, called "vortex embedding", is a potential-based method wherein vortex particles undergo Lagrangian convection with the induced flow predicted by a solution of the Potential equation. Because there is no vorticity dissipation here, the method requires only a coarse grid. The method is fast, effective, and a good engineering tool. It has only been used for the analysis of hover flows to date. Another method, that is more general, is the method of "vorticity confinement". This approach applies an artificial antidiffusive correction term that assures the non-spreading of thin vortical regions. Because diffusive spreading does not occur with this method, relatively coarse grids again can be used and the method is highly versatile. The approach permits not only the diffusionless convection of vortices, but also the computational modeling of other thin vortical regions, notably the flow adjacent to a body surface. An advantage of the scheme is that it permits the use of simple non-surface conforming grids to compute blunt body flows. As a result it is possible to perform rotor/fuselage computations with little more work than is required to compute the rotor alone. This approach has also been used to compute the flow over naval vessels - blunt bodies whose wake flows are of importance to rotorcraft operation.

The experimental and computational concepts presented herein illustrate that there are many new avenues of study open to the rotorcraft community and - combined with the undiminished need for improved rotorcraft operation - these point to a highly productive future for rotorcraft research.

OVERSET-GRID CFD MODELS FOR ROTORS AND WAKES

Roger C. Strawn

Research Scientist, Army/NASA Rotorcraft Division
Army Aeroflightdynamics Directorate (AMRDEC)
US Army Aviation and Missile Command
Ames Research Center, Moffett Field, CA
rstrawn@mail.arc.nasa.gov

Almost all of the aerodynamic design problems associated with rotorcraft involve interactions between the rotating blades and their aerodynamic wake systems. Prediction of the rotor wake is one of the most challenging problems in rotorcraft computational fluid dynamics (CFD). Typically, the computed vortical wakes diffuse too rapidly due to grid-related numerical dissipation. For general unsteady rotor flowfields, current numerical schemes and computational grids are unable to preserve the vortices long enough to accurately predict the noise and airloads caused by blade-vortex interactions (BVI's).

This presentation describes results from steady-state Reynolds-averaged Navier-Stokes computations for hovering rotors and their vortex wake systems. The computations are designed to directly assess grid-related effects on the numerical results and employ: 1) structured overset-grids with high resolution on the rotor blades, 2) a systematic variation of grid resolution in the rotor wake, and 3) a systematic variation of outer boundary locations.

The calculations show that the combination of high-order differencing schemes and fine computational meshes can provide rotor blade performance predictions that are independent of both the rotor-wake grid size and the far-field boundary conditions. These performance predictions also show good agreement with experimental measurements for a four-bladed UH-60A model rotor in hover. The figure below shows an azimuthal cross-section of vorticity contours for the UH-60A rotor. This 64-million grid point computation required 138 hours on 112 SGI Origin 2000 processors in order to reach a steady-state solution. The presentation will also assess the computational requirements for general unsteady forward-flight calculations with multiple blade-vortex interactions.

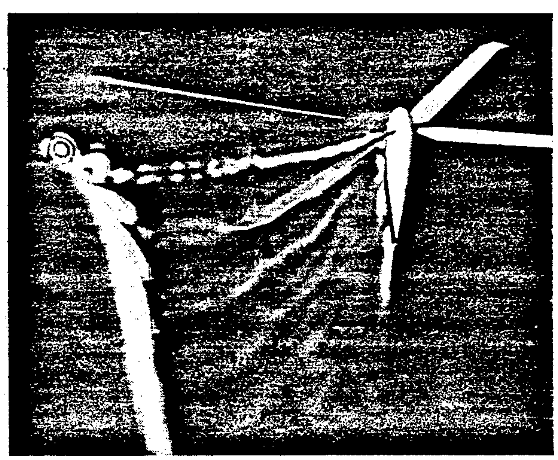


Fig. 1. Computed vorticity magnitude contours on a cutting plane located 45° behind the rotor blade.

ASSESSMENT OF AIRCRAFT AND ROTORCRAFT WAKE FLOW FIELDS FOR WAKE HAZARD APPLICATIONS

Todd R. Quackenbush, Alexander H. Boschitsch, and Alan J. Bilanin

Continuum Dynamics, Inc.
Ewing, NJ
www.continuum-dynamics.com

NASA has identified the objective of tripling airport throughput over the next decade as an air transport goal, and a likely major component of such an effort is the utilization of rotorcraft to provide feeder service to major airports. Among the key challenges in ensuring safe, high-volume terminal area rotorcraft operations are identifying and mitigating potential hazards posed by vortex encounters between rotorcraft and fixed wing aircraft. To address these challenges, a family of fast yet high-fidelity vortex wake modeling methods must be developed for eventual incorporation into both off-line assessment tools and pilot-in-the-loop simulation environments. Though considerable additional technology development is required, several elements of a hierarchy of physics-based models for assessment of a range of possible encounter scenarios are currently in hand. This paper will review the development status of these models and examine key features of the predicted flow fields, particularly with respect to the likely impact of wake-induced forces and moments on the flight dynamics of nearby aircraft. Also described are databases suitable for model validation as well as further technology developments that are likely necessary to address the full range of complex aeromechanical phenomena in future terminal area operations environments.

SESSION 10:

EXPERIMENTS WITH WAKE VORTICES, 3

Chairman:

James Hallock, Volpe

TOWARDS WAKE ALLEVIATION FOR TRANSPORT AIRCRAFT

A. Corjon[1], F. Laporte[2], T. Leweke[3]

AIRBUS France, CERFACS, IRPHE

Since the introduction of Boeing B747 in the commercial transport aircraft fleet, problems occurred due to wake vortex encounters. All research efforts, made to characterize aircraft wakes, have given only a few tangible results: first, the definition of the ICAO matrix of separation distances, classifying all aircraft according to their Maximum Take-Off Weight (MTOW), used even when not suitable (Heathrow airport, Boeing B757); second, the most advanced and complete ATC system, AVOSS (developed by NASA), which is not routinely used; third, some theoretically-based formal attempts to accelerate the vortex decay by acting on the emitting aircraft (Boeing Patent). Airport congestion is a combination of several factors and the one linked to wake vortices is not obvious to solve. One of the possibilities is to act on the generating aircraft's trailing vortices.

Two strategies have to be considered:

- Suppressing completely the constraints linked to wake vortices, i.e. ensuring that the lifetime of the vortices is always shorter than the time needed to travel 2.5 nm (about 70s), whatever the meteorological conditions. Results in this direction have been obtained (uncoupled ailerons, splines), but their operational cost is too high.
- Alleviation of the wake vortex hazard, i.e. ensuring a known level of hazard compatible with current separation standards. This approach is based on a better knowledge of the behavior of trailing vortices in the atmosphere.

In fact, there is not too much differences between these two strategies. The main one is on the cost-effectiveness of such a system.

A methodology has been developed that allows characterization of the wake of an Airbus type aircraft, identification of control parameters of the unique counter-rotating vortex pair that generally remains in the far wake, and control of the identified parameters. Modifying these parameters has effects on the development of short-wavelength instabilities (elliptic), long-wavelength (Crow) instability, decay in the atmosphere, and induced rolling moment. Alleviation devices based on this approach will allow to create 'older' vortices with much more favorable conditions for decay in the atmosphere and will then permit to rate the equipped aircraft in a lower class.

There were large debates to know if vortices can "continuously" decay or only "catastrophically". This also lead to attempts to define "Low-Vorticity Vortices", as opposed to "Quickly Decaying Vortices". Hopefully, vortices are physical entities, and their behavior is not guided by a particular school of thought. New attempts will take advantage of leading to a system which will remain cost-effective and retro-fitable to any aircraft.

[1] Dr. A. Corjon, EADS Airbus SA, 316 route de Bayonne, 31060 Toulouse Cedex 3 - alexandre.corjon@airbus.aeromatra.com

[2] F. Laporte, CERFACS, 42 G. Coriolis, 31057 Toulouse Cedex - flaporte@cerfacs.fr

[3] Dr. T. Leweke, IRPHE, Technopôle de Château-Gombert, BP 146, 13384 Marseille Cedex 13 - thomas.leweke@irphe.univ-mrs.fr

MERGER OF CO-ROTATING VORTEX PAIRS

W R Graham and T Bertenyi

Department of Engineering, University of Cambridge

The fundamental question in the capacity problem is as follows: given a leading aircraft, what is the hazard to a follower? If the follower encounters one of the leader's wake vortices, this translates into the need to predict the formation and evolution of this vortex. At present, the rolled-up vortices formed immediately downstream of an aircraft wing can be quite well predicted, but many open questions remain with regard to their subsequent development. One particular such question is how the multiple rolled-up vortices generated by a wing in high-lift configuration combine to form the trailing pair typically observed at large downstream distances. The study of vortex merger reported here is intended as a contribution to this issue.

The investigation has centred around wind tunnel experiments on co-rotating vortex pairs, generated by wings attached to the tunnel floor and side wall. Traverses with a single-tube yawmeter (effectively a five-hole probe) have been carried out over cross-flow planes at a range of downstream locations, yielding an extensive set of mean-flow data. These measurements have subsequently been analysed to obtain the vortex circulations, core diameters and separations at each plane.

For equal circulations, the results show that each vortex retains an independent, essentially axisymmetric identity for most of the distance to merger. During this phase, core sizes increase and separation decreases. Merger then occurs over a short distance, after which a single axisymmetric vortex emerges. Unequal strength vortices behave similarly, in that the distance over which they merge is relatively short. However, notable differences in behaviour are observed; the weaker vortex is significantly distorted during the rotation before merger, and is then wrapped around the stronger as they combine.

To quantify these observations, we have followed Brandt and Iversen [1], who suggested that the distance to merger, x_m, should depend on the tunnel velocity, U, and the vortex circulations, (Γ), core sizes (r_c) and initial separation (d_o), via the relationship $\Gamma_1 x_m / U d_o^2 = f(d_o / r_{c1}, \Gamma_1 / \Gamma_2, r_{c1} / r_{c2})$. In each set of tunnel data, the circulation and core size ratios are effectively constant, so that the relationship can be tested by plotting $\Gamma_1 x_m / U d_o^2$ against d_o / r_{c1}. The results show a good collapse, and suggest furthermore that for equal strength vortices $\Gamma_1 x_m / U d_o^2 \sim 5$ over a wide range of d_o / r_{c1}. As noted above, unequal strength vortices merge more quickly. The common 'rule-of-thumb', that aircraft flap and tip vortices merge after one rotation orbit, is not found to be justified.

Lastly, the degree to which the merging process can be described as 'two-dimensional' is investigated via consideration of the theoretical 2D flow invariants. The results suggest that three-dimensional effects are not strong, and thus that vortex merging can be simulated using 2D flow computations.

[1] Brandt, SA and Iversen, J.D., 1977 J. Aircraft **14,** 1212-1220.

EXPERIMENTS ON SHORT-WAVE INSTABILITIES IN VORTEX PAIRS

Thomas Leweke

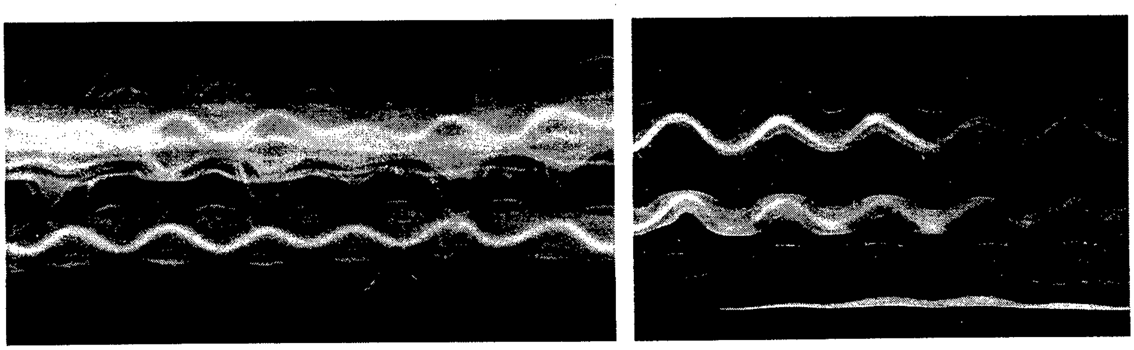
Institut de Recherche sur les Phénomènes Hors Equilibre (IRPHE)
CNRS / Universités Aix-Marseille
49 rue Frédéric Joliot-Curie, B.P. 146, F-13384 Marseille Cedex 13, France

Experimental results concerning the short-wavelength instability in pairs of counter-rotating or co-rotating vortices will be presented. The former is a simplified model of the far wake behind a transport aircraft, whereas the latter represents the vortex configuration in the near wake behind a single wing in high-lift configuration (lowered flap).

Pairs of uniform parallel vortices were generated in water by the impulsive motion of two flat plates, and their evolution was followed in time, using dye visualisations and Particle Image Velocimetry. At sufficiently high Reynolds numbers, both flows, counter- and co-rotating pairs, were found to develop a three-dimensional instability, whose axial wavelength scales on the vortex diameter, and which is associated with internal deformations of the vortex cores (see figure). The spatial structure of the amplified perturbations show characteristic features of the elliptic instability occurring in strained vortical flows, and quantitative measurements of wavelength, radial structure, and instability growth rates are in good agreement with predictions from elliptic instability theory.

In the case of counter-rotating vortices, the late stages of the instability are characterised by a strong interaction of the two vortices. Secondary structures develop and lead to a pronounced exchange of fluid between the two sides of the flow. As a consequence, the average circulation in each half-plane is found to drop significantly in a short time interval, an effect which is still enhanced by the interaction with the long-wavelength Crow instability always developing simultaneously in this flow. In the co-rotating vortex pair, the short-wave instability interacts with and perturbs the process of merging into a single vortex, which is the basic (two-dimensional) phenomenon characterising this flow. Measurements show that, in the presence of the instability, merging is initiated earlier (i.e. for smaller relative core sizes), and leads to a more turbulent final vortex than in the two-dimensional case.

A detailed description of these phenomena will be given, and the relevance of these results for realistic aircraft wakes will be addressed.



Counter-rotating vortex pair — Co-rotating vortex pair

Dye visualisation of short-wave instabilities in vortex pairs.

THE ROLE OF PIV IN THE DESIGN OF TRANSPORT AIRCRAFT FOR PREMATURE BREAKDOWN OF TRAILING VORTICES

Roland Stuff

DLR, German Aerospace Center, Göttingen

The hazard of wake vortices as encountered by following aircraft is given by circulation and vortex spacing. The discrete vortices are rolled up from the vortex sheet shed from wide body aircraft, and the hazard may be greatly reduced if the two legs of the trailing wing vortex pair meet and merge already in the extended near field. This can be accomplished by premature breakdown of vortex cores due to the Rayleigh-Ludwieg instability[1,2,3,4,5]. After this breakdown the vortex cores grow so rapidly that they come across the wake centre line and merge with the opposite vorticity emanating from the other side of the aircraft. Only after this merger a rapid decay of circulation can be expected.

As the Rayleigh-Ludwieg instability seems not to be well known in the English literature, a review of vortex breakdown and instabilities will be given. Using these findings, any aircraft may be characterised by a design point in the diagramme, where the circulation ratio of wing and tail vortex is plotted over the corresponding spacing ratio. From this diagramme, the necessary condition for premature breakdown according to Ludwieg can be taken. The necessary condition implies that the self induction of the tail vortex is superseded by the induction from the wing vortex pair, so that the tail vortex moves downward. The analytical stability criteria of Ludwieg provides the sufficient condition for premature vortex breakdown.

Whereas 2 Component Particle Image Velocimetry (2C-PIV) can be used for the necessary condition, 3 Component Particle Image Velocimetry (3C-PIV, Stereoscopic PIV) has to be used for the sufficient condition, since the stability criteria of Ludwieg is given by the radial gradients of the swirl and axial velocity components.

Any aerodynamic measure, which shifts the design point of the particular aircraft in the diagramme mentioned above to the right and to the above, supports a premature vortex breakdown. Also, assuming elliptical lift distributions for wing and tail, a tool is provided for the assessment of the vortex hazard already in the preliminary design stage. As the features of the aircraft become more specific during the design process, the measurements may be repeated to take into account the actual lift distribution. In addition , the necessary condition can be determined from near field 2C-PIV measurements of the entire wake[6,7]. This makes it possible to minimize the wake hazard in wind tunnels through variation of aerodynamic parameters. In a similar way, wind tunnel measurements may provide the basis for assessment and certification of future aircraft as to the wake hazard.

[1]Ludwieg, H., Stabilität der Strömung in einem zylindrischen Ringraum, Z. Flugwiss.1960, 8, pp. 135-140.

[2]Ludwieg, H., Ergänzung zu der Arbeit Stabilität der Strömung in einem zylindrischen Ringraum, Z. Flugwiss. 1961, 9, 1961, pp. 359-361

[3]Ludwieg, H., "Vortex breakdown" DLR-FB 70-40, 1970.

[4]Wedemeyer, E., "Vortex breakdown". In AGARD-LS-121 on High Angle, Attack Aerodynamics, pp 9-1 to 9-17, 1982.

[5]Lord Rayleigh "On the dynamics of revolving fluids". Proc. Roy. Soc. London (A) **93**, pp 148-154, 1916, reprinted in Scientific Papers, Vol. VI, pp 447-453.

[6]Stuff, R., The Relationship between the Near and FAR Field of Wakes from Aircraft with High Aspect Ratio Wings, in Notes on Numerical Fluid Mechanics, **77**, Springer, 2001.

[7]Stuff, R,. The Near-Far field Relationship of Vortices Shed from Transport Aircraft, AIAA paper 2001-2429, 19th AIAA Applied Aerodynamics Conference, 11-14 June, 2001, Anaheim, California.

SESSION 11:

ROTORCRAFT EXPERIMENTS, 2

Chairman:

Piergiovanni Renzoni, CIRA

MEASUREMENTS OF THE TRAILED VORTEX WAKE FROM A HELICOPTER ROTOR

J. G. Leishman and P. B. Martin

Department of Aerospace Engineering,
Glenn L. Martin Institute of Technology,
University of Maryland, College Park, MD 20742

Improved helicopter designs require a much better understanding of the flow physics produced by the intense wake vortex system generated by the main rotor. A helicopter rotor wake is known to be highly dynamic, vortical, and three-dimensional in nature, being comprised mostly of intertwining tip vortices generated by the blades. These tip vortices may remain close to the rotor plane as localized, coherent flow structures for several rotor revolutions after they are generated. As a result, the vortical wake may produce large variations in the local induced velocity field and in the aerodynamic loading on following blades. Locally, the blades may closely intersect individual tip vortices, resulting in a phenomenon known as blade vortex interaction (BVI). BVI can produce very large unsteady, three-dimensional rotor airloads, affecting rotor performance and vibration levels, and may also result in impulsive noise generation. The reduction of BVI induced rotor noise has become an important goal from both military and civil perspectives. However, the complete understanding and prediction of the aero-acoustics of the rotor system requires a better understanding of the fundamental physics of the blade tip vortices. In particular, a better knowledge of the formation, convection, and viscous diffusion of the vortices will help validate vortex models and rotor wake prediction methods. In turn, this should lead to improved better predictions of rotor performance, vibrations, and acoustics, and perhaps to effective strategies aimed at the alleviation of adverse vortex induced phenomena. To this end, the present work reports on high-resolution three-dimensional velocity-field measurements and flow visualization results that were acquired in the wake of a sub-scale helicopter rotor blade. Using three-component laser Doppler velocimetry (LDV), the measurements documented the trailing tip vortex formation, its initial structure, and the viscous evolution of the vortex core. The test conditions covered a range of wake-ages from as young as one-degree, up to about one rotor revolution. For each wake age, vortex core properties were estimated from the velocity-field measurements. The high spatial and temporal resolution of the measurements (obtained, in part, through a precise alignment of the LDV optics using a laser beam profiler) has shown that the tip vortex core radius can be less than 3% of chord just at formation, but grows asymptotically as it ages. A significant axial velocity deficit was found in the vortex core, which was of the order of the peak swirl velocity at early wake-ages but quickly diminished as the tip vortex aged. Using a Richardson parameter combined with strobed laser light-sheet visualization of the tip vortex flow, the results suggest that the inner core of the tip vortex is mostly laminar at the vortex Reynolds numbers obtained in this experiment. It was found that bands of turbulent eddies, originating from an adjacent vortex sheet trailed by a blade, underwent a relaminarization process as they were entrained into the vortex core. The evidence suggests that the entire tip vortex structure is neither fully laminar or fully turbulent, but is instead in a continuous state of dynamic evolution with a region of relatively slow laminar diffusion and a region of accelerated turbulent diffusion. It is suggested that the variation of peak swirl velocity is the result of the competing influences of an inviscid roll-up process and viscous diffusion within the tip vortex.

DETAIL OF MAIN/TAIL-ROTOR VORTEX INTERACTION ON ROTORCRAFT

R. Galbraith, F. Coton and R. Green

University of Glasgow

The paper describes the work carried out at Glasgow University on orthogonal interaction of a rotor-tip vortex with a fixed blade mimicking the tail rotor.

The vortex is generated from a single bladed rotor mounted in the contraction of the Glasgow Argyle wind tunnel. The pitch of the blade was varied using a smooth cam such that it is pitched up as the blade approached the tunnel working section and pitched down as it departed. This resulted in a sequence of near orthogonal vortices travelling down the working section. They were true trailing vortices containing the associated axial flow component.

The fixed blade was mounted offset to the centre of the wind tunnel and was liberally instrumented with pressure transducers. The blade could be adjusted both vertically and in pitch.

The interaction was also studied in a smaller wind tunnel used for a feasibility study. The latter stages that study included particle image velocimetry of the interactions and data from that study will be presented.

It is clear from the data that for the aerofoil surface, on which the axial flow of the vortex is towards the aerofoil, there is a pressure pulse resulting in a compression which, as the vortex convects across the chord, disappears and a suction wave develops. On the opposite side, where the axial flow is away from the aerofoil, there is increased suction that is observed throughout the convective process. When these interactions were observed using particle image velocimetry, and the velocity vectors decomposed into the radial and tangential components, the immediate interaction appears to be the combination of a simple vortex and a source. The source being positive on the compression side and negative on the suction side.

To assess how appropriate the aerodynamic modelling in the wind tunnel has been, the presentation will finally discuss the replacement of the fixed blade by an instrumented tail-rotor. That rotor will have fewer transducers and hence less fidelity. Nonetheless, similar temporal pressure data, from both the fixed and the rotating rotor, will indicate appropriate modelling of the interaction.

ALTERING THE TIP VORTEX OF A ROTOR

Kenneth W. McAlister and Chee Tung

Army/NASA Rotorcraft Division
Aeroflightdynamics Directorate (AMRCEC)
US Army Aviation and Missile Command
NASA Ames Research Center, Moffett Field, California

James T. Heineck

Experimental Physics Branch
NASA Ames Research Center, Moffett Field, California

Small devices were placed near the tip of a hovering rotor blade in order to alter the structure of the trailing vortex. This was achieved through the generation of either a secondary vortex (positive or negative sense) or massive turbulence. The impact of these devices on the primary trailing vortex during the first revolution was quantified using detailed three-component presentations of the rotor wake obtained with a stereo particle image velocimeter. Even without a device attached to the rotor, the trailing vortex wandered from revolution to revolution by an amount that increased with wake age. In addition, the point of maximum vorticity did not always coincide with the apparent center of the vortex. These issues were addressed by conditionally averaging the images according to a realignment of the velocity measurements based on the position of the vortex and by defining the center of the vortex to be the center of swirl. The variation in circumferential velocity along a radius anchored to the center of swirl was used to identify the peak vortex velocity, which in turn defined the size of the vortex core.

For all vortex generator cases where the angle of incidence was fixed, the rotor torque was found to be lower (by as much as 6%) than for the basic blade alone. However, there was an 8% increase in torque in the free (unrestrained) vortex generator case and an 18% increase in the turbulence generator case. High drag devices would clearly only be deployed when circumstances warranted, such as during a helicopter descent when excess power is available and the threat of blade-vortex-interaction noise is greatest.

The vortex trailing from a vortex generator with a fixed angle will orbit the primary tip vortex at an angular rate of about 6° for every degree of wake age when the two vortices have the same sense. When the subordinate vortex has the opposite sense, the direction of the orbit remains the same, but the angular rate is greatly reduced. In both cases the subordinate vortex cannot be distinguished from the primary vortex after $\psi = 60°$, and eventually a more intense primary vortex is produced. The most dramatic change occurred in the turbulence generator case, which resulted in a 65% reduction in maximum vorticity and a core size that nearly doubled after reaching $\psi = 280°$.

PIV MEASUREMENTS OF WAKE VORTICES

Markus Raffel

Institut für Aerodynamik und Strömungstechnik
Deutsches Zentrum für Luft- und Raumfahrt (DLR)
Bunsenstraße 10, 37073 Göttingen, Germany

Over the past decade particle image velocimetry (PIV) has matured from its developmental stage to a reliable whole field flow measurement technique and now finds uses in a continuously broadening range of applications. An especially important field of PIV applications is the measurement of wake vortices in aeronautics. PIV systems for the investigation of air flows in wind tunnels and other flow facilities must be capable of recording low speed flows (e.g. flow velocities of less than 1 m/s in turbulent boundary layers) as well as high speed flows with flow velocities exceeding 500 m/s (e.g. supersonic flows with shocks). Flow fields above solid, moving, or deforming models in aerodynamics are usually associated with complex three dimensional flow structures of different length and time scales, which must be properly resolved by the PIV technique. The application of PIV in large, industrial facilities poses a number of special problems:

- large observation areas,
- large observation distances between camera and light sheet,
- time constraints in the set-up of the PIV system,
- strict safety requirements for laser, seeding, turbine or helicopter simulators, and
- high operational costs of the facility.

In spite of these stringent requirements, the PIV technique is very attractive in modern aerodynamics research because it helps in the understanding of unsteady flow phenomena such as shear and boundary layers, wake vortices, and separated flows above models at high angle of attack. PIV enables spatially resolved measurements of the instantaneous velocity field within a very short time and allows the detection of large and small scale spatial structures in the flow. The PIV method can further provide the experimental data necessary in the validation of an increasing number of high quality numerical flow simulations. For this purpose carefully designed experiments with well known boundary conditions have to be performed in close co-operation with those scientists doing the numerical simulations. To allow a comparison with the numerical results the experimental data of the flow field must possess high resolution in both space and time which is a requirement satisfied to a great extent by the PIV method, especially in regard to obtaining the information about the unsteady flow field.

The application of the PIV technique has been demonstrated by various experimental investigations on wake vortices. Two experiments were performed in order to investigate details of the vortex formation from helicopter blade tips of in a large wind tunnel. Furthermore, the wake measurements of a propeller, which have been performed in a smaller facility, and in addition to that, simultaneous measurements of the velocity and density fields were conducted in a transonic wind tunnel in order to characterise the structure of compressible vortices. These results will be presented together with further examples of wake vortex PIV measurements in aerodynamics.

Session 12:

CALCULATIONS OF WAKE VORTICES, 3

Chairman:

Alex Corjon, Airbus

STABILITY PROPERTIES AND UNSTEADINESS OF WAKE VORTICES

Laurent Jacquin, David Fabre & Denis Sipp

ONERA, Department of Fundamental and Experimental Aerodynamics

SUMMARY

Propagation of inertial waves and amplification of co-operative instabilities are basic linear mechanisms which lead to unsteadiness in trailing wake vortices. In a wind tunnel, where only a small downstream distance is usually surveyed, these unsteady phenomena lead to displacements of the vortices, which are of small amplitude but which can be measured thanks to the presence of very sharp velocity gradients within the vortices. Examples of theoretical and experimental characterizations of these unsteady phenomena will be given in due course.

A distinction is made between long-wave and short-wave perturbations.

Long-wave instabilities. The most promising way to produce less harmful wakes behind an aircraft is to promote the long-wave co-operative instabilities which may develop in a system of several, at least two, vortices and which lead to destructive interactions between the two halves of the wake. Such instabilities may be quantified through considering the stability of vortex filaments and by neglecting the detailed structure of the vortex cores. A relevant configuration is that of a double pair of vortices as those considered by Crouch (1997), Rennich & Lele (1999) and Fabre & Jacquin (2000). The two vortex pairs may originate at different regions of the wing depending on the flap setting. They may be of the same sign (co-rotating pairs) or of the opposite sign (contra-rotating pairs). Crouch (1997) considered the case of co-rotating vortex pairs whereas Rennich & Lele (1999) and Fabre & Jacquin (2000) considered the case of contra-rotating vortex pairs. The respective properties of different configurations will be discussed with the objective to define optimal vortex arrangements which lead to significant amplification of initial perturbations.

Short-wave instabilities. Short-wave instabilities are also relevant in applications because these instabilities are known to play a dominant role in the merger of the vortices. A detailed description of the vortex core structure becomes now necessary for characterizing instabilities which develop on scales of the order of the vortex core width. This will be discussed considering experimental observations and theoretical analysis. In particular, it will be shown that basic flows involving only one lengthscale, e.g. the Rankine vortex or the Lamb-Oseen vortex and which are often used to characterize short-wave instabilities, are poorly representative of real wake vortices (Jacquin et al.,2001).

Crouch J.D., Instability and transient growth for two trailing vortex pairs, J.Fluid Mech., vol. 350, pp. 311-330, 1997.

Fabre D. & Jacquin L., Stability of a four-vortex aircraft wake model, Phys. Fluids, vol 12, N°10, pp. 4238-4243, 2000.

Jacquin L., Fabre D., Geffroy P. & Coustols E., The properties of a transport aircraft wake in the extended near field; AIAA paper 2001-1038

Rennich S.C. & Lele S.K., A method for accelerating the destruction of aircraft wake vortices, AIAA A98-16497, 1998.

OPTIMIZATION OF THE (INVISCID) UPPER LIMIT OF THE ROLLING MOMENT INDUCED BY A VORTEX PAIR

A. Elsenaar

National Aerospace Laboratory NLR,
Anthony Fokkerweg 2,
1059 CM Amsterdam
The Netherlands

The strength of a wake vortex is directly related to the lift of the aircraft following the relation $\Gamma = \frac{W}{\rho U_{\infty} bs} = \frac{1}{2}\frac{C_L Ub}{ARs}$ with W, the A/C weight and b the wing span. The distance between the vortices s.b follows from the spanwise load distribution over the wing. Usually the vortex sheet that leaves the trailing edge of a wing rolls-up into two distinct counter-rotating vortices with strength $+\Gamma$ and $-\Gamma$. These vortices induce cross-wise velocities V_{ϑ} in a plane perpendicular to the vortex axis. V_{ϑ} obeys in the absence of dissipation the induced drag relation $D_i = C_{D_i} \frac{1}{2} \rho U^2 S = \frac{1}{2} \rho \int\int V_{\vartheta}^2 dA$. C_{D_i} follows from the Oswald efficiency factor e (also a function of the load distribution) with $C_{D_i} = C_L^2 / \pi Ae$. In a further schematization, the vortex center is assumed to be surrounded by a viscous and a vorticity core. Outside the vorticity core the flow is irrotational and the cross-wise velocity (at a distance r of one vortex) follows from $V_{\vartheta} = \Gamma(r)/2\pi r$. All vorticity (for a fully rolled-up vortex) is thought to be concentrated within the vorticity core. For the high Reynolds numbers of actual aircraft ($\Gamma / \nu \approx 10^7$ to 10^8), the viscosity core is so small that it can be neglected: the vortex flow field is basically inviscid. The (vorticity) core radius follows then directly from the induced drag relation when a family of velocity distributions is assumed to apply inside the vorticity core. The velocity distributions that can be calculated from these assumptions can be regarded as a high Reynolds number upper limit for the vortex flow field. There is some experimental evidence that this upper limit is approached when roll-up is com plete and in the absence of vortex decay (no external turbulence). This velocity distribution can subsequently be used to calculate the induced rolling moment for a follower A/C that flies right into the vortex center. The two parameters, vortex distance s and induced drag factor e can (within limits) be selected such that an optimum induced rolling moment results. Some examples will be given. The analysis suggests that the best compromise from the point of view of separation distances is obtained for an inboard loaded wing with a low induced drag. In practice decay due to external turbulence can not be neglected. Other limitations, also from the point of view of vortex development (like multiple vortices) restrict the load distributions that can actually be achieved. But the present model might give some feeling for the possibilities to reduce wake vortex strength by design.

SESSION 13:

DISCUSSION

Chairman:

Jim Whitelaw, Imperial College

AIRCRAFT VORTEX SPACING SYSTEM (AVOSS) OVERVIEW AND FUTURE DIRECTION

Neil O'Connor

NASA Langley Research Center

A number of factors lead to a reduction in airport capacity in weather conditions that prevent the use of visual approach procedures. These factors include a reduction in the number of available runways and the longitudinal wake turbulence separation constraints used by Air Traffic Control (ATC). These wake constraints evolved over time to prevent wake encounters in weather conditions most conducive to long-lived wakes, and are unnecessarily large in weather domains that lead to rapid wake decay or drift away from the flight path. During visual conditions aircraft separation responsibility belongs to the pilots, who use their knowledge of weather conditions, lead aircraft type, and lead aircraft flight path to effectively self-separate from wake encounters. In many situations the resulting spacing is less than would be required in instrument operations. The AVOSS is designed to structure this process and minimize the difference in aircraft spacing between visual and instrument operations. The operational concept of AVOSS is to determine the spacing required to prevent wake vortex encounters, given the ambient weather conditions in existence at the airport.

The AVOSS system uses sensed weather information to predict wake vortex behavior and develop safe spacing criteria. The meteorological subsystem uses sensors and modeling techniques to describe the vertical profiles of the wind, turbulence, and temperature from the surface to the glide slope intercept altitude. The wake predictor uses this weather profile and descriptions of the aircraft fleet at the airport to predict wake drift rate, sink rate, and decay rate for each modeled aircraft type. Runway throughput estimates are generated using the wake predictions. Wake sensors are used to check the predicted behavior. No ATC interface was included in the AVOSS demonstration.

The AVOSS system was demonstrated at the Dallas Ft. Worth International airport in July of 2000. This paper will present an overview of the AVOSS as demonstrated. Included will be discussion of the system's potential impact on capacity and delays along with thoughts on the overall maturity of a Wake Vortex Advisory System (WVAS). A first generation WVAS is envisioned building on the success of the AVOSS. Such a system would offer limited capability while allowing operational development. For example, an initial WVAS might be restricted to certain weather conditions. Development of a research effort leading to such a system is currently underway.

AN ASSESSMENT OF WAKE VORTEX SAFETY ASPECTS WITH A PROBABILISTIC APPROACH, AS PART OF THE S-WAKE PROJECT

A.C. de Bruin, G. van Baren, L. Speijker
bruina@nlr.nl

National Aerospace Laboratory NLR (The Netherlands)
The S-Wake project is carried out under a contract awarded by the European Commission.

Abstract:
The potential risk imposed by wake vortices can be an important constraining factor for airport capacity. To investigate the levels of flight safety under current ATM rules and guide possible new ATM procedures that may have improved safety and/or increased capacity, a European co-funded research project S-Wake has started.

The S-Wake project aims to develop and apply tools for assessing appropriate (safe) wake vortex separation distances. The specific objectives of S-Wake are:

- to define suitable weather categories for wake vortex safety for aircraft on the approach glide path;
- to improve the physical understanding of wake vortex evolution and decay in the atmosphere;
- to establish realistic flight simulation environments for investigating wake vortex encounter safety aspects and pilot's response;
- to establish a validated probabilistic safety assessment method;
- to analyse the safety aspects for current practice by collecting and analysing large amount fl;ight data recorcings;
- to define possible new concepts which allow a safe mitigation of current separation rules under certain conditions.

A brief introduction to the S-Wake project will be given. The presentation will then focus on the probabilistic method that is being developed and used within S-wake for assessing wake vortex safety.

A **probabilistic approach** is followed to evaluate wake vortex induced risk related to different separation distances between landing aircraft on a single runway. This probabilistic model is based on a stochastic framework that incorporates sub models for wake vortex evolution, wake encounter, and flight path evolution, and relates the severity of encounters to possible risk events (i.e. incidents/accidents) that might occur. In the framework of the S-Wake project the WAke Vortex Induced Risk assessment (WAVIR) methodology is being applied and validated with incident data collected at Heathrow airport. A brief introduction to the method will be given, but the presentation will mainly focus on the outcomes of the initial simulations.

To study the feasibility of a new weather dependent separation scheme and of new ATM procedures for single runway approaches, an extensive initial risk assessment – with different aircraft landing behind a Boeing 747-400 – has been made. The impact of weather and wind conditions (e.g. turbulence, stratification, crosswinds and head- and tailwinds) and procedural aspects (e.g. glide slope intercept altitudes, navigation performance, glide path angles, steep descent approaches) on incident/accident risk is evaluated.

From the initial risk assessment results obtained it is found that a reduction of the current separation minima - and consequently an increase of capacity - is possible under most operational and weather conditions. However, it is also found that the separation distances should be increased under some particular conditions.