A VISION OF WAKE VORTEX RESEARCH FOR NEXT 20 YEARS.

Peter Choroba, EUROCONTROL Research and Development Centre, Bretigny sur Orge, France

Abstract

International regulations require commercial airliners to be separated in flight by up to six nautical miles (11.12 km) due to the potential hazard caused by the swirling air left in their wakes. This 'wake vortex' is now the subject of intense worldwide research to understand the nature of the phenomenon, to develop reliable technology for its detection and prediction and thus find ways of making air travel safer while reducing congestion around airports. This paper describes author's beliefs on current and future research in wake vortex domain in relation to survey research being currently conducted within his PhD thesis.

Introduction

A flying aircraft generates a turbulent wake as a direct consequence of its lift. An aircraft's wake is in the form of two counter-rotating swirling rolls of air - the wake vortices - that trail from the wings of the aircraft. The wake vortex pair may last for several minutes and may stretch for many kilometers behind the aircraft. The strength of the vortices basically depends on the aircraft weight, divided by the product of air density, flying speed and wingspan. This property generally increases with aircraft weight. The lifetime of a vortex depends upon local meteorological conditions. Vortices last longer in calm air and atmospheric turbulence hastens their decay.

Why do wake vortices matter? It is a question of safety. The rapidly swirling air in a vortex can catch the wings of a following aircraft with potentially disastrous results. Tests with experienced test pilots have shown that even heavy size commercial airliners can be thrown out of control if they follow too close behind a large aircraft such as a Boeing 747. Wake vortices are normally invisible and pilots have no warning that they are flying into one. For this reason, the International Civil Aviation Organization (ICAO) lays down strict rules about the permitted spacing between aircraft, based on their size. In instrument flying conditions aircraft may follow no closer than three nautical miles (5.56 km), and a small aircraft must follow at least six nautical miles (11.12 km) behind a heavy jet such as a Boeing 747.

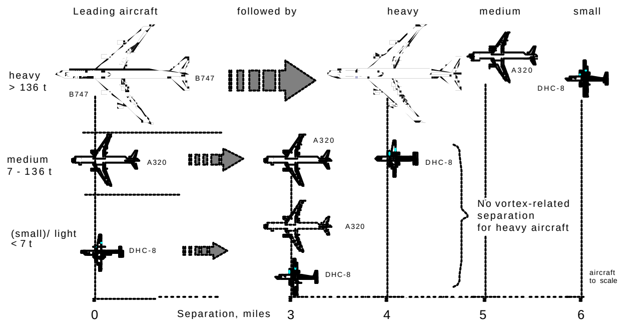

Figure 1 - ICAO separation scheme for single runway approaches

Many airline pilots have had encounters with vortices, usually on the final approach to airports. They are experienced as a buffeting of the aircraft. While of little concern to passengers and crew who are wearing seat belts at this stage, pilots regularly report minor injuries to crewmembers standing up or moving around the cabin. However, thanks to ICAO regulations on separations (Fig.1), there have been no serious accidents reported with passenger airliners in IFR operation until November 12 2001, when an Airbus 300 crashed in New York due to the wake encounter.

"ICAO separations are conservative: they do not completely avoid the effects of wake vortices, but they are sufficient to be safe in most meteorological conditions." [1] Particularly noteworthy is that appropriate regulation for closely spaced parallel runways (separated by less than 2500 ft) is lacking, resulting in inefficient use of some of the runway configurations. The present regulation prescribes that such runways must be used as single runways when the spacing is less then 2500 ft (or 760 m) and in case of low visibility conditions (IMC). Since building an additional closely spaced parallel runway at existing European airports is often the only possible feasible extension possibility, this matter is of crucial importance to increase airport capacity.

Since new high capacity aircraft (such as the Airbus A380) will be heavier and larger, and air traffic has grown continuously with an average rate of 4 % per year, today's aircraft separation rules are considered increasingly inefficient, and may result in unnecessary delays in the future. European Commission emphasizes in their Aeronautics Vision for 2020[2] the need of new operational concepts and systems that permit aircraft to operate in all weather conditions, to fly closer together at lower risk so as to allow optimal and efficient allocation of the airspace between the civil and military airspace, while limiting as far as possible the construction of new airports and runways. To achieve this goal, continuous research also in wake vortex domain is inevitable.

Motivation, methodology

This paper attempts to draw a full picture of current worldwide wake vortex research activities mainly in domains: technology development and ATC operation.

Common denominator within the paper is the preliminary result of survey research that is currently being conducted at different European airports (expected end of survey is August 2003). The methodology used to get valuable feedback from active controllers and pilots is an information collection task. The data are collected through an interview or through a questionnaire sent by email. We assume there are differences in phenomena's (wake turbulence) risk perception at different sized European airports, therefore not only air traffic controllers and pilots from top ten airports in Europe (by number of movements) are interviewed but as well controllers from "less busy" ATC centers and pilots of smaller airlines. Fifteen European APP centers and pilots from 15 European airlines are being contacted.

Pilots and controllers are asked to answer questions, which will provide a feedback about their current wake turbulence risk perception, way of working, knowledge of physics, technology and special wake vortex ATC procedures as well as their beliefs and ideas for the future research in this domain.

So far, the preliminary results seem to prove our hypothesis that wake turbulence is perceived as much more significant issue by research people then by operational people (ATCOs, pilots). Now the question we have to answer is: "Is this caused by low level of ATCOs and pilots' information about the risk of wake turbulence or wake turbulence in Europe is not yet such significant problem as we, researchers, use to declare ?" If either of them is the right answer, it means, we have to continue in our research and have to very active involve pilots and controllers in our research activities. Thus we can achieve both, increase the level of importance to be informed enough about wake turbulence as a safety an capacity issue and to prepare technologically and tactically our airports, airlines and ATC centers for the future, where not only a few European airports (most capacity congested) but many other airports will have to deal with this phenomena. In order to increase global airspace and airport's safety and capacity it will become an issue discussed not mainly at research centers as it is today.

We should start to work on not very easy and popular task, to build ATCOs' and pilots' trust to technology and promote the importance of being well informed about the risk of wake vortex encounter under different weather conditions. The common belief is that ICAO separation standards are too conservative, thus capacity restrictive and enough safe. ATCOs believe in both, pilots mainly only in the fact, that these standards are safe. Their main goal is to control aircraft safely and to land with passengers safely whereas in a statement of its Wake Vortex Policy [3], IFALPA noted that "although it is recognized that ground based prediction systems are needed to properly plan and execute ATFM and ATC on the basis of expected separation values to be applied, IFALPA believes there is a need to develop airborne wake vortex detection and indication systems…" and "where application of reduced wake turbulence separation minima by ATC is to be based on a predictive system issuing vortex advisory or warning, such a system should be supplemented by a monitoring system able to reliably detect real location, movement, intensity and duration of wake vortices." Therefore it might be assumed that pilots, as represented by their unions, would be reluctant to accept any general reduction in separation standards in a wake vortex context without a working combination of three of the described approaches – ground based prediction backed up by both airborne and ground based detection. Survey shows, that IFALPA as an international organization has thus a bit different view as pilots themselves. Isn't it because of the fact, that IFALPA is already involved in wake vortex research activities (WAKENET) therefore has more information about the phenomena? Time is running very fast and research in technology development in like manner. Soon we will be able to introduce a dynamic air traffic control wake vortex safety and capacity system. To succeed in making this operational as soon as possible, we should get strong positive feedback from all the actors. This type of system in mid term vision together with near term procedural solutions can provide a significant increase of safety and capacity at specific airports.

The next factor that definitely has to be perceived very sensitive is a wake vortex encounter reporting. Pilots have problems to distinguish wake turbulence and atmospheric turbulence unless they hit really very serious wake of preceding aircraft and thus their induced roll moment is significant. Scenario of wake turbulence encounter in aircraft simulators is usually an unknown term. Pilots get only theoretical training how to react in case of such incident. It seems very doubtful that adding simulated training specifically for wake vortex encounters would improve safety. It is important to remember that pilots have little influence on the size of the initial roll disturbance if they encounter a strong vortex. Thus the most important training requirement is for speed and safe recovery from unusual attitudes. General training in recovery of such attitudes is more important than the cause of those unusual attitudes.

Development and validation of high accurate and reliable wake vortex prediction models is strongly dependant on statistic. Owing to the large variability of almost all parameters, including operational aspects and weather factors, the prediction of vortex location and decay cannot be based on purely deterministic calculations but requires statistical approaches. The more incidents we have reported the better chance of operational requirements satisfaction we might achieve. Operational people want to have high reliable prediction tools, where the level of accuracy should be getting near 100%, as much as possible. This number is a nightmare for researchers and a common safe request for controllers and pilots. One possible approach is to forecast mean vortex strength and trajectories plus security bounds for each individual aircraft (or groups of aircrafts) for a given (forecasted) weather situation. This procedure is very demanding with respect to weather and vortex forecasting skills as well as monitoring instrumentation. A more simple approach is the collection of all relevant combinations of vortex behaviors in weather situations which results in wake vortex behavior classes with fixed aircraft separations [4]. The classes must be designed such that they can be forecasted from standard output data of the weather services. Since dense meteorological measurements typically will not be available at most of the European airports in the near future, this approach may be considered as an intermediate step towards individual wake vortex forecasting.

There is a conflict between capacity-increase requirements and safety constraints. When do the security bounds nullify any capacity increase?

USA has a specific problem with Closely Spaced Parallel Runways, since they operate 41 airports with such a layout. CSPR is very serious capacity limiting runway configuration. Therefore US research has to find solutions as soon as possible and sets higher priority nowadays more on near term procedural solutions, even though researchers in NASA, FAA, MITRE … work intensive on mid and far term solutions as well. Europe doesn't have so many airports with CSPR and wake vortex hazard perception is more safety oriented for the time being and capacity has lower priority. Not all airports nor all airways suffer capacity restrictions due to wake vortex separation requirements – they may not have enough traffic even at peak times for this – and no airport is restricted all the time. Some airports operating with a single runway, e.g. London Gatwick, although very busy may gain little or no benefit from being able to reduce separation due to wake vortex since their mixture of arrivals and departures already usually requires 6 NM gaps between arriving aircraft to get departures airborne. Worldwide researchers are sharing and coordinating their knowledge and findings with a common goal, to reduce wake vortex separations by maintaining (if not improving) current level of safety in the future.

Next 3 chapters are describing near term, mid term and far term research activities commented by our assumptions.

Near term – till 2005

Steady wake vortex research in physics, technology and ATC can already today provide operational and technology requirements for this term, especially for introducing new wake vortex related procedures. Very good and detailed list of such procedures was collected by the Mitre Corporation in 2001[5]. By using down-selection process they propose two most suitable candidate procedures and their operational variations. Problems with uncertainties in measurements, forecasting, statistical validation and insufficient incident reporting are negative factors limiting introduction of active ATC wake vortex prediction systems in operation within next 3 years. Research in these domains is noteworthy and it can be expected that at the end of near term, results will prove reliability of the tools. So far, the easiest solution of wake vortex problem at airports (mainly with CSPR) is introduction of the special wake vortex ATC procedures, which do not require special technology support. The benefit of wake vortex related procedures depends on the operational applicability of each specific procedure. Some procedures may promise a larger benefit, but may require a greater technological component, and a correspondingly greater commitment of resources for development and implementation. Other procedures may not provide the same degree of benefit but may require less technology and may imply less development risk.

Probably two most known procedures are currently HALS/DTOP and SOIA.

SOIA

Simultaneous Offset Instrumented Approach was developed by FAA for San Francisco Airport [6] where two runways separated by 225 m only prohibit independent operation under IMC. The system aims at simultaneous operations under IMC when the cloud ceiling is not lower than 1600 feet: Two aircraft approach non-staggered but safely separated by 3000 feet laterally until they reach the missed approach point at about 1000 feet height and 3.3 nautical miles before threshold. The final approach is flown under VMC. SOIA is in the implementation phase at San Francisco and St. Louis.

HALS/DTOP

HALS / DTOP (High Approach and Landing System / Dual Threshold Operation) was developed for Frankfurt Airport by DFS (Deutsche Flugsicherung). It consists of the use of an artificial displaced landing threshold on 25L, displaced by 1500 meters from the approach end of the 25L, designated as 26L. Only medium or light aircraft (the ICAO wake classification) are authorized for using the displaced threshold. By using the displaced threshold, the glide slope fro 26L in nearly 270 feet above the glide slope of 25R.” This procedure is based on DFS data gathered at Frankfurt showing that the highest the wakes have been observed to climb there is 72 m (236 ft). During normal operations at Frankfurt, when IFR separations are used (i.e., when visual separation is not used), aircraft are typically cleared to alternate runways and are staggered by wake turbulence separation. Thus, if a medium aircraft followed a heavy aircraft on 25R on 25L, the medium aircraft would be staggered behind the heavy by 5nm. When the HALS/DTOP procedure is used, a heavy aircraft would use 25R; a following medium aircraft could use runway 26L, and would be separated by standard radar separation (2.5 nm within 10 nm of threshold) behind the heavy aircraft. HALS/DTOP has been deployed in two phases. Phase I consisted of using the displaced threshold on 26L without any modifications in the separation standards used. Phase II, now underway, reduces the separation standard for aircraft following heavies to the standard radar separation. Phase I started in September 1999 and phase II in June 2001. HALS is used designed for use down to CAT I minima. [5]

TIME-BASED

The time-based arrival separations procedure is an example of specific modifications to wake vortex standards to facilitate increase safety with possible capacity benefits. The implementation of such a procedure would likely require the development and implementation of controller tools in order to translate a time standard in the space domain. However, the procedure should not require any further real time wake prediction and monitoring. Eurocontrol Research and Development Centre in Bretigny officially started project TIME-BASED on 1st September 2002. The main goal of this project is to avoid a loss of capacity in strong wind conditions. The initial phase carried out in 2002 was to examine the concept in greater depth by defining appropriate time intervals corresponding to current distance intervals, estimating the potential benefits that would arise at a major European airport and to identify the required changes. This phase is now planned to be further explored by a depth analysis of possible incidence of wind variation as well as aircraft speed management types on in trail separation along the approach during very last landing phase (after Outer Marker) [7].

The concept is also discussed in our survey with positive reactions from controllers and SOME pilots. Why only SOME pilots? Mainly pilots of AIRBUS aircrafts claim, that speed management is done automatically in last phase of approach, and they prefer not to take it over manually. This constraint must be considered in further research and supplementary solution should be proposed.

SAFETY ASSESSMENT

Although the current separation minima have proven to be sufficiently safe, the current safety level is unclear and there is a deficiency of validated tools to support new developments in operation usage at busy airports. Speijker et al. [8] propose a probabilistic model to assess safety and to evaluate the relation between wake vortex induced risk and aircraft separation distances. To support the development of validated safety assessment models and tools, and for the purpose of incident and accident investigation, it is also important to gather and analyze incident/accident hazard data, e.g. through pilot reports on roll upsets attributed to wake vortex encounters. Such voluntary reports have been collected in the UK since 1972. However, it is not known how close the reported rate of encounters is to the actual rate of encounters, nor whether the reporting rate varies from year to year. The EU project S-WAKE addressed this issue through development of an algorithm to detect and analyze vortex encounters from Flight Data Recorders (FDR). Based on this research we have number of incidents that occurred at London Heathrow airport in 2001 but only including British Airways aircrafts. Using this type of data gathering might significantly help in near term wake turbulence research in all domains, especially in safety assessment and can be also useful to guide the rule making. Not only new prediction systems but as well all the wake vortex procedures have to be assessed from safety point of view. This task has been coordinated also within Eurocontrol/FAA action plan 3.

Survey proves that pilots are really reporting to their airlines wake turbulence encounters, of course only in case they are sure it was wake turbulence. Gathering data from airlines' safety managers would be also very helpful even though it doesn't give very accurate number of incidents - still better than nothing.

WAKENET 2, project of EC (thematic network for interdisciplinary information exchange) aims besides other goals to improve data collection by measurements of wake turbulence and characterization in near term, as well as establishing of an incident database [9].

Pilots wake vortex situation awareness is not assumed in this term, however they expressed in the survey interest in having such information in the cockpit.

Mid term – 2005-2010

We assume that incident reporting activities will be improved mainly within the framework of the WAKENET 2 and WAKENET USA projects. The coordination between airline safety managers will be established to build a main database of European incidents. Implementation and use of algorithm developed in S-WAKE will increase accuracy of incident rate calculations.

WV information (ground prediction, detection) visualization provided to pilots would help them feel safer as they indicate in our survey. Information can be provided in mid-term as a reproduction of ground based measurements and prediction information downloaded via datalink. IFALPA requires that prediction and monitoring systems should be capable of assessing the entire airspace where reduced separation minima are to be applied. Hence the airspace should not be limited to short final approach areas, but include the total approach area, in particular from glide slope intercept to landing and departure areas where applicable. Fulfilling of this task requires improved monitoring tools and forecast models. Based on current research, progress in understanding of physics of the phenomena, it is assumed by the end of mid-term highly reliable technology will be available and first active (dynamic) integrated VW air traffic control systems will be not only tested but already implemented in real operation. In the meantime a question: "What does it mean highly reliable?" must be answered.

Controllers exposed their interest in having a complex wake vortex ATC system proposing separations based on weather and wake monitoring, forecasting. IFATCA as an official organization has not been yet directly involved in research in the same manner as IFALPA, but we already work with controllers they are active also in IFATCA. ATCOs call (from survey) for deliberate research in development of integrated system in order to serve reliable tool that will not rapidly increase their workload and will definitely improve safety and gain some capacity. Design of the HMI must be done very carefully with strong involvement of operational people.

Very good chances to succeed in mid-term implementation of active wake vortex advisory system for ATC have these projects: WakeVAS, AVOSS (US), WVWS (DLR+DFS), SYAGE (CENA, STNA) and ATC-WAKE (EC project).

Far term – 2010-2020

Vortex alleviation

The Control of aircraft wake vortices by constructive means at wings and flaps (as flap setting, devices, jets) in order to ease their alleviation is still far from being resolved, despite an enormous effort in the past 30 years, in particular in North America. A detailed overview over the research activities in USA (esp. by NASA) can be found in Rossow [11] Vyshinsky [12] summarized the recent research efforts at the Central Aero hydrodynamic Institute in Russia. Reduction of wake turbulence by aircraft design is a goal of not only aircraft industry (Boeing, Airbus), but there are also research institutes in Europe (DLR, ONERA) or European projects (C-WAKE, AWIATOR) trying to achieve the same aim.

However, it might be expected that there will be many technical problems to solve before any change is introduced as standard on production aircraft. The feasibility of truly effective wake vortex reduction system has yet to be proven. An aircraft wake is an inherent result of the generation of lift and therefore wake elimination will not be possible, at best a reduction of wake vortex strength can be obtained. Although Boeing patented a system to reduce wake vortices in 1999, research and development is continuing and there does not seem to be a time-table for its introduction other than the comment '… if the flight tests are successful, the system could be fitted to in-service aircraft after 2005'. Realistic vision is that such devices are unlikely to be introduced on new production aircraft for perhaps ten years.

The Boeing device is said to be 'retrofit table to the majority of existing aircraft'. [13]. If a practical device is developed it is likely that it will be introduced on new aircraft. Once such a device is being delivered to airlines on new aircraft, airports with a capacity problem partially caused by wake vortex separation requirements will probably, unilaterally begin to restrict landing slots at peak times to aircraft fitted with such devices. Since these are the major airports in the main markets and peak times come about as it is seen to be commercially desirable to operate flights at that time, then this will rapidly drive non-equipped aircraft out of these markets. Aircraft would be retrofitted or replaced by new, equipped aircraft. Aircraft without this equipment would find limited markets and their values would be driven down by the equivalent cost of converting them. Such devices would also reduce property damage, primarily to roofs, around airports and, if able to be used throughout flight, would also reduce wake vortex encounters in the cruise. The cost will be incurred by the airline in acquiring/retrofitting and operating such aircraft or in the depression of the market values of unequipped aircraft. The benefit will be gained by the airline and the airport through increased capacity and reduced delays. After initial capacity gain and possible reduced delays/increased slots at desirable times, growth will ensure that capacity again becomes a problem. The introduction of this equipment on their aircraft will have slightly delayed the need for the airport to build new runways.

Airborne detection

Airborne detection of wake vortices requires a system that can remotely detect wind speed variations. Similar to ground based systems, lidar seems to be the most suitable technique. The principles of on-board lidar systems are similar to ground-based systems, differences between on-board and ground systems are generated by weight, size and power limitations for on-board systems. The EC funded MFLAME study concluded that for on-board systems 2µ pulsed Lidar is most suitable, with a detection range from 800 to 2400 m. [14]. On-board lidar systems could also be integrated with systems for detection of wind shear and clear-air turbulence because these systems use similar technology. The MFLAME has a follower project I-WAKE, where it is believed detection, warning and avoidance system could be brought to market by the end of this decade.

An airborne warning and detection system is considered to be a warning system similar to TCAS i.e. the last line of defense against hazards. It is assumed that the introduction of airborne detection and warning in itself does not allow a reduction of separation minima (TCAS introduction has also not resulted in a reduction of separation minima). Implementation of airborne detection and warning will not lead to changes in separation minima and as such does not directly influence capacity. In the case of a warning when in approach operational procedures will most likely require to go-around. Therefore the number of go-arounds could perhaps increase due to the introduction of airborne wake vortex detection, and this theoretically leads to reduced capacity. The current go-around rate at large European airports is estimated at 7.7x10-4 per approach, where approximately 3% of all go-arounds are caused by wake turbulence [15]. Based on this information, any change in capacity due to the introduction of airborne wake vortex detection is considered to be negligible. [15]

Information on the presence on wake vortex, as detected with the on-board sensor, needs to be displayed to the flight crew. A logical way of doing this would be to present wake vortex information on the Navigation Display (ND), in combination with alert labels on the Primary Flight Display and aural cockpit warnings. A prototype system was developed and tested in the simulator during the EU funded ISAWARE project. In the ISAWARE system, a wake vortex is represented on the ND as a dashed red/black line.

Pilots have different requirements on the wake vortex visualization. Majority of them prefer implementation of this information into ND, but on the other hand they consider 3D visualization as a feasible solution as well, since they are flying in 3D volume opposite to controllers sitting in front of 2D display. Controllers in the same task prefer simple 2D information over 3D, but they are not unique in the form of providing wake vortex information, whether it is supposed to be only a simple vector representing a potential danger distance incl. safety buffer, or more complex solution a triangle area defined by main vortices covering the danger area behind an aircraft. It's believed after detailed analysis of the survey and thanks to its result we will be able to define operational requirements more precisely.

Conclusions

This paper describes author's vision on wake vortex research in next two decades partially influenced by preliminary results of his "feedback survey" which is currently ongoing. We believe that there is much to gain from an active partnership between US and European centers in implementing VW related procedures and technology. Europe doesn't have so many capacity constrained airports with CSPR as USA and therefore has a better chance to react and to be prepared for the future. Common solution should be in near term improvement of incident reporting necessary for conducting safety assessments of new wake vortex procedures. These procedures should not require special wake vortex monitoring and prediction. Physics of the phenomena is almost today perfectly understood, further research will improve the reliability of forecasting models and detection tools. In mid-term, we foresaw to have finished development of different wake monitoring and prediction systems and techniques in order to succeed in implementation of active WV advisory systems as ATC-WAKE, WAKEVAS, and WVWS. The local installation of the integrated system at the airports will require new safety regulation, since the present wake vortex safety recommendations and best practices do not take new modified ATC systems into account. Specific attention must be given to the issue of development and harmonization of new wake vortex safety regulation. To enhance acceptability of the integrated system (and other new technologies, including high capacity aircraft such as the Airbus A380 and on-board wake detection and warning instrumentation), possible end-users and regulatory authorities have to be involved in the development of such system to achieve the goal as soon as possible.

References

[1] T. Gerz, F. Holzapfel, D. Darracq, 2001, Aircraft wake vortices (A position paper)

[2] Report of group of personalities, 2001, European aeronautics: A vision for 2020

[3] IFALPA, 1998, Wake vortex policy

[4] Frech M., Gerz T., Carriere J.-M., Lunnon B., 2000, A definition of wake vortex behavior classes (S-Wake technical note)

[5] Mundra A.D., Cooper W.W., Smith A.P., Lunsford C.R., Dasey T., 2001, Potential wake vortex air traffic control procedures

[6] Lankford D., McCartor G., Hasman F., Greene G., Yates J., Ladecky S., Templeton D., 2000, San Francisco International Airport SOIA procedures

[7] Crick P., Nicolaon J.P., Vidal A., 2002, Time-based (draft)

[8] Speijker L.J.P., Kos J., Blom H.A.P, van Baren G.B., 2000, Probabilistic wake vortex safety assessment to evaluate separation distances for ATM operations

[9] Elsenaar A. & Consortium, 2001, WakeNet 2 a European Thematic Network for Aircraft Wake Turbulence

[11] Rossow V.J., 1999, Lift-generated vortex wakes of subsonic aircraft

[12] Vyshinsky V.V., 1999, Flight safety, aircraft vortex wake and airport operational capacity

[13] Kelley-Wickemeyer, 1999, Flight International, Boeing

[14] Combe H., Kopp F, Keane M., 2000, On-board wake vortex detection, definition, ground experimentation and first results in MFLAME

[15] Roelen A.L.C., Molemaker R.J., Piers R., Hayes P., Joyce A., Graham G., 2001, A cost benefit analysis of wake vortex measures