WakeNet3-Europe

EC Grant Agreement No.: ACS7-GA-2008-213462

Aircraft Wake Vortex
State-of-the-Art & Research Needs

Compiled by: ....**F. Holzäpfel (DLR) et al.**

(for a complete list of contributors see page 3)

Date of compilation:.....2012

Dissemination level:.....Public

Version:.........................v1

Issued by:......................**A. Reinke (Airbus), C. Schwarz (DLR)**

Date of issue:................10 NOV 2015

Number of pages:.........201

4.2 Airborne Systems

Main contributing authors:
Andreas Reinke, Sebastian Kauertz, Airbus
Dennis Vechtel, Tobias Bauer, Christopher Wolkensinger, Dietrich Fischenberg, Dominik Niedermeier, Institut für Flugsystemtechnik, DLR Braunschweig

4.2.1 Overview

Airborne systems for wake vortex detection, prediction, warning, avoidance and impact alleviation are envisioned to enhance safety during all phases of flight. This specifically includes the cruise flight phase, during which relevant wake vortex encounters are reported regularly. Related operational concepts are treated in §3.6 of this report.

In general, three basic embodiments of airborne wake vortex systems can be distinguished:

- Wake encounter alerting with and without avoidance based on (probabilistic) wake vortex model predictions and enabled by advanced air-to-air data exchange
- Wake encounter alerting with and without avoidance based on mid to long range forward-looking wake vortex sensors
- Wake impact alleviation based on advanced flight control techniques enabled by short range forward-looking sensors and/or online wake characterization.

Hybrids of these basic embodiments are feasible, too. The five fundamental enabling technologies are hence:

- Operational, probabilistic wake vortex model. Research needs are addressed here as well as in §5.1.
- Mid to long range forward-looking, airborne wake vortex sensor. Research needs are addressed here as well as in §5.2.
- Advanced flight control techniques to suppress wake-induced disturbances based on new as well as existing air data sensors. Research needs are addressed in this chapter.
- Short range forward looking, airborne air data sensors. Research needs are addressed in this chapter as well as in §5.2.
- Online characterization of the wake vortex (determination of the wake properties like strength and position). Research needs are addressed in this section.

In addition to these fundamental enabling technologies a number of supporting technologies are also involved. These include:

- Real-time fusion of traffic data coming from multiple sources as well as their interpolation and extrapolation. Research needs are addressed in this section.
- Real-time fusion of meteo data coming from multiple, airborne and ground-based sources as well as their interpolation and extrapolation. Research needs are addressed here as well as in §5.3.
- 4D real-time conflict detection as well as 4D real-time, constrained conflict resolution. Research needs are addressed in this section.
- Real-time encounter severity estimation. Research needs are addressed in this section.

4.2.2 State-of-the-art

Today, no airborne wake vortex system exists. A number of patents related to airborne wake vortex systems have been filed since the 1990s. These primarily concern solutions related to the display of wake vortices on the flight deck, but also address other aspects.

In Western Europe, airborne wake vortex systems and their enabling technologies have been studied in a number of research projects, including:

- AWIATOR (2002-2007)
- I-WAKE (2002-2005)
- FLYSAFE (2005-2009)

Today, airborne wake vortex systems are specifically studied in the context of three research projects:

- SESAR projects 9.11 & 9.30 (see §4.2.2.1)
- Green-Wake (see §4.2.2.2)
- DLR project “Wetter & Fliegen” (Weather & Flying) and its successor “WOLV” (see §4.2.2.3)
- ALICIA (see §4.2.2.4)

In addition, airborne wake vortex systems will become relevant in the context of several new operational concepts developed in the frame of SESAR and NextGen, which envisage progressively transferring more and more separation responsibility from the ground to the air.

The “Integrated Wake Vortex Safety System”, proposed by the Russian State Institute of Aviation Systems (GosNIIAS), includes an important airborne part.

4.2.2.1 SESAR projects 9.11 & 9.30

Within the SESAR research programme the two projects 9.11 and 9.30 are directly related to development of airborne wake vortex systems, which are called Wake Encounter Prevention System (WEPS) in the context of these projects [Reinke 2010, Kauertz 2011]. Both projects are led by Airbus and build on earlier related research projects like I-WAKE and FLYSAFE, among others, to which Airbus was a contributor. The aim of the projects is to advance the definition and the operational concept of such a system up to a flight-test ready demonstrator. The provisional run-time of the projects is 2010 to 2015. Several parts of the work plan are sub-contracted to different European research institutions.

The SESAR projects 9.11 & 9.30 relate to wake avoidance based on vortex models (WEPS-P) and wake impact alleviation based on advanced flight control concepts enabled by sensor and wake characterisation (WEPS-C), see Figure 14. Wake avoidance based on mid- to long-range forward-looking wake vortex sensors is not considered.

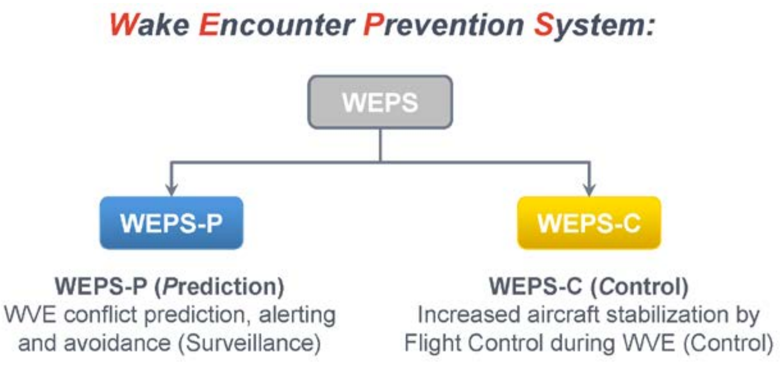

Figure 14: Sub-functions of WEPS

In order to verify and validate WEPS-enabled capacity increases and safety enhancements, both projects will set up technology demonstrator platforms. As part of these activities, a number of fundamental as well as supporting technologies will be addressed in some detail. These include: operational vortex models, advanced flight control techniques, online characterization of the wake vortex, consolidation of traffic and meteorological data, conflict detection and resolution, and encounter severity estimation.

The WEPS under evaluation in these projects is designed to mitigate the increase in wake encounter risk expected with the steadily growing air traffic density, and during all flight phases. It is related to new wake turbulence separation concepts for TMA operations as developed in the SESAR operational project 6.8.1 and is envisioned to complement future pair-wise separation schemes (see §3.4 and §3.5). One goal of these projects is to validate the system's risk reduction potential (safety aspect) and to verify its potential to reduce separations (capacity aspect) in combination with pair-wise separations.

WEPS is envisioned to reliably recognize imminent wake encounters, with a time horizon of a few minutes, to enable safe avoidance and/or dedicated alleviation by flight controls. In this sense, WEPS is of tactical nature, i.e. it is not intended to adjust an aircraft's overall flight plan, but rather to enable short-term, small-scale conflict resolution. WEPS is also not intended in a first step to provide the pilots with the means to determine what their separation should be. In general however it can be used to identify and indicate the required separations.

SESAR project 9.11 specifically concerns those parts of the system that are related to the model-based prediction of the wake behaviour, enabled by air-to-air data link exchange of relevant data. This part is termed WEPS-P, where the P stands for "Prediction in order to avoid". The global conceptual approach of WEPS-P is depicted in Figure 15. Apart from verification and validation activities, aspects of integration in current and future aircraft play an important role in the project as do necessary research activities related to new and major technical sub-functions.

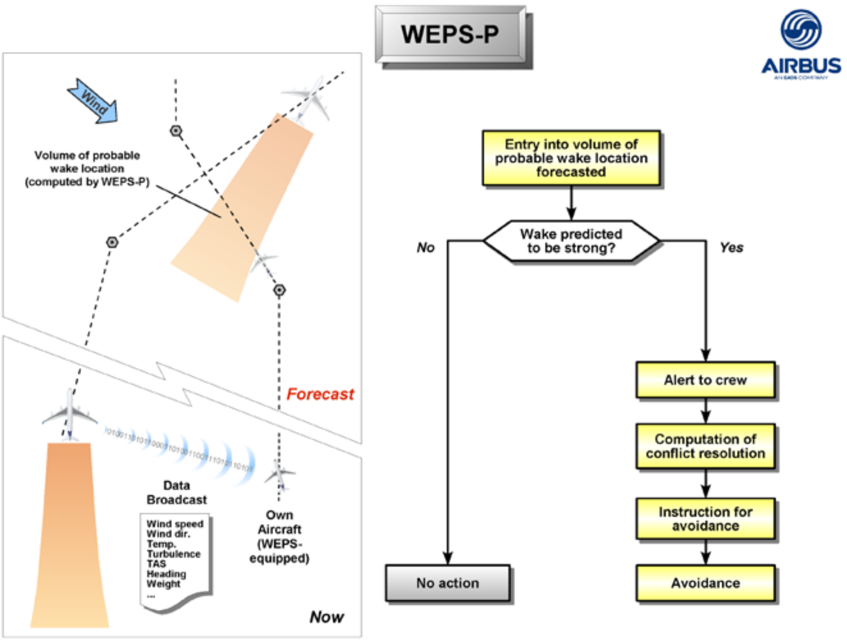

Figure 15: WEPS-P concept schematic

SESAR project 9.30 concerns those parts of WEPS that are related to the alleviation of wake impact on an encountering aircraft by means of flight controls and enabled by new forward-looking sensor technologies, e.g. LiDAR. This part is termed WEPS-C, where the C stands for "Control in order to alleviate". The global conceptual approach of WEPS-C – which is envisioned as an extension to WEPS-P – is depicted in Figure 16. The project focuses on application of a LiDAR sensor, while the development of such a sensor itself is not included.

Likewise to project 9.11, project 9.30 centres on verification and validation activities but also includes some research on fundamental technologies and integration. Both projects will also determine requirements on data link capabilities, i.e. the required extension of the transmitted data by additional parameters needed by WEPS.

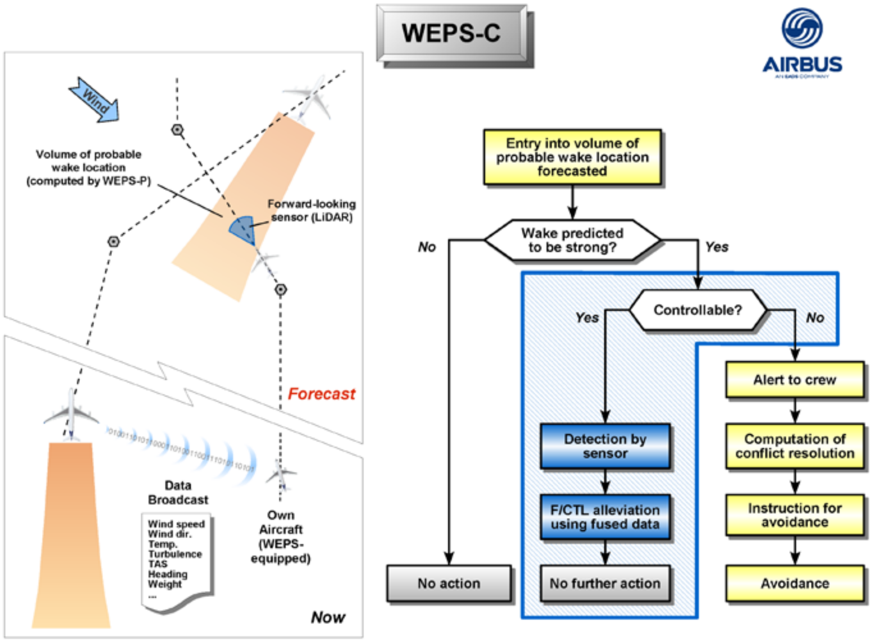

Figure 16: WEPS-C concept schematic

An early WEPS-P demonstrator system has been tested in flight by Airbus in 2010, see Figure 17. This test was performed in opportunity of dedicated wake encounter flights conducted in the framework of A380 wake turbulence separation assessment. It allowed testing a representative wake prediction and warning system in real time and using an air-to-air data link. Apart of testing the system's behaviour in a realistic environment, the test results also provide valuable information with regard to the accuracy of model-based predictions since the wake location and strength was explicitly probed in these tests.

Figure 17: Airbus flight test of airborne wake prediction

4.2.2.2 Green-Wake

Green-Wake is a project of the 7th Framework Programme to support the EC objectives of improving air transport safety and increasing airport capacity. The project started in November 2008 and has been extended to be completed by August 2012. The objective of Green-Wake is to develop and validate innovative technologies that will detect wake vortex and wind shear hazards in a timely manner and input demands to the aircraft's flight control system to automatically alleviate the threat to safe flight that these phenomena generate. As a result this will improve aircraft passenger safety and comfort and improve the operating efficiency of an aircraft, as well as airports, by providing a safe means to decrease separation between trailing aircraft.

To that effect Green-Wake will develop and test an Imaging Doppler LiDAR system that is capable of detecting and measuring wake vortices and wind shear phenomena of the order of 50 to 200 meters in front of an aircraft allowing action to be taken to reduce the hazard. The aim of the project is to develop a system suitable for integration into a commercial aircraft, but also to look at how data are to be presented to the aircrew. A demonstration of the Green-Wake wake vortex detection system is shown in Figure 18.

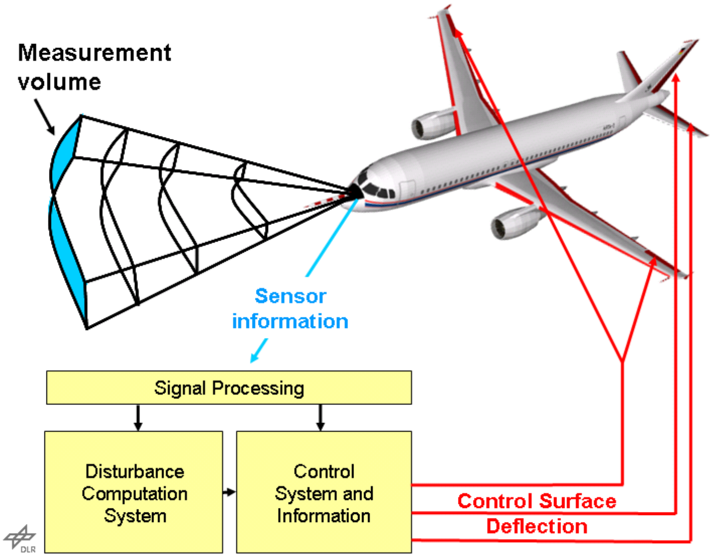

Figure 18: Concept of Green-Wake vortex detection system

Current Status

The consortium has completed an extensive review of the requirements and how the state-of-the-art technologies available can address the measurement application. The wake vortex and wind-shear simulator is nearing completion and the Doppler LiDAR system concept has been developed and a prototype is built during the remainder of the project.

The simulator is one of the three major outputs of the Green-Wake project. The LiDAR instrument, the main deliverable of the project, is currently built. A first version of the prototype has been evaluated and tested in the wind tunnel. The final ground based prototype instrument running in real time will produce a 3-dimensional hazard map, aimed at enhancing the presentation of hazard information. It will characterize the movement of the air and detect wake vortices and wind-shear at a range of up to 200 m.

Further Developments

Further information on the project and contact details for project representatives can be found on the Green-Wake project website at www.greenwake.org. Details of related publications can be found in [Schmitt 2007], [Schwarz 2007], [Rahm 2007].

4.2.2.3 DLR project Wetter & Fliegen

The DLR internally funded project "Wetter & Fliegen" (Weather and Flying) is a four year project with a run-time from 2008 to end of 2011 with participation of several DLR institutes. A variety of airborne topics are studied in the framework of this project: sensor requirements for the direct use of forward-looking measurement data for flight control purposes, wake characterization methods as well as automatic control and wake warning and avoidance applications.

Airborne wake vortex warning systems

Airborne wake vortex warning systems serve to increase the pilots' situational awareness in case of a predicted, imminent or even current encounter. Concerning the latter, DLR has concluded from simulator studies with an Airbus A330 model that this aircraft's autopilot usually can handle a wake vortex encounter better than a pilot flying manually; nonetheless pilots tend to disconnect the autopilot because of uncertainty whether there is a malfunction in the flight control system [Vechtel 2010]. Here the indication of a wake presence appears helpful, as it does in support of wake alleviation functions (such as a special wake vortex mode of the controller). The necessity of displaying further information (e.g. encounter geometry) needs to be investigated.

If a hazardous wake encounter is predicted, best use can be made of a wake warning system if it can be employed to perform evasive manoeuvres. It is obvious that a depiction of the encounter geometry and surrounding obstacles increases the pilot's situational awareness during execution of the manoeuvre. Even if wake evasion is not possible due to the flight situation, an indication of a possible threat due to wake vortices can increase flight safety.

DLR is working on a Wake Encounter Avoidance and Advisory system (WEAA) which has the aim to avoid potentially hazardous wake vortex encounters by modifying the flight path as required. A conceptual system design has been performed, a simplified version of which is depicted in Figure 19. The basic idea behind this system is that evasive manoeuvres should be performed without the necessity to obtain an ATC clearance and just by subsequently informing ATC similar to TCAS manoeuvres. DLR aims at a proof-of-concept for selected system components with evaluation through flight simulation.

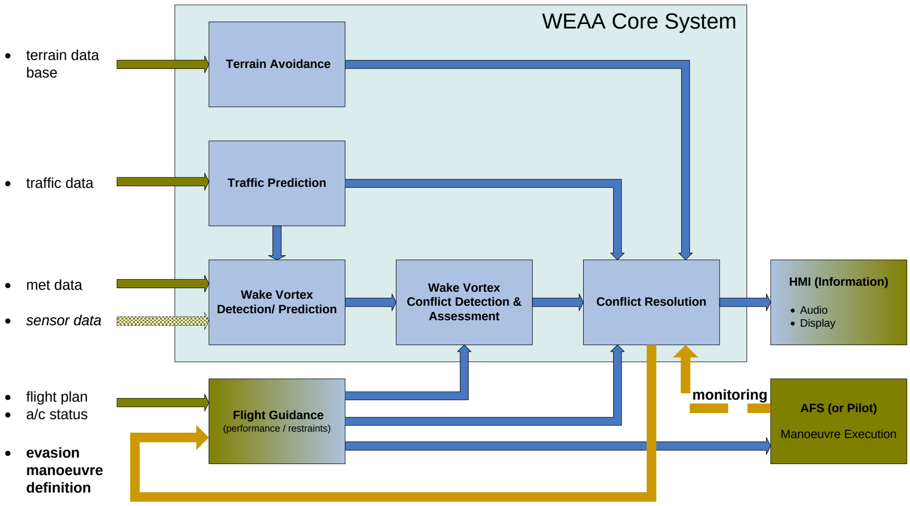

Figure 19: Simplified overview of conceptual architecture of DLR's Wake Encounter Advisory and Avoidance system (WEAA) [Vechtel, Bauer, 2010], [Schwarz et al. 2010].

The system

- performs data fusion of own aircraft data (flight state, flight plan, system states), traffic data obtained via ADS-B and meteorological data for wake prediction (at least wind vector) in real time;
- predicts wake vortices from performance data and planned trajectories of surrounding aircraft using meteorological data;
- performs a conflict detection, using prediction of own trajectory, followed by hazard assessment where required;
- generates an evasion trajectory, taking into account terrain data (from EGPS/TAWS database), which is designed to avoid triggering TCAS or GPWS warnings;
- provides guidance for the necessary evasive manoeuvres to the pilots, e.g. on PFD and VSI; and
- gives an overview display of the situation to increase the pilot's situational awareness, e.g. on the ND.

First implementations of trajectory generation algorithms have been developed. An operational concept development and display design for the HMI have been carried out [Raab 2010] and initial evaluation has been carried out in a simulator study. The work is on-going in the successor project "WOLV" which starts in 2012.

LiDAR sensor and vortex characterisation

Regarding the derivation of forward-looking sensor requirements driven by an automatic wake vortex control system, numerous offline simulations have been conducted in order to determine the performance of the controller as function of the sensor characteristics (such as sampling rate, measurement errors and resolution) and field of view. However, it is already foreseeable that the line-of-sight velocities available from current forward-looking sensors (e.g. as provided by LiDAR) cannot directly be used for an automatic control system.

Experience with on-board measurement is available from wake vortex encounter flight experiments at DLR. The encounter aircraft usually was equipped with one or multiple sensors (five-hole probes or vanes) that recorded three-dimensional airflow vectors while passing through the vortices (in-situ). The analysis method developed by DLR utilises an analytic wake vortex model and estimates its respective model parameters (i.e. circulation, vortex locations and spatial orientation) from the recorded flight test data. The applied wake vortex model with the identified parameters subsequently allows a very accurate reconstruction of the measured wake vortex flow field (Figure 20).

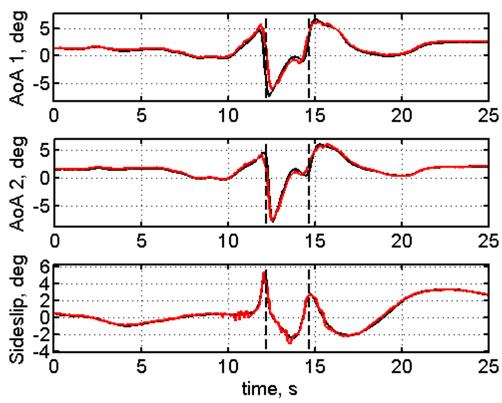

Figure 20: Fuselage vane signals (angle of attack and sideslip) measured in flight test (red line) and reconstructed signals using the identified analytic wake vortex model (black line).

This wake characterisation method developed by DLR is very versatile and not limited to three-dimensional flow-vectors as input. In order to achieve forward-looking detection capabilities, the algorithms were adopted to operate even with one-dimensional line-of-sight velocity measurements of a forward-looking LiDAR (Light

Detection and Ranging) sensor [Fischenberg 2009, Hahn et al. 2010]. In the considered configuration, the sensor scans a spherical pattern in front of the aircraft and measures the respective line-of-sight flow components at several discrete measurement locations (Figure 21).

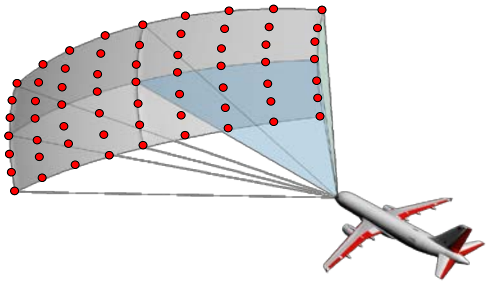

Figure 21: Spherically shaped scan pattern of an on-board forward-looking LiDAR sensor

Compared to the three dimensional flow vectors from the in-situ measurements using dedicated five-hole probes for research, the single line-of-sight velocities measured by LiDAR provide much less information about the flow field in front of the aircraft. The flow profile of a vortex is inherently predominantly two-dimensional so that especially for near axial arrangements the measured line-of-sight velocity components are very small. Consequently, large scan angles of the measurement pattern are necessary to assure that the LiDAR is able to measure flow components of a wake vortex even for shallow encounter angles.

The DLR characterisation method again utilises an analytic wake vortex model to reconstruct the flow field based on the measured line-of-sight velocities of the LiDAR. An a-priori analysis of the measurement data generates initial values of the model parameters. A subsequent Online Identification iteratively optimises these parameters in order to achieve the best possible reconstruction of the measured line-of-sight velocities (Figure 22). A patent application for the method was filed [Fischenberg 2009].

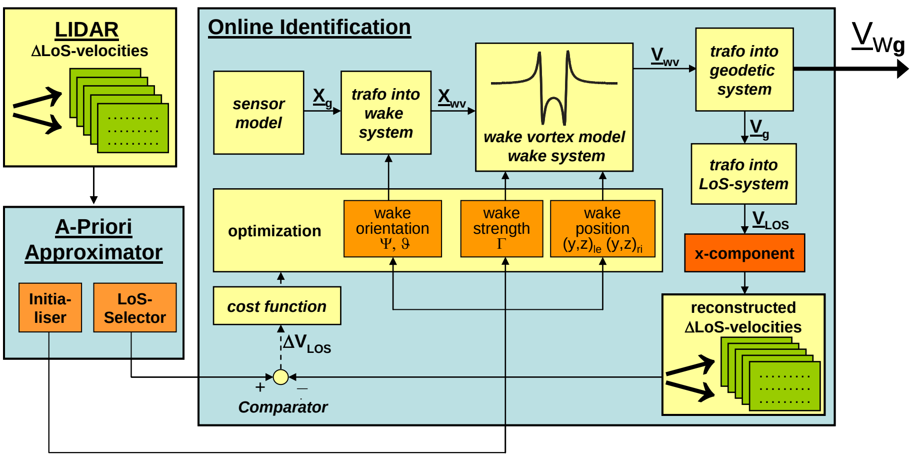

Figure 22: Outline of DLR's forward-looking wake vortex characterisation method

Wake impact alleviation

Regarding automatic control applications DLR has gained experience in the last years with automatic control specifically for wake vortex impact mitigation using forward-looking sensor data, designated as feed-forward control concept (see Figure 23). Assuming ideal knowledge of the 3-dimensional wind field in front of the aircraft, an Aerodynamic Interaction Model is used for the determination of the forces and moments induced by the wake vortex. The required control deflections needed for a (partial) compensation of the induced moments are calculated by inverting the aerodynamic control derivatives.

Several flight tests have been conducted on the DLR research aircraft ATTAS with the emphasis on the pilot evaluation of different in-flight simulated wake vortex encounters with and without automatic assistance [Hahn and Schwarz 2008], [Hahn et al. 2010]. In the most recent flight tests the automatic system was enhanced by using the Direct Lift Control (DLC) Flaps of the ATTAS in order to assess the benefits of the load factor compensation [Hahn et al. 2010] (see Figure 23). The resulting pilot ratings were compared to the results obtained in preceding flight tests (see Figure 24).

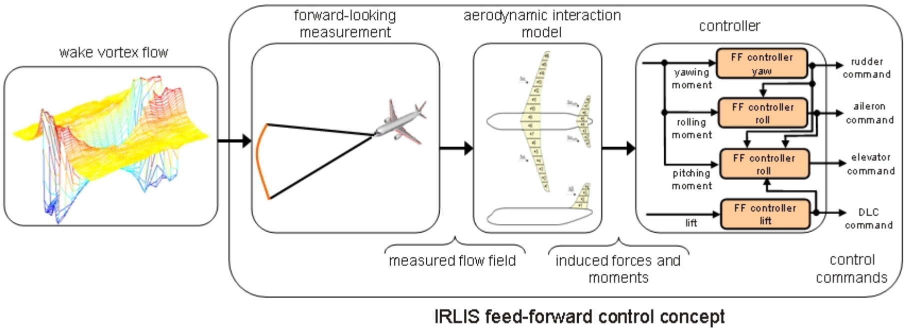

Figure 23: Principle of the feed-forward control assistance system

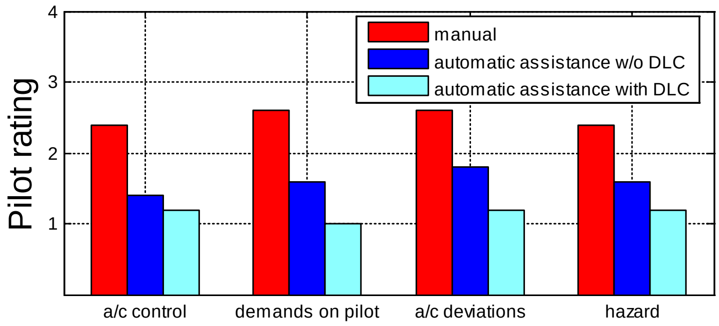

Figure 24: Average pilot ratings for in-flight simulated wake vortex encounters

Additionally, within the project “Wetter und Fliegen” DLR is working on an automatic control system for wake vortex mitigation feeding back conventional sensor data available on modern passenger aircraft. The research work in this area concentrates on the design of the structure and the gains of such a control system specifically used as a wake vortex alleviation system.

4.2.2.4 ALICIA project

ALICIA is a research and development project funded by European Commission under the Seventh Framework Programme, operational between 2009 and 2013. ALICIA aims at developing new and scalable cockpit applications which can extend operations of aircraft in degraded conditions. Stated commercial aircraft operational capabilities that shall support the

achievement of ALICIA’s objective include “Fixed wing transport aircraft shall be able to support and improve flight crew situation awareness of approach and landing hazards (e.g. low visibility, visual illusions, energy management on contaminated runway, terrain, obstacles, wake vortices, microburst, etc.).”.

4.2.3 Research Needs

The airborne wake vortex detection / characterisation, warning conflict resolution and impact mitigation is a quite novel field and hence only little research work is known until today. The development of systems that reliably predict wake vortices in front of aircraft is highly desirable. By reducing the probability of wake vortex encounters, such systems would contribute to safety enhancements of the commercial air transport system. Furthermore, forward-looking detection systems are seen as a key technology to enable a reduction of today’s wake turbulence separation requirements in order to increase airport and airspace capacities.

The majority of research needs related to airborne wake vortex systems concern the different enabling technologies, for example, the associated wake vortex sensor. Related technology research needs are addressed in §5.2 of this report. Research needs specific to the underlying operational concepts are listed in §3.6.

4.2.3.1 Airborne, short-range forward-looking air data sensors

Continued research is needed to advance the technology of forward-looking air data sensors. Airborne, short range, forward-looking air data sensors are required to enable novel technologies for the suppression of wake impacts, especially those affecting the roll axis, by flight control. Such sensors need to reliably measure air velocities in front of an aircraft during all phases of flight and with high availability and accuracy in the order of 1 m/s or below. LiDAR is regarded as the potential enabling technology.

- Development of short-range LiDAR air data sensor demonstrator and flight tests

  Apart from measurement accuracy, frequency, range and availability, relevant requirements also exist with regard to size, weight and power consumption of such sensors. Important research efforts are required to achieve such sensor maturity. Also, for the purpose of testing such a new sensor itself as well as for the verification and validation of all connected aircraft functions – including coupled flight control systems – and in order to reduce any later certification risks, it is necessary to develop a technology demonstrator, to install it on a flight test aircraft and to evaluate the overall system operation through flight trials.

4.2.3.2 Airborne, mid- to long-range wake vortex sensors

Continued research is needed to identify and advance fundamental technologies for the mid- to long-range detection, tracking and possibly characterisation of wake vortices. Such a sensor would enable novel airborne wake vortex concepts permitting wake avoidance based on measurement instead of model predictions, with the associated increase in accuracy and acceptance.

- Assessment of sensor technologies suitable for the mid- to long-range detection, tracking and characterisation of wake vortices.

  Candidate solutions need to be identified and assessed taking into account functional as well as aircraft installation requirements. Sensor technologies also suitable for other surveillance functions like weather, turbulence, volcanic ash, obstacle detection etc. should be preferred. Promising solutions should be evaluated using technology prototypes. Complementary and/or alternative technology solutions should be investigated.

- Evaluation of advanced sensor-model-fusion technology to improve mid- to long-range sensor capability with regard to wake vortex detection, tracking and characterisation.

  Sensor capabilities may be improved by combining sensory information with wake vortex model predictions based on data link. Associated concepts should be developed and evaluated with regard to their potential to reduce sensor weight and power consumption.

4.2.3.3 Real-time, on-board meteo data fusion

Continued research is needed with regard to the real-time provision of fused meteorological data required for wake vortex predictions. It is necessary to investigate how this can be derived on-board an aircraft using meteorological data disseminated through data links from multiple, dissimilar sources. Such meteo functions need to provide estimates of wind speed and direction (wake transport by wind) as well as atmospheric turbulence (effect on wake decay) in the vicinity of the aircraft. Optimally, such functions also provide reliable accuracy estimates for use in probabilistic vortex models.

- Identification of data requirements with regard to parameter definitions, update rates, accuracies and reliabilities.

  Comprehensive data requirements need to be established taking into account the functional architectures of related airborne systems, their capabilities, and wake vortex model requirements.

- Identification of potential data sources, data links and associated standards
- Methods for the fusion as well as temporal and spatial extrapolation of such meteo data

  Methods need to be developed and validated that allow fusion as well as temporal and spatial extrapolation of meteo data stemming from different and dissimilar sources (e.g. air-to-air and ground-to-air data links).

Further related research needs are detailed in §5.3 of this report.

4.2.3.4 Operational, probabilistic wake vortex prediction models

Airborne wake vortex systems need operational vortex models for all phases of flight. These models need to be sufficiently fast in order to support airborne, real-time applications. They need to be flexible with regard to varying levels of input data availability and accuracy. They need to be validated for different levels of application (safety net, capacity increase) and different phases of flight.

- Can all necessary input data, especially met and traffic data, be made available on-board the aircraft with the required accuracy, reliability and update rate?
- Solutions requiring minimum computational effort need to be established.

Further related research needs are detailed in §5.1 of this report.

4.2.3.5 Online wake characterisation

Additional research is needed towards the real-time, online characterization of a wake vortex (determination of the wake properties like strength and position) based on multiple information sources including existing as well as novel aircraft sensors and using enhanced technologies like model-sensor filters. Such wake characterisation can provide significant benefits over directly using sensor measured velocities in combination with novel wake encounter alleviation flight control techniques. Today, detection methods and algorithms are still in an early stage of development. Potential is seen in the further adaptation of the detection algorithms to the individual properties of specific sensor technologies. Since recent development work still is based on numerically generated measurement databases it is highly desired to work with genuine measurement data or even to move to hardware-in-the-loop experiments in the future.

4.2.3.6 Alerting and conflict resolution

Additional research is needed with regard to the appropriate way of alerting pilots, the identification of a resolution manoeuvre and the necessary guidance for such a manoeuvre in case of airborne wake vortex system activation.

- Human-Machine Interface and Human Factors of wake vortex alerting as well as conflict resolution.

  What is the best way (Human-Machine Interface and Human Factors) to warn the pilot and suggest a conflict resolution (visually and/or aurally)? It must be analysed how visual/aural warnings could be optimised to give the pilot the best situational awareness.

- Concept and algorithm for the creation of avoidance trajectories taking into account terrain (TAWS), other traffic (TCAS) and own aircraft capabilities.

  Identification of an evasion trajectory for conflict resolution has to be optimised regarding computational effort (computation time) and deviation from the planned flight path. An optimised concept/algorithm for evasion trajectory generation needs to be developed which takes into account terrain (TAWS), other traffic (TCAS) and own aircraft capabilities. The benefits and feasibility to perform evasive manoeuvres in 3-D need to be evaluated (i.e. not only lateral or vertical evasion). Finally research is necessary to confirm whether a tactical approach (i.e., no change in flight plan) is generally sufficient for the avoidance manoeuvre.

4.2.3.7 Flight control alleviation of wake-induced disturbances

Additional research is needed with regard to new fly-by-wire flight control concepts allowing improved stability of wake encountering aircraft.

- Evaluation of adapting flight control feed-back gains in wake encounter situations.
- Evaluation of novel flight control concepts for improved stabilisation in wake encounter situations.

  Up to now evaluations of the feed-forward automatic assistance have mainly been performed using idealized measurement data. This especially concerns the assumption of the availability of the complete 3-dimensional velocity vector. In fact today's forward-looking sensors are only capable of providing reliable line-of-sight measurements. Therefore a future research field is the combination of on-board detection algorithms, such as the online identification method described in [Fischenberg 2009], and the feed-forward control assistance system as described in this section. In this case the required velocity vectors are derived from a wake vortex model whose parameters are identified by using forward-looking measurements.

  Another open issue for the application of such a system is the prevention of unintended commands that might even increase the effect of the wake vortex induced aircraft reaction, and the robustness of the approach (a vortex must not be interpreted into a (turbulent) flow field when there is none).

  Further research is needed for the integration of wake vortex mitigation systems in modern highly augmented and automated aircraft, because previous research work was concentrating on aircraft with conventional mechanical flight control systems.

  The use of manual augmented control laws, such as the C*-law, and automatic control algorithms has great impact on the aircraft reaction during a wake vortex encounter. This raises the following questions: What is the best piloting technique for (highly) augmented aircraft during a wake vortex encounter? And what are the benefits of adapting the feedback gains of the manual or automatic control laws during a wake vortex encounter?

  First simulation trials have indicated that the pilot's reaction might be more appropriate if the pilots knew that the aircraft reaction results from a wake vortex encounter. Consequently an aural or visual warning might improve the pilot's reaction during the encounter. The design, the integration into the current cockpit architecture and the evaluation of such a system are future research topics, even if initial steps have been taken by [Raab 2010]. This system should also indicate the status of the automatic assistance system

- Evaluation of the impact of the vortex flow field on aircraft air data sensors and associated effects on flight control stabilisation capabilities.

  Specifically the two following interactions between the flow field and the control system also need further consideration

  - Local stall effects: Current Δ-aerodynamic models for vortex induced forces and moments are limited to the linear region of the lift curve, as stall effects cannot be taken into account. Is this sufficient in all cases, especially when slowly flying aircraft encounter high vertical wind velocities? It is especially necessary to ascertain that the authority of the control surfaces, in particular the ailerons, is not negatively affected.
  - Effects of vortex field on flow sensors: The high local velocities affect the alpha and air speed sensors of the aircraft; additionally the barometric height measurement is perturbed if the vortex core with its changes in static pressure is encountered. The effects on the flight control system need to be investigated (e.g. an angle of attack protection might be inadvertently triggered; the aerodynamic state assumed may not be representative of the aircraft).

4.2.3.8 Harmonized and integrated operational concepts

Additional research is needed to assure harmonization between airborne and ground-based wake vortex advisory systems and their contributions and roles as part of new wake vortex separation rules. Research is also needed to allow airborne wake vortex system operations and hence benefits in the context of existing and future air traffic operational concepts.

- Integration of airborne wake vortex avoidance systems with ATC in general and interoperability with new ground-based wake vortex advisory systems.

  The capabilities of new airborne wake vortex systems need to be taken into account in related ATC operational concepts. Research is needed to assure harmonised operations yielding maximum benefits. Harmonised definition and application of pair-wise dynamic separation concepts within SESAR, NextGen and in other world regions needs to be assured.

- Acceptability and operational treatment of small-scale tactical avoidance manoeuvres as a result of wake vortex avoidance.

  Small-scale avoidance manoeuvres are an important possibility to reduce the risk of severe wake encounters, especially en-route. The effects on flight safety need to be studied and system requirements need to be derived.

- Harmonization and integration with other operational concepts

  Conceptual research related to the integration of new airborne wake vortex system capabilities with the manifold new aircraft operational concepts envisioned as part of SESAR and elsewhere (e.g. ASAS Self Separation, 4D-Business Trajectories, Wake Vortex Free Approach) is required. New technologies under research for stand-alone wake vortex detection, prediction, alleviation and avoidance systems are expected to be well suited to also assure wake encounter safety in combination with such new operational concepts but additional effort is required to identify integration options, to integrate these functionalities and to assure harmonised concepts. Required Performances should be set up for different ASAS-SSEP levels. This would allow the integration of technologies available in the near term into airborne systems for lower required performance levels. Technologies available in the long term could then be integrated to reach higher performance levels.

4.2.3.9 Safety assessment

Additional research is needed to identify how the capabilities of airborne wake vortex systems and vulnerability of follower aircraft can properly be taken into account in wake vortex safety assessments (see §6.2) and using which metrics (see §5.5.2.5).

- Definition of means of compliance and safety case requirements

  Probably the biggest hurdle towards the development of airborne systems aiming at reducing wake turbulence separation requirements while assuring today's safety level is the uncertainty with regard to means of compliance and safety case requirements. While there have been recent advances related to wake turbulence safety assessments (e.g. A380, WIDAO), these primarily take into account the characteristics of the wake vortex but not specifically the capabilities of the follower aircraft. Industry will remain cautious towards developing new aircraft wake vortex systems as long as it is unclear if and how such systems' new capabilities will be taken into account in future separation standards and how such systems can be qualified.

4.2.3.10 Required operational environment

Additional research is needed to fully define the required operational environment.

- Availability of additional air-to-air and potentially ground-to-air data link capabilities specifically required by airborne wake vortex systems.

Research need to identify harmonized system needs.

- Definition of performance levels and requirements for wake vortex related operational concepts

  Research is recommended on the impact of wake vortex separations on these new ATM concepts, themselves based on different performance levels of evolving airborne wake vortex mitigation and alleviation systems. While dedicated systems (e.g. on-board wake vortex mitigation systems) should be linked to operational concepts (e.g. ASAS applications with wake vortex recognition) already in the short term, it should be noted that systems in the mid and long term are expected to satisfy the operational concept requirements based on different technologies (e.g. wake vortex prediction, wake vortex detection, usage of available and upcoming data links or a combination of different technologies, etc.). Therefore, research is also recommended on defining performance levels in terms of accuracy, integrity, continuity and availability for wake vortex related operational concepts.

4.2.3.11 Validation of operational efficiency

Additional research is needed to fully validate the operational efficiencies of airborne systems.

- Evaluation of system demonstrators in an operationally relevant simulated environment including normal and abnormal operational circumstances

  The operational efficiency, benefits and acceptance of airborne systems depend on their ability to prevent a significant number of wake vortex encounters while at the same time not leading to undue numbers of false alarms. Whereas the probability of prevention is linked to the risk reduction provided by such systems (and hence its operational benefit with regard to safety and capacity), too high levels of false alarms will render such system simply unacceptable. Hence, representative systems need to be tested in normal as well as abnormal operational conditions using ground-based simulations in addition to analysis. Acceptable false alarm rates need to be established through pilot evaluations.