AIAA 2010-7680

Wake Encounter Flight Control Assistance Based on Forward-Looking Measurement Processing

Klaus-Uwe Hahn [1], Dietrich Fischenberg [2], Dominik Niedermeier [3] and Christian Horn [4]
German Aerospace Center DLR, Institute of Flight Systems, Department Flight Dynamics and Simulation, Lilienthalplatz 7, 38176 Braunschweig, Germany

Weather dependent delays, incidents and even accidents play an important role in aircraft operation. Any airplane is subject to air motion. Thus, turbulence is an important parameter in aeronautics. The phenomena which are summarized as gusts and turbulence strongly affect the passenger comfort and the safety of aircraft. Especially the turbulence caused by the wake of other aircraft can cause undesired motions mainly roll and vertical displacements. Active control technology can be applied to alleviate wake vortex effects on aircraft and support the pilot to carry out his control task. With the aid of specific controllers such vortices can be safely encountered even if the required control power temporarily exceeds the available capacity. Aircraft equipped with such a controller will be less affected by unforeseen wake vortex encounters or even will be able to follow another aircraft closer than authorized by the current separation distances without any compromise concerning safety. A very promising concept for wake vortex disturbance alleviation is the feed-forward disturbance compensation. The application of such an approach requires the accurate determination of the flow disturbance to calculate the necessary counter measures in terms of required control activities. Thus, the disturbance flow determination plays an important role and needs to be investigated thoroughly. Modern LIDAR technology has the potential to measure the flow filed in front of the aircraft and to provide the required disturbance information in advance before it affects the aircraft. The final goal of the DLR approach is the development of an Integrated Ride and Loads Improvement System (IRLIS) which is able to cope with the whole frequency range of atmospheric flow disturbances relevant for aircraft operation. The presented paper will summarize the status of the work performed during the last years and the current activities.

Nomenclature

b	=	wing span
D	=	depth of measurement volume
f	=	function
H	=	altitude
l	=	length
n	=	indicates measurement point
r	=	yaw rate/radius/radial coordinate
t	=	time
v	=	lateral velocity component
w	=	vertical velocity component
V	=	velocity
x, y, z	=	longitudinal, lateral, vertical coordinates
Γ	=	circulation/vortex strength
γ	=	flight path inclination
η	=	elevator deflection
Δ	=	difference
δ	=	control surface deflection
ε	=	elevation angle
Φ	=	bank angle
σ	=	standard deviation
ξ	=	aileron deflection
Ψ	=	azimuth angle

abbreviations

ADS-B	Automatic Dependent Surveillance-Broadcast
AGL	Above Ground Level
AIM	Aerodynamic Interaction Model
ASRS	Aviation Safety Report System

[1] Corresponding author, department head, klaus-uwe.hahn@dlr.de
[2] Research scientist
[3] Research group leader
[4] Research scientist

ATTAS	Advanced Technologies Testing Aircraft System
D	dimension
DoF	degrees of freedom
DLC	direct lift control
DLR	German Aerospace Center (*Deutsches Zentrum für Luft- und Raumfahrt*)
FbW	fly-by-wire
ICAO	International Civil Aviation Organization
IFS	in-flight simulation
ILS	instrument landing system
IRLIS	Integrated Ride and Loads Improvement System
LIDAR	light detection and ranging
LoS	line of sight
MSL	mean sea level
MTOW	maximum takeoff weight
O-ID	online identification
RWY	runway

subscripts

c	=	core
FLS	=	forward looking sensor
GLS	=	glide slope
g	=	geodetic
s	=	shape
t	=	tangential
WV	=	wake vortex
WVL	=	wake vortex line

I. Introduction

ATMOSPHERIC flow disturbances adversely affect aircraft motion and consequently the flight operation and safety. The effect of air mass motion on aircraft can be very different. The scale of the flow fluctuations related to aircraft dimensions, respectively wing span and chord, plays an important role for the aircraft reaction. While low frequency flow variations have a significant impact on the energy state of the aircraft[1] the higher frequencies of air fluctuations will cause undesired accelerations[2]. The scale and strength of aircraft self-generated wake vortices also result in a very sudden reaction of another aircraft encountering it. Therefore, the wake vortex phenomenon is often called "wake vortex turbulence". But, depending on the encounter conditions, the aircraft response to a wake vortex encounter can be very different compared to its behavior in homogeneous natural turbulence. For parallel-like encounters, a very rapid and sometimes extreme severe roll response is typical. The severity of the aircraft response increases with the vortex strength (as generated by heavy aircraft), and the encounter proximity to the vortex enter (stronger rotational flow), and decreased with the vortex age due to its decay. To avoid unintended encounters, specific separation distances have been established for approach and landing depending on weight classes of generating and encountering aircraft. The current standard separations[3] can be assumed to be proven by their daily operational application. Nevertheless, from Fig. 1 an average of about 45 reported encounters per year can be identified from which roughly five per year have to be considered to be incidents (damages or even injuries; data: US between 1999 and 2009)[4]. In principle, there are three different approaches to reduce the number of such incidents:

- active and passive actions[5,6,7,8] to reduce the generated vortex strength and to accelerate its decay
- precise (on ground or/and on board) prediction of wake vortex movement to avoid affected areas[9]
- application of active control technology to alleviate wake vortex effects on aircraft[10]

Considering the predicted air traffic increase[11] of the coming decades and the corresponding demand for traffic throughput at airports underlines the need for measures to cope with the wake vortex problem[12]. To contribute to possible solutions of this problem, associated with the future demand in air traffic increase DLR has increased its efforts on this subject starting in 1999, setting up two consecutive projects named "Wirbelschleppe I" and "Wirbelschleppe II" ("Wirbelschleppe" means wake vortex) resulting in the currently running project "Wetter und Fliegen" ("Weather and Flying"). The

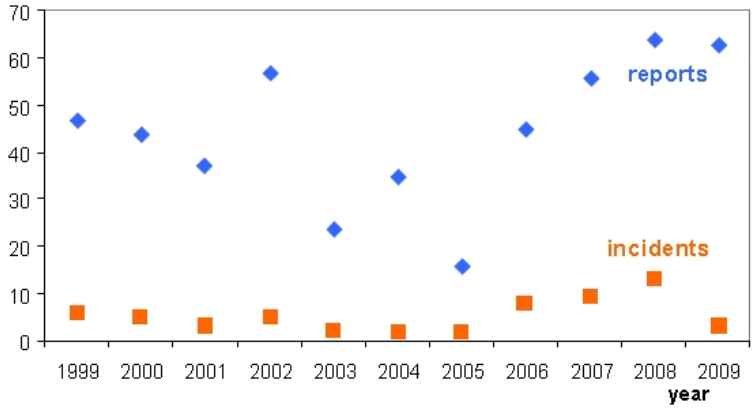


Figure 1. Wake vortex encounter reports and incidents between 1999 and 2009 in the US[4]

projects have been dedicated to the full spectrum of the wake vortex phenomenon. In the following the focus will be on the approach, development and demonstration of an active control concept to alleviate the impact of wake vortices on aircraft.[13]

II. Control Concept

Experiences on the application of feed-forward disturbance rejection applied to atmospheric flow disturbance alleviation have been collected at Institute of Flight Systems for several decades. Based on this knowledge, a similar approach was used for the active control concept of wake vortex encounters with the aim to improve the aircraft behavior. For the presented control approach it is assumed to have full knowledge of the flow field in front of the aircraft which is going to be encountered. Details on the flow disturbance determination will be discussed in sections III and IV.

The principle of the control concept is illustrated in Fig. 2. Knowing the wake vortex flow field in front of the aircraft from forward-looking sensor information the flow disturbance distribution along the aircraft in space and time can be computed. Using a suitable Aerodynamic Interaction Model (AIM) the resulting additional forces and moments induced by the flow disturbances can be determined[14]. For the wake vortex control concept an AIM taking into account the wing, the horizontal and the vertical tail is used, discretization details see Fig. 2. Knowing the aircraft aerodynamics and the control surface efficiencies the required control surface deflections to compensate for the wake vortex induced disturbances can be calculated. For the basic wake vortex controller pitch, roll and yaw control commands are computed. Due to the fact that the control deflections can be calculated in advance from the look-ahead sensor information the application of the control deflections can be perfectly synchronized with the arrival of the respective flow disturbance at the aircraft's wing, horizontal and the vertical tail.

In between the region of the two wing tip vortices an encountering aircraft is exposed to strong downdrafts causing very high sink rates. In such a situation the vertical motion of the aircraft can be improved if the aircraft is equipped with special flaps for independent direct lift control (DLC flaps) in addition to the primary controls. DLC flaps are considered to be fast moving flaps at the trailing edge of the aircraft's wing with a size similar to that of the landing flaps. Since the DLC deflections δ_{DLC} also directly affect the pitch moment they are considered for the elevator command. This approach of controlling moments and forces is understood to be the initial version of the Integrated Ride and Loads Improvement System (IRLIS) able to cope with wake vortices and natural atmospheric turbulence. These basic functions of the system will be further extended and completed in future.

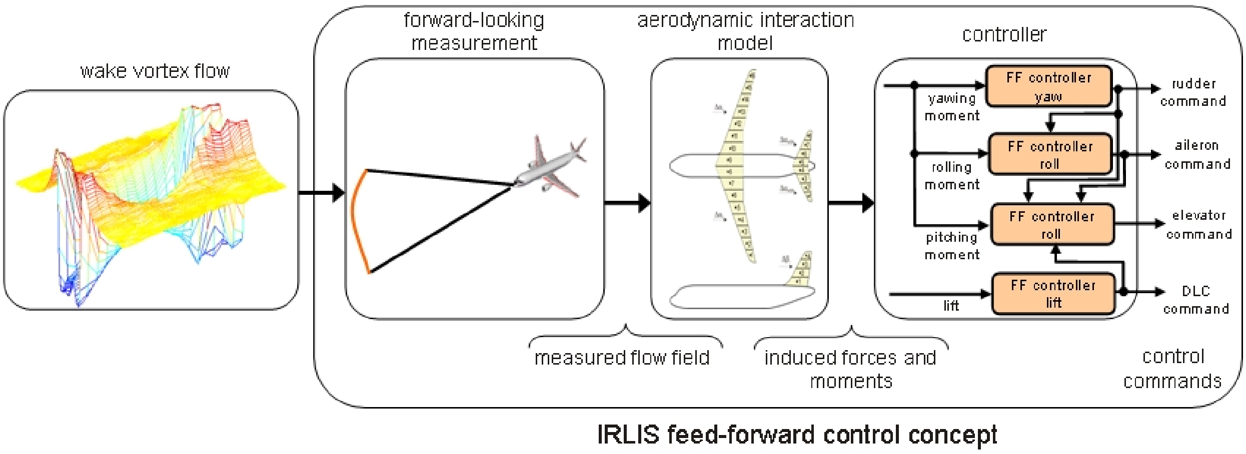


Figure 2. Principle of the IRLIS flight control assistance system

III. Look-ahead Measurement Concept

As a conclusion from investigations into different measurement concepts (combinations of airframe fixed, air path fixed, 1D, 2D, with or without interpolation between the measurement spots)[16] to provide the required disturbance input to the control assistance system it is proposed to use an air path fixed measurement concept for most precise flow disturbance determination in front of the aircraft. Unfortunately, discussions with LIDAR manufacturers on the near future potentials and possibilities of their systems it became clear that a permanent adjustment of the vertical scan angle according to the actual air path variations seems not to be feasible with existing

LIDAR sensors. Hence, the air path fixed measurement concept has to be excluded and it was decided to try an airframe fixed measurement concept adjusted to look roughly into the direction of the reference air path. For this concept the air flow is scanned and measured along a line (1D) in wing span direction at a certain distance in front of the aircraft (see Fig. 2). To make sure that the aircraft will encounter as close as possible the region where the ahead LIDAR measurement took place, the look-ahead distance should not exceed the shortest possible measurement distance. This minimum look-ahead distance is determined by the lead time needed due to the actuator dynamics and the computation time required for data processing and controller calculations. In this study the equivalent time delay for the actuation system is assumed to be $\Delta t = 115ms$ and the time delay for computation is $\Delta t = 150ms$, which summarizes to an overall equivalent time delay of $\Delta t = 265ms$. From this time delay the minimum look-ahead distance can be calculated for any respective airspeed $\Delta x = V \cdot \Delta t$.

A. Simulation System

For the investigation of the above forward looking measurement concept a 6DoF simulation environment was set up consisting of aircraft model, wake vortex flow model, LIDAR sensor model and the feed-forward controller described in section II.

As encountering aircraft model a VFW 614 twin engine jet aircraft was chosen since it is DLR's FbW test aircraft which is very well known and perfectly modeled by the application of parameter identification methodology based on high quality flight test data. Further more having a MTOW of about 21*to* it is in the lower portion of the 'medium' class aircraft following the ICAO mass classification.

The wake vortex flow field is modeled by an analytical model. It consists of two superimposed counter rotating wing tip vortices. It is assumed that each vortex can be described by the velocity model of *Burnham-Hallock*.[17] This approach (see section IV.A.) shows a very good fit for a continuous analytical model compared with real flight test data[18].

The LIDAR sensor model is a generic model which does neither include the physics of light of a real sensor nor the physical rules of measurement but only the principle of forward looking measurement. It calculates a specified number of measurement points on the virtual scanning line in wing span direction in front of the aircraft. The measurement angle from the sensor to those points is selected in order to cover the full wing span of the aircraft at the specified look-ahead measurement distance. The wind velocities at these points are determined by the analytical wake vortex model. Sensor model parameters are measurement range, frequency, error, depth and scan angles. A LIDAR is only able to detect the average flow velocity in the range of a specific depth of measurement volume in the beam direction, the so called line-of-sight (LoS). A measurement volume with a dimension of plus and minus 2.5% of nominal LIDAR range was defined and divided into 10 segments providing plus minus 5 extra points before and after the nominal point of measurement (see Fig. 3). At all these points the wake vortex flow is calculated individually. The resulting velocity to virtually represent the LIDAR information is computed from those individual velocities by weighing them by means of a half wave of a sinusoidal shaping function *fs*. The weighing function is used to amplify the importance of those measurements which are closer to the nominal measurement point positioned in the center of the measurement volume at the nominal LIDAR range. In addition measurement errors are modeled as normally distributed values for a given standard deviation and superimposed on the nominal velocity. Following the advice of the LIDAR manufactures the standard variation has been chosen to be $\sigma = 1m/s$. All three earth related velocity components (in *x*-, *y*- and *z*-direction) of the flow disturbance vector are perturbed by the normally distributed errors. Using this simplified LIDAR model, supporting the main parameters of interest, the look-ahead measurement concept was investigated systematically in numerous offline simulations. The wake vortex generating aircraft is chosen to be a category 'heavy' aircraft with a MTOW of 190*to* and a wing span of about $b = 60m$. The age of the wake is set to 130*s* equivalent to a separation distance of 5*nm* (9265*m*).

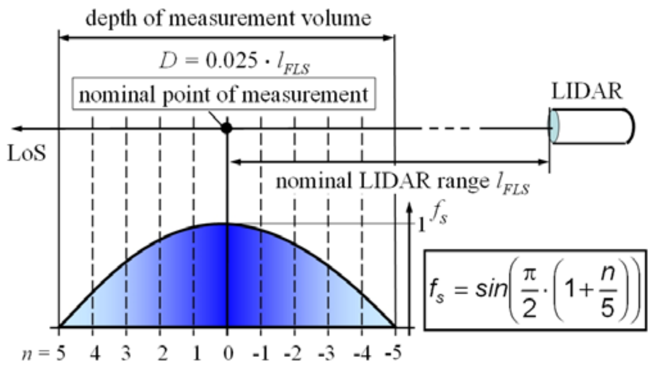


Figure 3. Sinusoidal shaping function for measurement points of a LIDAR measurement volume along the LoS in the vicinity of the nominal LIDAR range

By means of the above introduced simulation system, the wake encounter flight control assistance scheme described in section II was investigated. Today's standard transport type aircraft are not equipped with DLC flaps and hence the basic version of the control system was initially designed to use only aileron and rudder to reject the vortex induced air loads.

B. Ideal Disturbance Information

First of all it was assumed that the measurement of the flow field provides the full and correct velocity vector at any measurement point of interest. The results of these simulations are shown in Fig. 4. The nominal reference flight path (green dashed-dotted line) in the vertical plane (glide slope) is inclined with $3deg$ which represents a typical landing approach situation on a standard ILS beam. The lateral position of the nominal flight path in the horizontal plane (localizer) is in the geodetic co-ordinate system $y_g = 0m$. The wake of the generating aircraft is assumed to be $y_g = -30m$ the off the center line, the respective wake vortex lines are aligned horizontally in parallel with the vertical plane of the localizer signal at an altitude of $H = 1km$. Thus, the right wing tip vortex line (black dashed line) is at a lateral distance of about $y_g = -6.3m$ of the nominal flight, the left wing tip vortex line is at a lateral distance of about $y_g = -53.7m$ (out of the diagram). This represents a situation where the aircraft is passing the wake on its right.

The blue curves in Fig. 4 illustrate the flight with an autopilot trying to keep the aircraft on the ILS. The autopilot cannot prevent high bank angles Φ and large lateral deviations Δy_g from the reference flight path. The approach situation when the autopilot is supported by the feed-forward wake vortex controller is given by the red curves and the flight path deviations and bank angle excursions are reduced considerably. With respect to the results it can be stated that the wake vortex controller works properly if the flow disturbance is known correctly.

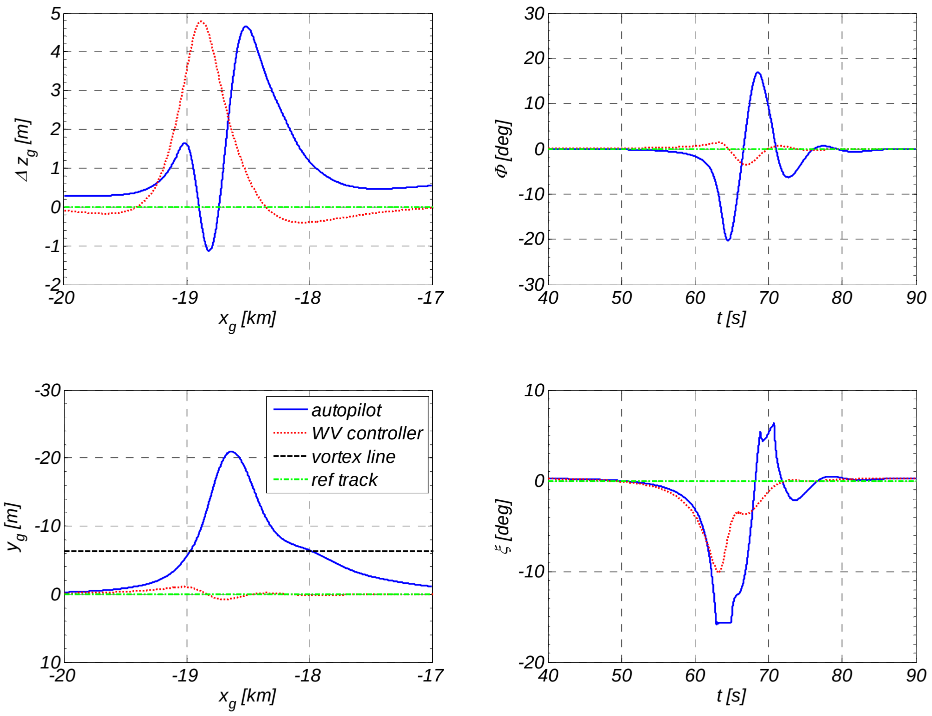


Figure 4. Flight track and time histories of a flight through wake vortex flow field (offline simulation with autopilot exclusively and autopilot supported by wake vortex controller)

C. Disturbance Information from Line of Sight Measurement

Due to the physical principle of a LIDAR sensor it is only possible to get measurement information in the line LoS direction of the laser beam. Velocities perpendicular to the laser beam cannot be detected. Since a vortex flow field in general presents a concentric radial flow around its vortex line the angle between laser beam and wake vortex lines is very important for the measurement. The smaller this measurement angle the less the content of information about the flow field to be probed can be provided by the LIDAR signal. Fig. 5 illustrates the comparison of ideal (black curve) and LoS (red curve) measurements in terms of lateral v_{WV} and vertical w_{WV} velocities. The corresponding vortex flow field is that one already specified in section previous. The angle in the horizontal plane between the LASER beam and the vortex lines for the selected measurement spot is about $\Delta\Psi_{WVL}$ = 7.5*deg*. The fixed elevation angle between the aircraft's longitudinal axis and the LIDAR beam is $\Delta\varepsilon_{WVL}$ = -4.5*deg* (downwards). This angle is chosen to have the LIDAR looking roughly into the direction of the flight path vector. The figure makes clear that the loss in flow field information can become considerable.

Accordingly, this unsatisfactory result leads to a significant loss of control efficiency compared to the case when ideal disturbance information is available. Fig. 6 demonstrates the consequences. Again the encounter simulations are performed for the scenario corresponding to the one described in section III. Due to the fact that the angle between LASER beam and vortex lines is small, the unprocessed LIDAR signal does only contain marginal flow field information. As a consequence, the controlled and the uncontrolled (=autopilot only) results are almost identical. The role of the correct and precise determination of the flow disturbance from forward looking measurement is obvious. Consequently, the development of a suitable post-processing procedure for the LoS signals is mandatory for the successful application of the resulting data in a flight control system.

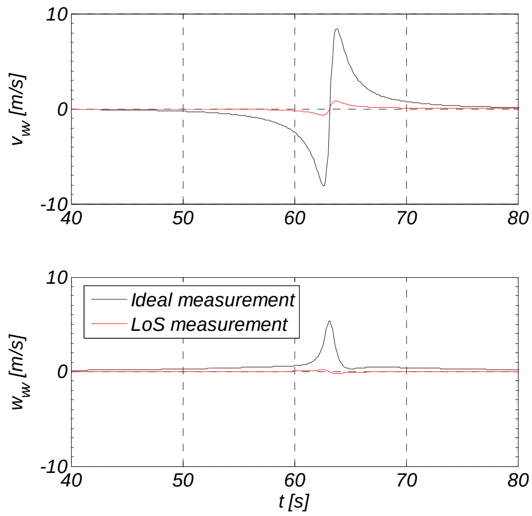


Figure 5. Ideal disturbance knowledge compared to in Line of Sight (LoS) measurement

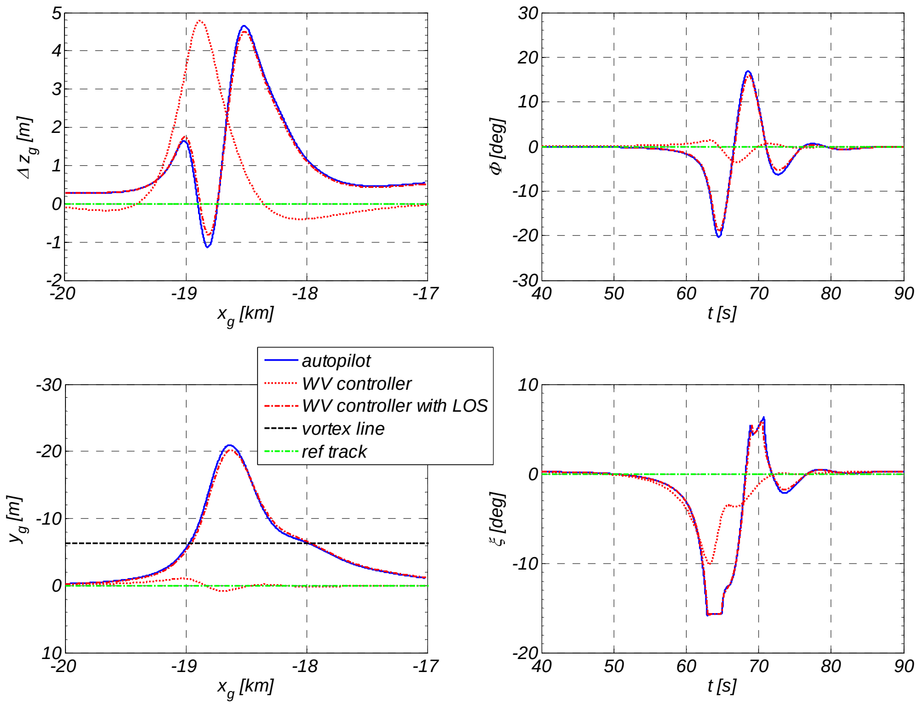


Figure 6. Flight track and time histories of a flight through wake vortex flow field (offline simulation with autopilot exclusively and autopilot supported by wake vortex controller and with and without line of sight effect of LIDAR)

IV. Disturbance Processing Using Forward Looking Sensor

The LoS measurement quality is very dependent on the wake vortex encounter and measurement scenario. At small encounter angles the LoS measurements would detect only small parts or even nothing of the wake vortex velocities. A post-processing of the LoS measurements is indispensable before using it, e.g., in a feed-forward disturbance compensation controller.

A. Concept for Processing LoS Measurements

In the following a processing concept is introduced which is capable to reconstruct the vortex strength, its position and orientation in the geodetic reference frame in high quality. The outcome of the presented approach is an excellent approximation of the true flow field velocities in any resolution. An important element of the concept is the fact that not only a single LoS snapshot (in Fig. 7 with 15 LoS measurement directions) will be interpreted but also the *time history* of all these measurements.

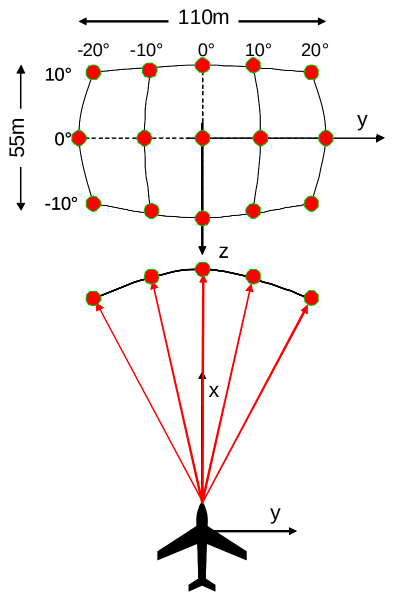


Figure 7. Forward looking sensor onboard implementation with 15 measurement directions

The overall concept is shown in Fig. 8. The idea is to fuse the information of the LoS measurements with that of a wake predictor. The wake predictor gives a first rough guess of the potential wake position, strength and orientation and is based on available information from other aircraft in the area of interest. A minimum requirement for data transfer from these aircraft is their actual aircraft mass, position and flight path. Both information, LoS measurements and the wake predictor's first guess are then used as inputs into an Online-Identification (O-ID) algorithm, which determines the precise wake strength and the wake position and orientation. The O-ID is based on algorithms developed for offline wake determination with flow measurements from 5-hole-probes.[18] The respective data were recorded during the passage the flow field of interest. In the present case, the algorithms are modified in order to apply them for on-line computations with forward looking LoS measurements. The outcome is a precise representation of the flow field in front of the aircraft before getting into contact with any wake turbulences.

The O-ID determines the parameters of an analytical wake model iteratively by minimizing the differences between measured and reconstructed LoS-measurements[19]. This is done by using the time histories of all available measurement directions (15 in Fig. 7) within a suitable, distinct time window. Ideally, the time window is permanently scrolled and updated every time after a new measurement snapshot vector is available. The O-ID algorithm works iteratively and should converge within the update rate, e.g. within 0.1*s*. A typical time window under consideration is 10*s*. The analytical vortex model by *Burnham-Hallock*[17] was found to be very adequate for online application. The model describes the radial velocity distribution V_t within a vortex with only two parameters: circulation Γ and core radius r_c:

$$V_t(r) = \frac{\Gamma}{2\pi} \frac{r}{r_c^2 + r^2} . \tag{1}$$

A wake is described with two superposed vortices counter rotating with the same strength. As the vortex core radius is relatively constant during wake aging, it was found sufficient to apply a constant value of 4% wing span.[18] This is also used here for online application. Thus, a total of only seven parameters is necessary to describe a wake flow field in front of an aircraft, and all can be identified during the O-ID: (1) vortex circulation, (2-5) lateral and vertical position of left and right vortex in the wake system, and (6-7) wake orientation in the geodetic reference frame (elevation, azimuth). The algorithm based on an analytical wake model can be applied for wake ages a few wing spans after generation (wake rollup complete) and prior to strong wake deformation.[18]

The O-ID algorithm (Fig. 8) uses a parametric LIDAR sensor model, which covers main sensor features like pulse frequency, update rate, measurement geometry, resolution and accuracy. The sensor model computes the position vector $\underline{X}_G$ in the geodetic reference frame covering all measurement directions. These positions are transformed into the wake system $\underline{X}_{WV}$, and, applying the analytical wake model, the wake velocities $\underline{V}_{WV}$ at each measurement position are computed. These velocities are then transferred back into the geodetic reference frame $\underline{V}_G$, followed by a transformation into the LoS system $\underline{V}_{LOS}$. Only the components in LoS measurement direction are then compared to the measured ones ("comparator"). A cost function is evaluated and an optimizer tries to minimize any differences between the measured and reconstructed LoS velocities by tuning the seven model parameters. Note: not a snapshot is fed into the optimisation but a distinct evaluation time window. After convergence the fully reconstructed wake vector in the geodetic frame $\underline{V}_G$ is available for use, e.g., in a feed-forward disturbance compensation. As the algorithm is iterative, a robust and fast convergence is essential. This is supported by a minimum number of model parameters (7) and by suitable a-priori values from the wake predictor. The convergence should be achieved ideally before a new measurement vector is available (e.g. 0.1*s*).

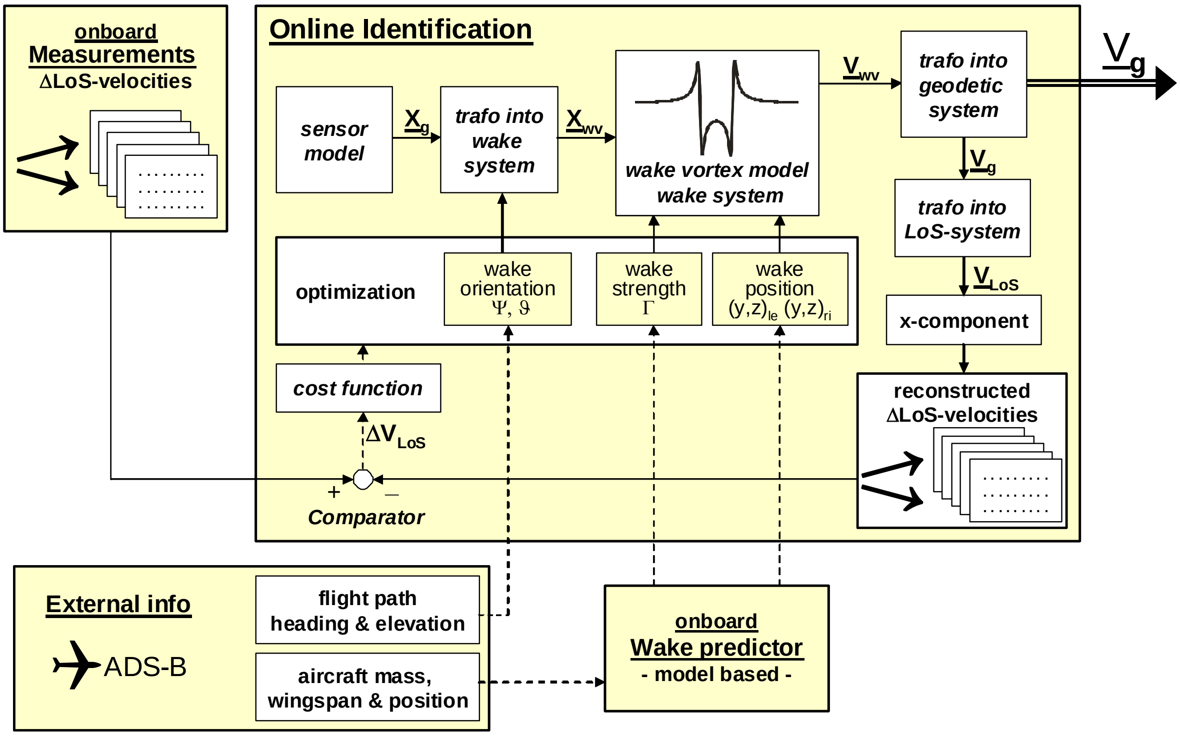


Figure 8. Concept for determination of wake vortex strength, position and orientation from Line of Sight measurements (patent pending)

B. Verification of Processing Concept

For verification, the concept is applied to the following simulated scenario: a wake is detected by the onboard LIDAR 150*m* ahead of the potential encounter aircraft, which is in typical approach speed and altitude. The wake orientation has an azimuth angle of $\Delta\Psi_{WVL} = 30deg$ and an elevation angle of $\Delta\varepsilon_{WVL} = 0deg$ relative to the encounter aircraft. The assumed LIDAR is specified by: 10*Hz* update rate for full vector, accuracy 3% (=4.5*m*) in measurement direction, four LoS directions (-20*deg* /-10*deg*, 20*deg* /-10*deg*, -20*deg* /10*deg*, 20*deg* /10*deg*) and measurement noise with a standard deviation $\sigma = 1m/s$. This example with only four measurement directions (spreading an area of 55*m* × 110*m* in front of the aircraft) is considered as a minimum requirement to provide the algorithm with the necessary information.

The O-ID algorithm is fed with 100 snapshot measurements (10*s* time window, 10*Hz* update rate). The initial values for the model parameters circulation, position and orientation are provided by a wake predictor, and are assumed to be inaccurate: wake strength 50% too small, vortex altitude error 10*m*, orientation error 5*deg*, lateral distance between left and right vortex 50% too small. Fig. 9 on the left side shows the simulation output using these predictor values, namely all four reconstructed LoS velocities $\underline{V}_{LoS}$ compared to the corresponding "measured" ones (note: the maximum measured velocities are 9*m/s*, which is only 36% of the maximum true velocity in the wake of 25*m/s*). Considerable deficiencies are visible between the curves indicating that the predictor values are more or less inaccurate. Now the O-ID is applied, trying to minimize the differences between the corresponding curves. Convergence fit is achieved after seven iterations, the remaining differences are mainly due to measurement noise. The wake strength is identified to 93% of the true value, the wake orientation error is < $0.1 deg$, the lateral distance error (left/right vortex) < $0.2 m$, and the altitude position error is < $1 m$. The achieved accuracy is considered to be suitable as input for a feed forward disturbance compensation.

Feeding more information into the algorithm the wake determination accuracy can be further enhanced. Using data of 15 measurement directions, as in Fig. 7, the wake strength is determined to 96% of the true value, position and orientation are identified nearly exact. However, nine algorithm iterations and more evaluation time are now necessary for convergence. Thus, the number of measurement directions should be a good compromise between geometrical resolution and algorithm convergence. Optional, an information finder selects only those measurement directions with most information in an a-priori step before starting the O-ID algorithm.

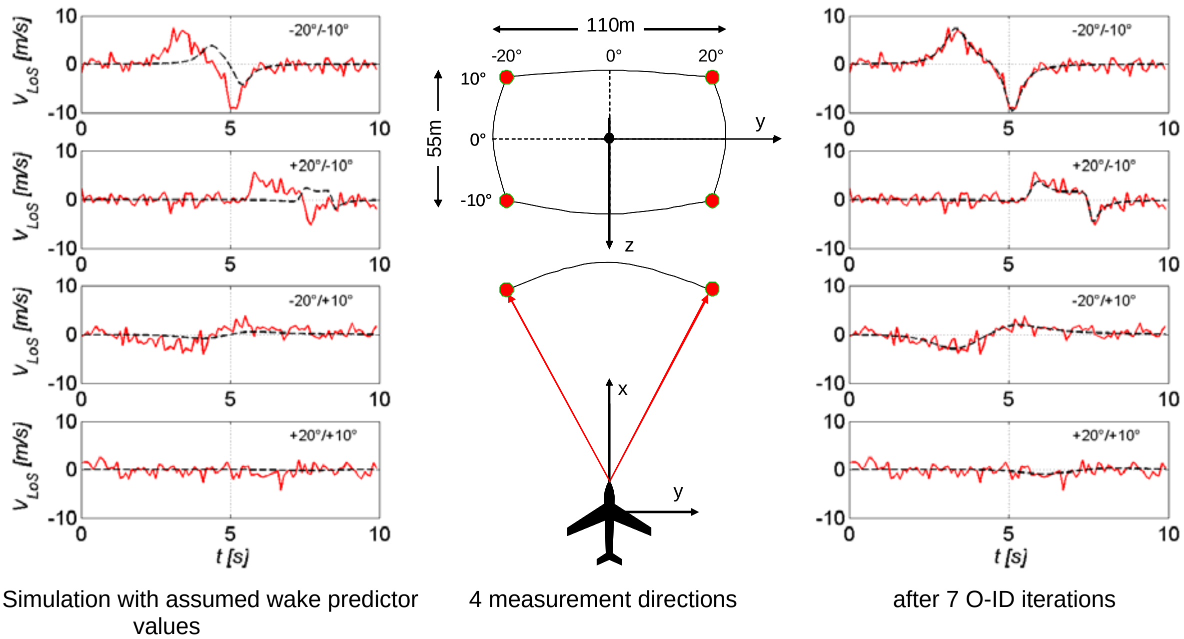


Figure 9. LoS "measurements" (——) compared to reconstructed LoS time histories (------)

V. Concept Validation Using Off-line Simulation

For the validation of the above described disturbance processing concept the same offline simulations were performed using the simulation system encounter scenario as described in section III. With this concept the full disturbance velocity vector can be computed at each selected measurement point in front of the aircraft. Fig. 10 shows encounters with active autopilot in combination with the wake vortex controller but using ideal and processed disturbance measurement information. The red curves present the result for the case of ideal knowledge of the flow disturbance. The blue curves illustrate the encounter situation with the O-ID processed LoS measured LIDAR data. For both cases the aircraft response is very similar and confirms the improved behavior. Thus, it can be stated that the presented wake vortex alleviation control concept, together with the O-ID processing of the LoS measurement, performs as desired.

VI. Flight Test Results

The feasibility of the feed-forward control concept was shown in the preceding sections using offline simulations. However, the acceptance of such an assistance system by the pilots is crucial, because the system uses a significant part of the control authority in order to compensate the wake vortex effects. Several flight test sessions have been conducted to rate different wake vortex encounters without and with the pilot assistance system in order to evaluate the benefit of such a system from a subjective point of view. In former flight test sessions it could be shown that the application of the automatic assistance system was rated good by the pilots[14]. However, in those flight tests ideal disturbance measurements were assumed and no airframe fixed staring direction of the LIDAR sensor was considered. Further more, no time delay and dynamics of the actuators were considered. All these effects have been accounted for in the updated flight tests described in this paper.

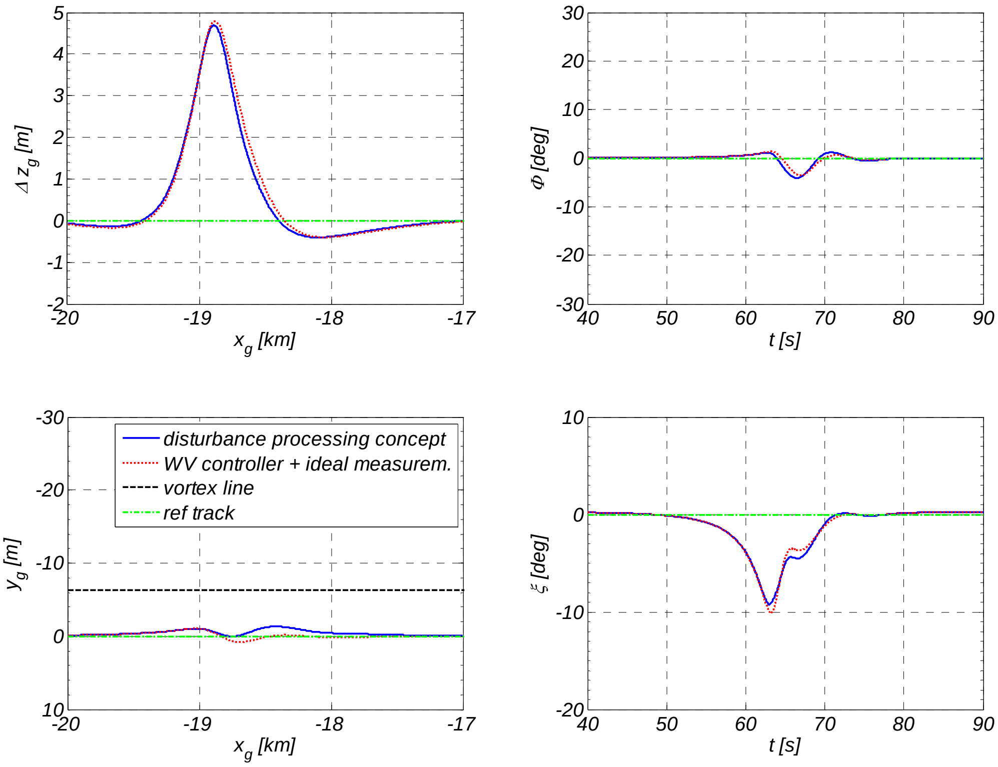


Figure 10. Flight track and time histories of a flight through wake vortex flow field (offline simulation with autopilot supported by wake vortex controller and with and without line of sight effect of LIDAR)

A. In-Flight Simulation Concept

The flight tests were conduced by using the in-flight simulation capabilities of the DLR testing aircraft ATTAS (Advanced Technologies Testing System), which is a modified VFW 614. The set-up of the in-flight simulation (IFS), as used for the pilot evaluation experiments is presented in Fig. 11.

By using nonlinear model-following control the aircraft acts like the simulated aircraft model encountering a wake vortex. As the pilots are experienced with the VFW 614 ATTAS, the simulated model corresponds to the same aircraft type. The experimental pilot is flying the simulated aircraft using real controls, which are fed into the onboard computers simulating the aircraft model which directly reacts to these and to the effects of the virtual wake vortex flow. The resulting model outputs are then fed as command values to the nonlinear model-following controller, generating the required control surface deflections of the real aircraft in order to match the dynamic behavior of the simulated one. The experimental pilot then experiences the simulated aircraft dynamics, as long as the output variables of the simulated aircraft are well matched.

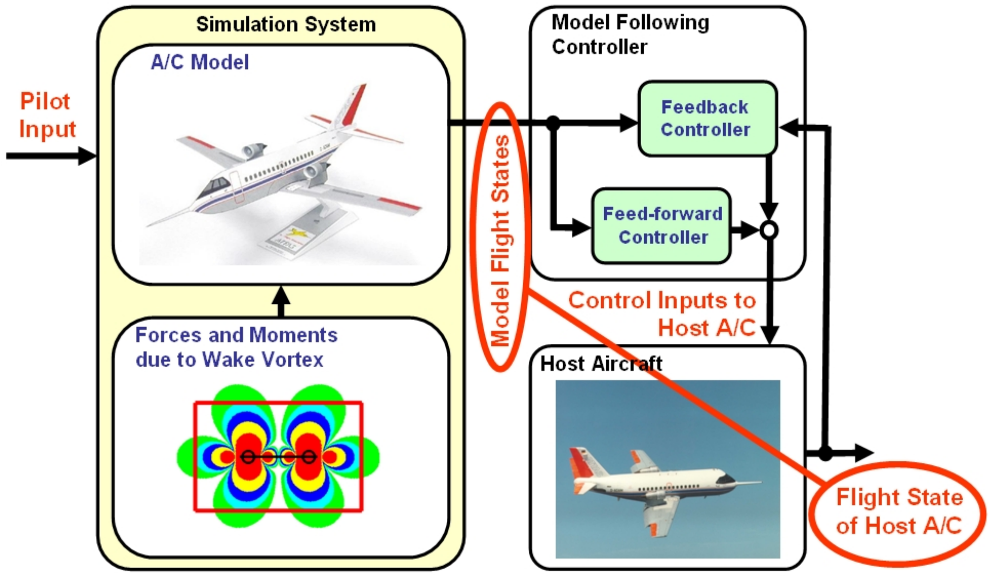


Figure 11. In-flight simulation concept

B. Flight Test Set-up

The flight test scenario is chosen similar to the simulation scenario. The encountering aircraft type is a VFW 614 with a MTOW of 21*t* (ICAO class 'medium'). The vortex generating aircraft is a category "heavy" aircraft (MTOW = 190*t*) with a separation distance of 4*nm*. The experiment scenario consists of an ILS-approach with an inclination angle of γ_{GLS} = -3*deg* beginning 6*nm* before runway threshold and a go-around after flare initialization (Fig. 12). For the ILS approaches two different airports were chosen. The initial altitude was at 2000*ft* MSL corresponding to 1700*ft* or 1900*ft* AGL, respectively. The experimental pilot had to intercept the glide slope and maintain the nominal glide path. The flaps were already set to landing configuration, whereas the landing gear deflection was commanded by the pilot at an unspecified altitude. The wake vortex encounters were initiated between 600*ft* to 1100*ft* AGL during the descent. The pilots were not informed about the encounter altitude in order to consider the element of surprise.

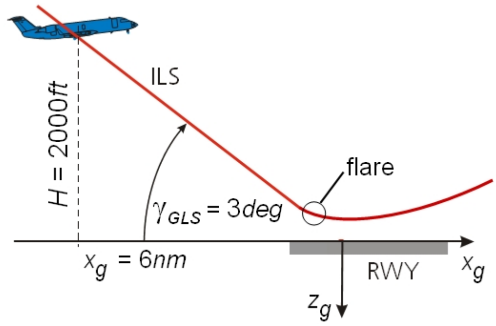


Figure 12. Approach scenario (side view)

Two professional pilots experienced in performing wake vortex encounters simulated in flight, participated in the experiments.

The additional forces and moments resulting from the wake vortex encounter were recorded in offline simulations. Thereby it was assumed that the aircraft moves with a fixed flight path, leading the aircraft either along the upper, the lower or the lateral parts of the wake vortex wind field. The horizontal encounter angles were slightly altered but of course were kept small to be close to a parallel like encounter. The recorded forces and moments were then replayed during the flight after the crossing of the initiation altitude above ground which was varied for each encounter. This type of encounter model is often referred to as time-fixed encounter.

The wind field of the wake vortices was calculated either by using the *Burnham-Hallock*[17] model or by data sets of wake vortex flow fields coming from Large-Eddy-Simulations[20]. The maximum required roll control ratio resulting from the wake vortex disturbances corresponded 0.8[14].

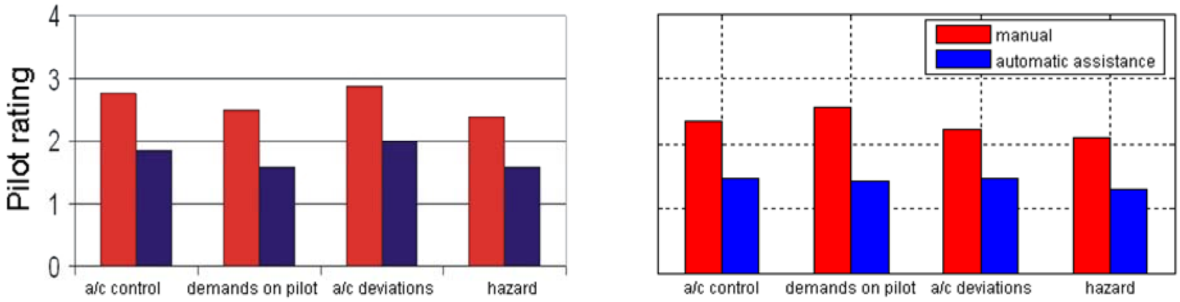
The sensor model used for the flight tests is consistent with the model described in section III.B. Additionally to the wake vortex forces and moments acting on the aircraft, the forces and moments resulting from the wind field as "measured" by the LIDAR model (i.e. considering the airframe fixed staring measurement direction and the lead time of the sensor information) are recorded, too. During the simulated encounter these recorded forces and moments are then fed to the automatic assistance system in order to compute the required control deflections.

C. Pilot Rating Scale

The pilot rating of each vortex encounter was performed by means of the wake vortex encounter rating scale.[14,21,22] The ratings for each approach comprise four categories: aircraft control, demands on the pilot, aircraft deviations from flight state and flight path, and hazard. Each category is graduated into four levels, with a rating of 1 denoting an uncritical case and a 4 denoting an unacceptable one. Ratings of 1-3 are considered acceptable. A rating of 4 in any category leads to an unacceptable overall rating for the respective wake vortex encounter. In case of a go-around decision, the "aircraft deviations" category has to be rated with 4, whereas the rating in "hazard" category does not necessarily need to be unacceptable, i.e. a go-around is not necessarily hazardous. The rating was performed immediately after each encounter.

D. Evaluation Results

Fig. 13 shows the effect of the pilot assistance system on the average pilot ratings. The results of former experiments based on 20 piloted approaches are given in Fig. 13 a) presenting the clear tendency of improved ratings when the assistance system is engaged.[13,23] According to these results the same trend is clearly confirmed for the more realistic updated IFS modeling of the continuing investigations as illustrated in Fig. 13 b). Again the automatic assistance system gets better ratings than the unassisted encounters. When more real effects of the whole process chain are considered, the ratings are even slightly better than in Fig. 13a). The reason for this was identified to be the exact synchronization of the control commands (considering computation delays and actuator dynamics). However, the results of this flight experiment are only based on 16 approaches (nine without and seven with automatic assistance).



a) ideal disturbance measurement [13,23] **b) realistic disturbance measurement**

Figure 13. Average pilot ratings for IFS wake vortex encounters

In addition to the control of the wake vortex induced moments by aileron, rudder and elevator the application of direct lift control (see section II) leads to supplementary improvement of the aircraft's vertical motion.[15] Fig. 14 shows the pilot ratings coming from the latest IFS experiments for the IRLIS concept indicating a further progress in automated pilot assistance with additional use of DLC surfaces. The in-flight simulated encounters were flown by two different pilots (pilot A: eight encounters, pilot B: seven encounters) and took place at altitudes between 700*ft* and 1100*ft* AGL. Five different wake vortices were applied for each of the three control concepts. The azimuth angles of the encounter $\Delta\Psi_{WVL}$ were in the range between 5*deg* to 30*deg*. The real turbulence during these flight experiments was considered to be light to moderate. Unfortunately, due to flight time restrictions, the number of encounter trials is only small. But the pilots perception of the response improvement of the aircraft is evident. Applying IRLIS results in an aircraft response during wake vortex encounter which is nearly not affected by this phenomenon (ratings close to 1).

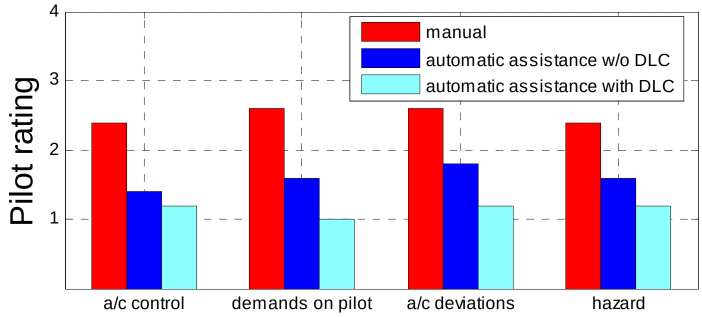


Figure 14. Average pilot ratings for IFS wake vortex encounters with IRLIS

VII. Summary and Conclusion

In all phases of flight the flow fields of wake vortices can strongly affect the passenger comfort and the safety when encountered by aircraft, hence, such encounters are to be avoided in any case. In case of an unintended wake vortex encounter active control technology can be applied to alleviate these flow disturbance effects on aircraft motion. A control system to cope with this phenomenon and to act as a safety net was developed. It can be shown that the aircraft response encountering wake vortex turbulence can be improved significantly. The controller is based on a feed-forward disturbance compensation concept which has the advantage that the automatic controller system does not change the aircraft handling. For the application of this control strategy it is necessary to determine the disturbance before it affects the aircraft to initiate counter measures in time. The disturbance can be computed from forward-looking sensor measurements. Due to the fact that a LIDAR is only able to measure in the line of sight direction, procedures are necessary to generate the required flow disturbance information from insufficient measurement signals.

It is shown that new post-processing procedures based on advanced online parameter identification algorithms can fulfill this task. Using this processed information the controller generates control surface deflections to counteract the roll response induced by lift variations along the wing span. In addition to the standard control surfaces (elevator, aileron and rudder) it is of great benefit if the aircraft is equipped with special flaps for independent direct lift control, as it is proposed for the Integrated Ride and Loads Improvement System (IRLIS). The proposed control system has been tested by means of simulation investigations as well as by flight experiments with simulated wake encounters. It can be shown that the aircraft response is improved significantly if the pilots are supported by active control technology based on the presented concept. This increases safety since more severe encounter situations can be coped with.

For the subjective assessment of the wake vortex encounters a dedicated pilot rating scale was used. By means of in-flight simulation, flight experiments were executed using DLR's flying test bed VFW614/ATTAS and the whole concept was demonstrated and assessed by pilots. A specific rating scale was used to collect the pilot assessments after each accomplished vortex encounter. The results show a clear tendency that the pilot assistance system improves the situation considerably. Within the frame of this project IRLIS will be further extended and completed to be able to cope with the whole frequency range of atmospheric flow disturbances relevant for aircraft operation, e.g. a thrust controller will be developed and introduced to provide the capability of coping with low frequency atmospheric motions like wind shear.

Acknowledgments

Most of the presented results have been achieved by DLR internal projects funded by DLR's Aeronautics Program Directorate. Numerous colleagues from different Institutes and from the Flight Experiment Department contributed to this work. The authors would like to thank everybody who contributed to the success of this work.

References

[1] Hahn, K.-U., "Effect of Wind Shear on Flight Safety," *Progress in Aerospace Sciences*, Vol. 26, no. 3, pp. 225-259, 1989.

[2] Etkin, B., "Turbulent Wind and Its Effect on Flight," *Journal of Aircraft*, Vol. 18, no. 5, pp. 327-345, 1981.

[3] International Civil Aviation Organization, "Rules of the Air and Traffic Services", ICAO Doc 4444-RAC/501 13th Edition, 1996.

[4] "ASRS – Aviation Safety Reporting System", National Aeronautics and Space Administration – NASA, URL: http://asrs.arc.nasa.gov and http://akama.arc.nasa.gov/ASRSDBOnline/QueryWizard_Filter.aspx [cited 7 May 2010].

[5] Barber, M.R. and Tymczyszyn, J.J., "Wake Vortex Attenuation Flight Tests: A Status Report," *1980 Aircraft Safety and Operating Problems*, NASA CP-2170, pp. 387-408, 1981.

[6] Voss, G., Gerz, T., Baumann, R., Stumpf E. and Press, M., "Wake Vortex Alleviation by Differential and Oscillating Flap Setting: A Flight Test," *Proceedings of the 27th AIAA Applied Aerodynamics Conference*, San Antonio, Texas, June 2009.

[7] Crouch, J.D., Miller, G.D. and Spalart, P.R., "Active-Control System for Breakup of Airplane Trailing Vortices," *AIAA Journal*, Vol. 39, no. 12, pp 2374-2381, 2001.

[8] Stumpf, E., Hahn, K.-U., Liersch, C., Preß, M., de Groot, K., Capart, R., Jaquin, L. and Wever, R., "ATTAS Smoke Try Out Test," AWIATOR Technical Report TR 1.1.3-3, 2004.

[9] Holzäpfel, F., Gerz, T., Frech, M., Tafferner, A., Köpp, F., Smalikho, I., Rahm, S., Hahn, K.-U. and Schwarz, C., "The wake vortex prediction and monitoring system WSVBS Part I: Design", *Air Traffic Control Quarterly*, Vol. 17, no. 4, 2009, pp. 301-322.

[10] Hahn, K.-U., "Coping with Wake Vortex," *23rd Congress of the International Council of the Aeronautical Sciences,* Toronto, Canada, Sept. 2002.

[11] EUROCONTOL, "Challenges to Growth 2004 Report (CTG04)", European Organization for the Safety of Air Navigation, Edition Number 1.0, EATMP Infocentre Reference 041109-01, Brussels, Dec. 2004.

[12] "Wake Turbulence: An Obstacle to Increased Air Traffic Capacity", Committee to Conduct an Independent Assessment of the Nation's Wake Turbulence Research and Development Program, National Research Council, ISBN: 0-309-11380-6, URL: http://www.nap.edu/catalog/12044.html [cited 10 June 2010].

[13] Schwarz, C. and Hahn K.-U., "Automated Pilot Assistance for Wake Vortex Encounter," *Deutscher Luft- und Raumfahrtkongress 2007, First CEAS European Air and Space Conference*, Berlin, June 2007.

[14] Schwarz, C.W., Hahn, K.-U. and Fischenberg D., "Wake encounter severity assessment based on validated aerodynamic interaction models," *AFM/ASE/GNC/NST Conference*, Toronto, Ontario, Aug. 2010.

[15] Hahn, K.-U. and Schwarz, C.W., "Alleviation of Atmospheric Flow Disturbance Effects on Aircraft Response," *26th Congress of the International Council of the Aeronautical Sciences*, Anchorage, Sept. 2008.

[16] Fock, H., Hahn, K.-U. and Schwarz, C.W., "Verwendung von vorausschauenden Strömungssensoren in Pilotenassistenzsystemen für den Wirbelschleppeneinflug (Application of forward looking flow sensors for pilot assistance systems for wake vortex encounters)," DLR report IB 111-2006/12, Deutsches Zentrum für Luft- und Raumfahrt, Braunschweig, Germany, March 2006.

[17] Burnham, D.C. and Hallock, J.N., "Chicago Monoacoustic Vortex Sensing System," Vol. 4, Wake Vortex Decay, Springfield, VA, National Information Service, 1982.

[18] Fischenberg, D., "Bestimmung der Wirbelschleppen-Charakteristik aus Flugmessdaten (in English: Determination of Wake Vortex Characteristics from Flight Test Data)," *Deutscher Luft- und Raumfahrtkongress,* Stuttgart, Germany, September 2002.

[19] Jategaonkar, R.V., "Flight Vehicle System Identification: A Time Domain Methodology," *Progress in Astronautics and Aeronautics Series*, Vol. 216 Published by AIAA, Reston, VA, 2006.

[20] Hennemann, U., "Deformation und Zerfall von Flugzeugwirbelschleppen in turbulenter und stabil geschichteter Atmosphäre," PhD Thesis, Technische Universität München, 2009

[21] Hahn, K.-U., Schwarz, C. and Friehmelt, H., "A Simplified Hazard Area Prediction (SHAPe) Model for Wake Vortex Encounter Avoidance", *24th International Congress of Aeronautical Sciences (ICAS)*, Yokohama, Japan, Aug./ Sept. 2004.

[22] Vechtel, D., and Amelsberg, S., "Full Flight Simulator Study for Evaluation of Aircraft Dynamics While Encountering Curved Wake Vortices," Institute Report IB 111-2009/17, DLR Institute of Flight Systems, Braunschweig, Germany, July 2009.

[23] Hahn, K.-U. and Schwarz, C., "Safe Limits for Wake Vortex Penetration," *AIAA Guidance, Navigation and Control Conference and Exhibit*, Hilton Head, South Carolina, Aug. 2007.