A METHOD TO VALIDATE WAKE VORTEX ENCOUNTER MODELS FROM FLIGHT TEST DATA

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Abstract

A method is presented for assessing the accuracy of aerodynamic wake encounter models (also named "aerodynamic interaction models"). The method uses real world data from in-situ measurements to produce the best possible fit of a given model structure. This process requires: (a) suitable encounter flight test data, (b) a high precision flight path reconstruction, (c) suitable parameters of an analytical vortex model, and (d) a high quality basic aerodynamic model. The vortex model parameters are identified in an a-priori step from the same wake encounter flight test data used for the subsequent validation of the aerodynamic interaction model. The accuracy assessment is done by analysing the errors between model outputs and the corresponding flight test data. The paper reflects the used incremental Strip Model structure and recommends appropriate a-priori data. Simulation results are analysed, and strip model extensions are implemented which imply a notable model quality improvement.

Nomenclature

AIM	aerodynamic interaction model
AoA, α	angle of attack
AoS, β	angle of sideslip
AR	aspect ratio
ax, ay, az	bodyfixed accelerations
$C_{L\alpha}$	lift slope
DoF	degree of freedom
EFCS	electronic flight control system
F	factor
FPR	flight path reconstruction
Λ	wing or tail sweep
LIDAR	light detection and ranging
MTOW	maximum takeoff weight
M	Mach number
p, q, r	rotational rates (roll, pitch, yaw)

1 Introduction

All aircraft with a lift producing wing generate wake vortices. This well known phenomenon can be dangerous for other aircraft. Vortices are generally not visible to pilots and may imply sudden and severe aircraft reactions, which can cause passenger injuries up to the total loss of an aircraft. Physically, a wake can be characterized by a counterrotating pair of two single vortices. The vortex strength mainly depends on aircraft weight, its wing span and airspeed. Consequently, heavy aircraft with high wing loadings flying at low air speeds produce strong wake vortices.

In particular during the approach and landing phases wake encounters happen more frequent due to the fact that there is an increased traffic density on the routes approaching a runway. To prevent encounters, separation rules were stated for safe airport operations [1]. The present rules have been proven to be applicable for daily use, but, as a matter of fact, limit the capacity of airports. As the presently applied rules are a relatively rough arrangement, there is a demand for regulation upgrade. A lot of research has been done during the last decade to establish safe operation limits for wake vortex penetration. Safe limits can be derived from wake vortex hazard assessments, e.g. [2]. Those assessments strongly depend on mathematical models formulating the wake characteristics and models describing the aircraft reaction generated by vortex flow fields [3]. So, there is a strong correlation between the validity of the models and the reliability of the encounter assessments.

Extensive work has been done in the past to derive analytical wake vortex models (e.g. [4]) and models for wake aging [5]. LIDAR measurements were mainly used for validation, in ground-based measurements [6] as well as in flight [7]. Wake encounter models, also named aerodynamic interaction models (AIM), are more difficult to validate. Real flight test data are necessary which are expensive and not easy to gather: at least two aircraft and the visualization of the vortices of the vortex generating aircraft are needed. In this paper, a method for the quality assessment of aerodynamic wake encounter models is presented. The method was developed and applied for the first time within the EU funded project S-WAKE [8]. Within this project the methodology was validated using high quality flight test data of more than 50 wake encounter [9]-[10]. The method was also used for wake determination from in-situ measurements of the Eurofighter wake encounter flight tests for EFCS validation [11].

Fig. 1 Wake vortices of interest:
(a) Airbus A380; (b) Eurofighter

Last but not least, the method was applied to validate the Airbus A318 and A320 wake encounter simulation models with flight test data to assess the wake vortex impact of the new Airbus A380 [12]-[13]. Recently, the method was refined in the DLR project “Wetter & Fliegen” for vortex strength determination and wake encounter model quality improvement. In the following the main results of these activities in the field of precise wake vortex encounter modelling will be presented.

2 Wake Encounter Flight Tests

As a basis, precise flight test data are essential for wake vortex encounter model validation. As explained in detail in the next chapter, the validation procedure is done in two parts: (a) wake determination including a flight path reconstruction and (b) the validation step, where the determined wake model parameter from (a) are used as an input.

The wake characteristics are identified from the measured test data. For this it is essential that the wake encountering aircraft gathers as much wake information as possible. This is ensured best for lateral wake crossing, where the pilot adjusts the flight path in that way both vortices are hit near their cores. As there are strong up- and downwinds in a wake, the encounter aircraft should not stay too long in the wake field, but on the other hand the period of data collection during the passage of the vortex flow should not be too short because of limited measurement information. A good compromise is a 2-4 sec duration which gives 200-400 samples of flow measurements at a 100 Hz rate. That is sufficient to cover the high velocity gradients near the vortex core and to identify the vortex core radius. The lateral encounter angle should be within 5°-20°.

Fig. 2 shows a typical test scenario. Wake visualization is important for appropriate vortex hits and can be done (a) with a smoke generator mounted on the wing, Fig. 3, (b) by oil injection into the engine exhaust, or, for flight tests in cruising altitude, (c) simply by the generator contrails, Fig. 4.

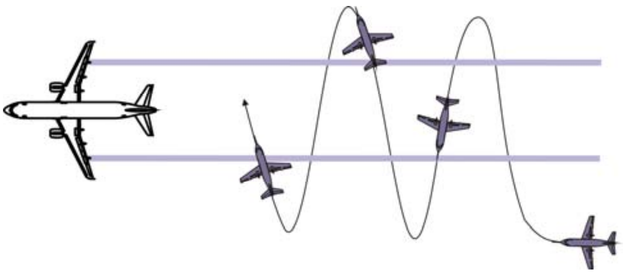

Fig. 2 Flight test scenario for wake determination and encounter model validation; in practice the lateral encounter angles are somewhat smaller (25° maximum)

Fig. 3 Wake visualisation by smoke in approach altitude

Fig. 4 Wake visualisation by contrails in cruising altitude

3 Flow Sensor Measurements

For wake identification, a high measurement quality of the available flow probe signals on the wake encountering aircraft is fundamental for the overall evaluation procedure. As a minimum requirement, one AoA-sensor and one AoS-sensor must be installed on the encounter aircraft for wake identification. The more flow sensors are available at different positions on the encounter aircraft, the better the information exploitation of the encountered wake will be [14], [16]. The measurement signals should be calibrated carefully and ideally be available at a sampling rate > 50 Hz. The calibration can be done with the FPR method and suitable flight test data, as documented in [15].

3.1 Measurements with Several 5-Hole-Probes on Booms

The ideal case: the test aircraft for in-situ wake vortex measurements is equipped with several 5-hole-probes mounted on booms. The booms ensure minimum influence of the fuselage and wing of the encountering aircraft on the wake velocity field. The 5-hole-probes also allow high frequency measurements that are free of any dynamic effects of the flow sensors as it is seen by vane measurements. Fig. 5 shows the Do128 (MTOW=4.3to; ICAO weight class LIGHT) of the Technical University of Braunschweig as a unique and excellent equipped test aircraft for onboard wind measurements: wind velocities are measured in all 3 axis (corresponds to an equivalent wind angle of attack and sideslip) with 100 Hz at four distinct positions: a/c nose, left and right outer wing and vertical tail [18].

Fig. 5 Do128 wake encounter aircraft of Technical University Braunschweig,
O= positions of flow probes

Typical Do128 measurements from an encounter into the wake of a MEDIUM class aircraft (MTOW=21to) are shown in Fig. 6, explicitly vertical and horizontal wake velocities at the four measurement positions. From those data, vortex strength, core radius, left and right vortex position and the geodetic wake orientation can be determined (see next chapter).

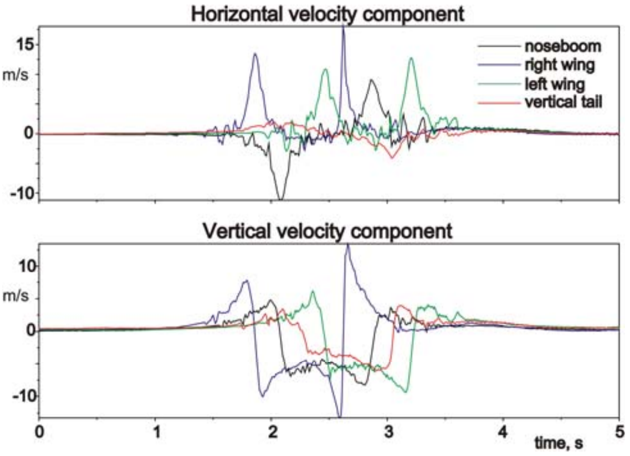

Fig. 6 High quality 100 Hz flow probe measurements of the Do128 aircraft during a lateral wake encounter

3.2 Measurements with Fuselage Vanes

Alternatively, aircraft equipped with one or two fuselage mounted angle of attack vanes and angle of sideslip sensor (besides inertial measurements) can also provide valuable wake encounter flight test data. Despite fuselage and wing influences on the measurements, it is possible to determine the overall wake characteristics like wake strength and vortices position from those test data. An example will be shown in chapter 4.

3.3 Calibration

Flow sensors have to be calibrated carefully. This can be done using suitable flight test data in undisturbed air which are evaluated with the FPR method [15]. Boom mounted flow sensors calibration can be done using linear approximations. Fuselage mounted vanes require more calibration effort, as they are influenced by the fuselage itself. In the linear region, a factor, a bias and a luff/lee influence in the AoA measurement can be found and calibrated.

$$\alpha_1 = F_1\,\alpha_{1,i} + \Delta\alpha_1 + F_{\alpha\beta}\,\beta_I \quad \text{(AoA left)}$$

$$\alpha_2 = F_2\,\alpha_{2,i} + \Delta\alpha_2 - F_{\alpha\beta}\,\beta_I \quad \text{(AoA right)}$$

$$\beta = F_\beta\,\beta_i + \Delta\beta \quad \text{(AoS)}$$

This calibration is quite accurate in undisturbed air and for typical rigid body frequencies, see example in Fig. 7 for a transport aircraft. In this case, vane dynamics was considered and also signal conditioning aspects (e.g. filtering).

It has to be pointed out that for wake turbulence measurements the flow at the fuselage vane positions suffer from unsteady und other effects like fuselage/wing interferences. Those effects are beyond the scope to be calibrated in a classical manner and have to be accepted when evaluating fuselage vane measured AoA/AoS.

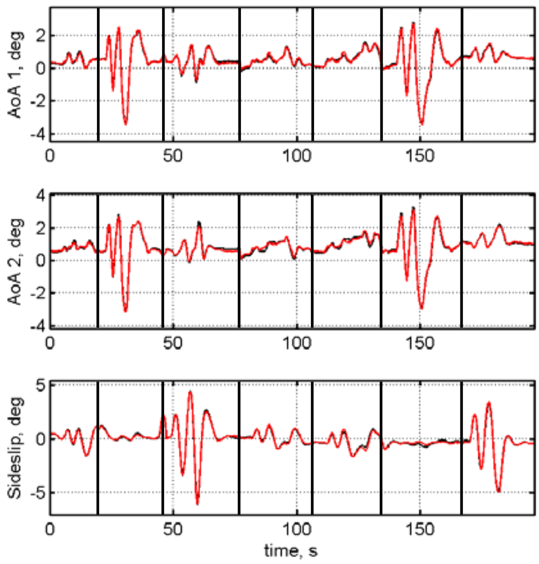

Fig. 7 Calibration results of AoA left/right and sideslip on a MEDIUM size transport aircraft in undisturbed air, model output (———); measured (———)

4 Wake Identification

Wake strength and position have to be known for wake encounter simulation and validation. For validation with flight test data, the wake model parameters are derived in an a-priori step from measurements. This step consists of a flight path reconstruction in the wake axis system and the identification of the parameter of an analytical wake vortex model, see Fig. 8 and [14], [16].

The inertial measurements (accelerations, rotational rates, Euler angles) of the encounter aircraft are used to reconstruct precisely the encounter aircraft flight path in the wake axis system. From this step, also the inertial flow angles α, β are obtained. They consider the aircraft's flow angles without any local flow. These inertial flow angles are reconstructed for all AoA/AoS measurement locations. The differences between these inertial local flow angles and the measured AoA/AoS during a lateral wake fly-through are clearly seen in Fig. 9. It is assumed that they are produced by the flow field of the encountered wake.

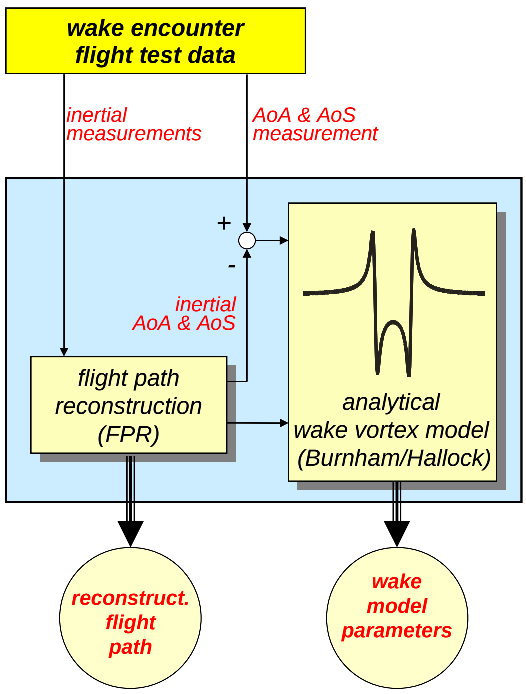

Fig. 8 Principle of wake identification and flight path reconstruction

Using parameter identification methods [15], these differences are minimized by tuning the parameters of an analytical vortex model. The model outputs $\Delta\alpha$ and $\Delta\beta$ are added to the reconstructed inertial flow angles. In the present evaluation, the analytical Burnham-Hallock vortex model [4] is used for flow field description. Model parameters are vortex strength (circulation), position in the wake axis system and wake orientation. The procedure as well as the discussion about the parameter quality is discussed in detail in [14], [16]. Results are shown in Fig. 10a (fuselage vane equipped encounter aircraft) and Fig. 10b (four boom mounted 5-hole probes equipped aircraft). Fig. 11 presents the identification result of the vortex positions relative to the encounter aircraft flight path for the example of a lateral wake fly-through where the core of the right vortex was hit.

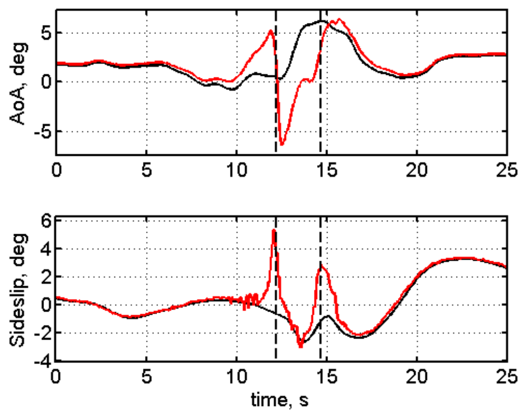

Fig. 9 Lateral wake fly-through: reconstructed inertial AoA/sideslip *without* local wake induced flow angles (———), flight test measured (———)

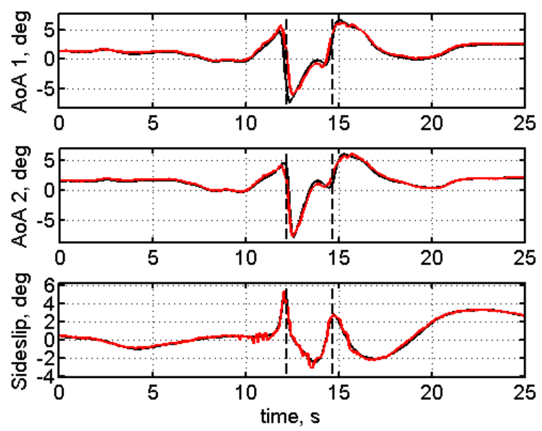

Fig.10a Lateral wake fly-through, fuselage vane equipped aircraft: reconstructed inertial + local wake induced AoA and sideslip (———), flight test measured (———)

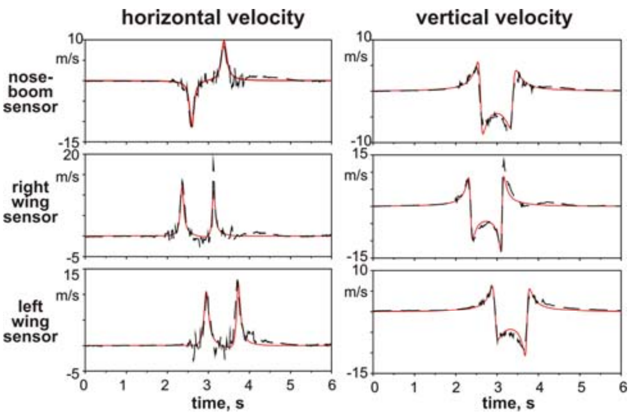

Fig.10b Lateral wake fly-through with high quality boom mounted 5-hole probes: wake model velocities (———), flight test measured (———)

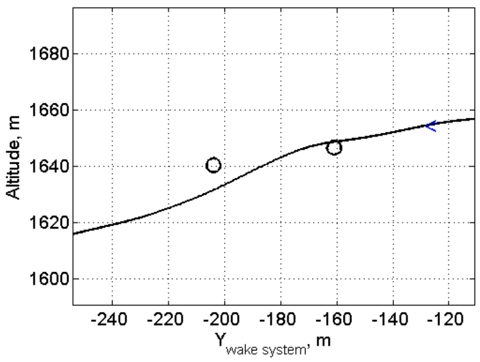

Fig.11 Lateral wake fly-through: reconstructed wake positions (**o**) and flight path in the wake axis y/z-plane (———)

5 Aircraft Basic Aerodynamic Model

For wake encounter simulation, forces and moments are computed in two non-dependent submodels: (a) the classical basic aerodynamic model, and (b) the *wake encounter model* (also named *aerodynamic interaction model AIM)*, which describes increments of forces and moments in a spatial wind field (Fig. 12).

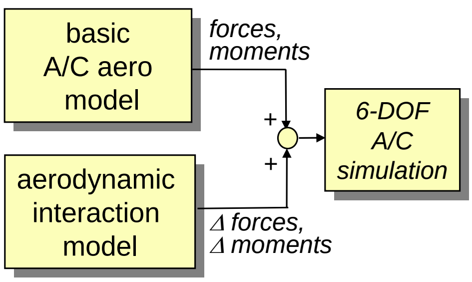

Fig.12 Forces and Moments from basic aero model and wake encounter model

For the validation of the wake encounter generated forces and moments, it must be ensured that model deficiencies are _not_ originating from the basic aero model. A high quality basic model is needed. This quality can only be achieved by tuning the model with parameter identification techniques using suitable flight test data that are recorded far away from any wake influence. In the flight tests the a/c eigen motions should be excited [15]: e.g. 3211 elevator inputs for short period excitation, elevator impulse for phygoid excitation, bank to bank manoeuvres (aileron inputs), rudder doublets (Dutch roll excitation). All manoeuvres should be repeated with different amplitudes. A working point model is sufficient, which is derived in the same velocity/altitude/thrust setting envelope point as chosen for the wake encounter tests.

6 Wake Encounter Model (Strip Method)

A popular and easy to use encounter model is the *Strip Model*. It is based on lifting line theory and describes the additional aerodynamic forces and moments acting on an aircraft in a spatial wind field, e.g. wake turbulence. The lift generating surfaces of an aircraft (wing, horizontal and vertical tail) are divided into strips, Fig. 13. A well proven number of strips in simulation is 16 (wing), 8 (horizontal tail) and 4 (vertical tail). At the 25% chord location of each strip the additional angles of attack (wing, horizontal tail) and angles of sideslip (vertical tail) due to the local wind/wake filed are computed. Using a suitable lift gradient, an additional lift is obtained for each strip. These local lift increments are weighted in span direction elliptically and then summarized. Additionally, the corresponding moments of all strips are computed and summarized. No drag effects are considered so far, so the present strip model describes wake effects in 5 degrees of freedom. More details are given in [9], [17].

The model is based on several a-priori data, which are depending on aircraft geometry and aerodynamics. The geometry of wing, horizontal and vertical tail and the lever arms for moment computation are generally well known from 3-D drawings. The aerodynamic derivatives (lift gradients for wing, horizontal and vertical tail, downwash gradient) may be known, if not, they can be estimated. The *Helmbold* equation, which considers the aspect ratio AR influence on lift gradients, leads to good a-priori values [17].

$$C_{L\alpha} = C_{L\alpha\infty} \frac{AR}{2+\sqrt{4+AR^2}}$$

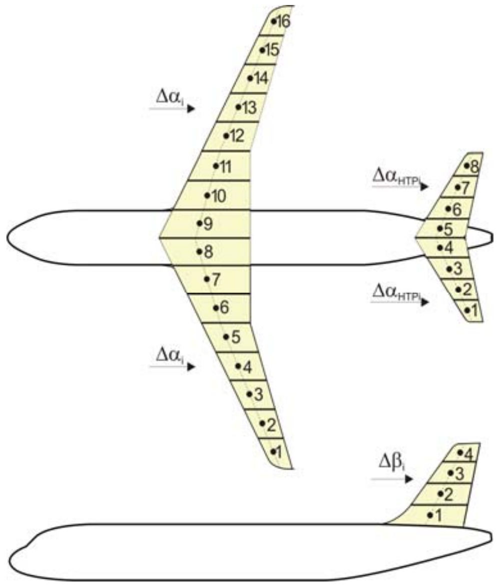

Fig.13: Strip model

The *Helmbold* equation is an approximation for high aspect ratio wings as well as low aspect ratio tails and a compromise between the *Prandtl* and *Barrows* formulation, see Fig. 14. The lift curve slope is also depending on wing sweep Λ, a simple approximation to account for this is given in [17].

$$C_{L\alpha} = C_{L\alpha\infty} \cos\Lambda$$

Mach dependency on the lift curve slope can be modelled acc. to *Prandtl-Glauert*.

$$C_{L\alpha} = C_{L\alpha,M=0} \frac{1}{\sqrt{1-M^2}}$$

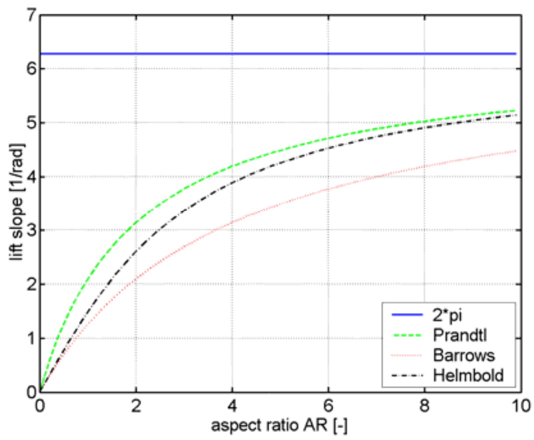

Fig.14 Different approximations for lift curve slope depending on aspect ratio AR

7 Validation

7.1 Method

The overall validation method is illustrated in Fig. 15. The *model* computes the sum of forces and moments of (a) the basic aerodynamic model and (b) the aerodynamic interaction model, which provides Δ-forces and -moments due to wake influence. The simulation is driven by the flight test measured control inputs (elevator, aileron, rudder etc.). The model outputs are compared to the corresponding measured flight test data, typically linear and rotational accelerations, rotational rates, altitude, and velocity.

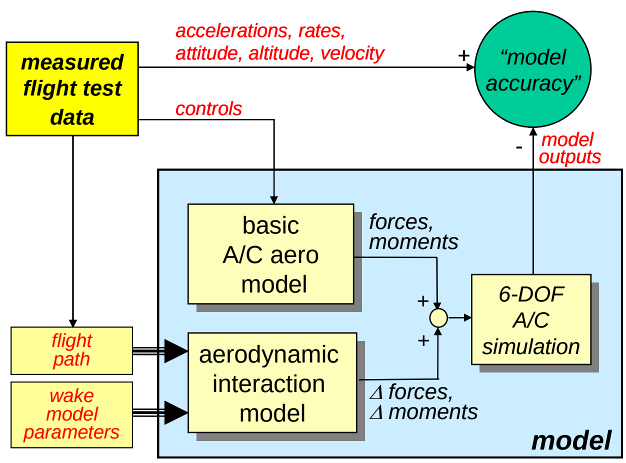

Fig.15 Method to validate wake encounter models from flight test data

Besides a high quality basic aerodynamic model, the exact knowledge of the wake model parameter (strength and position) for each encounter should be known. As already described above, these model parameters are determined in an a-priori step, using flight test measurements of the encounter aircraft to reconstruct precisely its flight path and inertial flow angles α, β. Secondly, the aerodynamic interaction model should be driven with the reconstructed flight path and Euler angles, which are also the outcome of the above mentioned a-priori step. This "driven mode" stabilizes the wake encounter simulation and proved to be essential, as wake induced forces and moments are very sensitive to small flight path inaccuracies.

The accuracy is assessed by computing the standard deviations of the error between model outputs and the corresponding flight test data and the maximum errors. Each degree of freedom is considered separately.

7.2 Wake Encounter Example

A typical validation example from a lateral fly-through flight test with Do128 aircraft (about 4t) into the wake of the VFW-614 aircraft (about 20t) is shown in Fig. 16, applying the method in Fig. 15. Typical model outputs (red lines) in all 6 DoF are compared to the corresponding flight test data (black lines).

Looking at each DoF separately and keeping in mind that this is a typical encounter out of more than 50 Do128 encounters, the model quality can be assessed as follows: the rolling motion (*roll rate p*) and the vertical motion (*vertical acceleration az*) during a wake fly through can be simulated in *high quality*. This can be considered to be an outstanding result for the strip model with its widely linear structure, applying the elaborate validation procedure including sensor calibration, wake identification and basic aerodynamic model inaccuracies. Both degrees of freedom (*p, az*) are the most important inputs into nowadays wake hazard assessment tools. The pitching motion (*pitch rate q*) is also simulated in good quality, despite some minor deficiencies at the beginning of the wake encounter. The lateral motion (*acceleration ay*) has some minor, but tolerable discrepancies. The longitudinal motion (*acceleration ax*) has discrepancies as no drag effects are modelled since this degree of freedom is considered to be not very important.

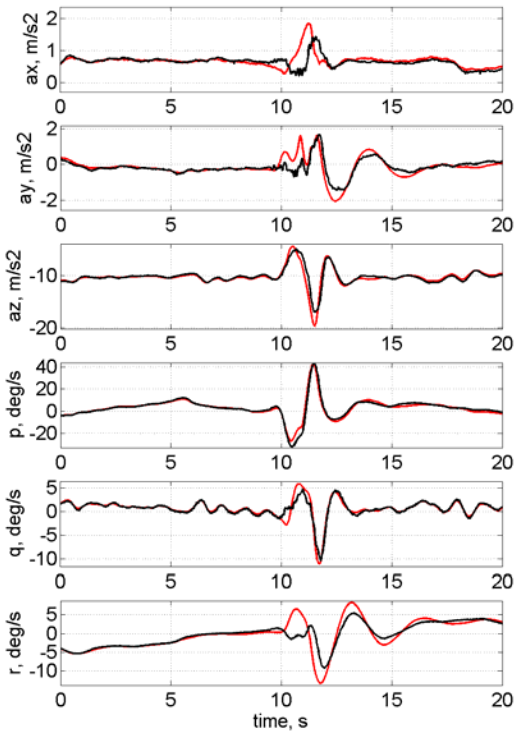

Fig.16 Do128 lateral wake fly-through:
simulation model output (———)
compared to flight test data (———)

However, the simulation quality in the yawing motion (*yaw rate r*) is rated more critical: the simulated model dynamics is at the wake entry *contrary* to what the flight test shows. This is a typical result found in many Do128 encounter validations. If such a model lacking a correct yaw response is used for pilot training in simulators, it could have a fatal training effect.

7.3 Strip Model Extensions

Some efforts were undertaken to further improve model quality, with special analysis in the yawing motion. In many validation cases, a correlation was found between the model faults in the longitudinal axis and the yawing motion.

Obviously, drag effects have considerable impact to the yaw degree-of-freedom.

So, the model was extended with drag effects. Drag depends on angle of attack in a nonlinear manner. Nonlinearities *cannot* be implemented in the strip model *independent* of the basic aero model. However, the fundamental idea of the strip model is this independency. To keep this, a linear formulation with one drag derivative, applied to each single strip, was used to consider wing and tail drag. Applying corresponding lever arms, the drag increments were also added to the yawing moment.

Moreover, the strip model does not consider any fuselage effects. An empirical model was implemented to account for this. The fuselage is divided typically into 20 strips (Fig. 17), computing a wake induced local sideslip angle at each strip. Using a suitable fuselage strip derivative, the summation of the strip increments gives a lateral fuselage force, and, considering the corresponding lever arms, a fuselage yawing moment.

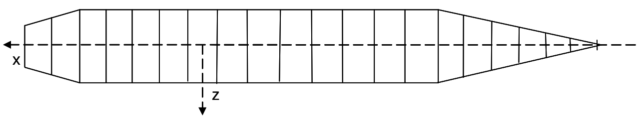

Fig.17 Strip model fuselage effect modelling

The determination of the two additional parameters, a *wing drag derivative* and a *fuselage derivative*, was done using the total validation procedure (Fig. 15) in an optimization mode to minimize the discrepancies between model output and flight test data. This identification process was performed using 23 high quality encounters of the Do128 aircraft into the VFW-614 ATTAS wake. The result: both derivatives were identified to about 0.8, and a considerable model improvement concerning the mean error standard deviation can be stated: about 51% in the yaw and 48% in the longitudinal axis for all 23 encounters. Through coupling effects, an improvement also in the roll axis (16%), in the lateral axis (10%) and the vertical axis (11%) are achieved. Fig. 18 summarizes the results for all evaluated wake encounter.

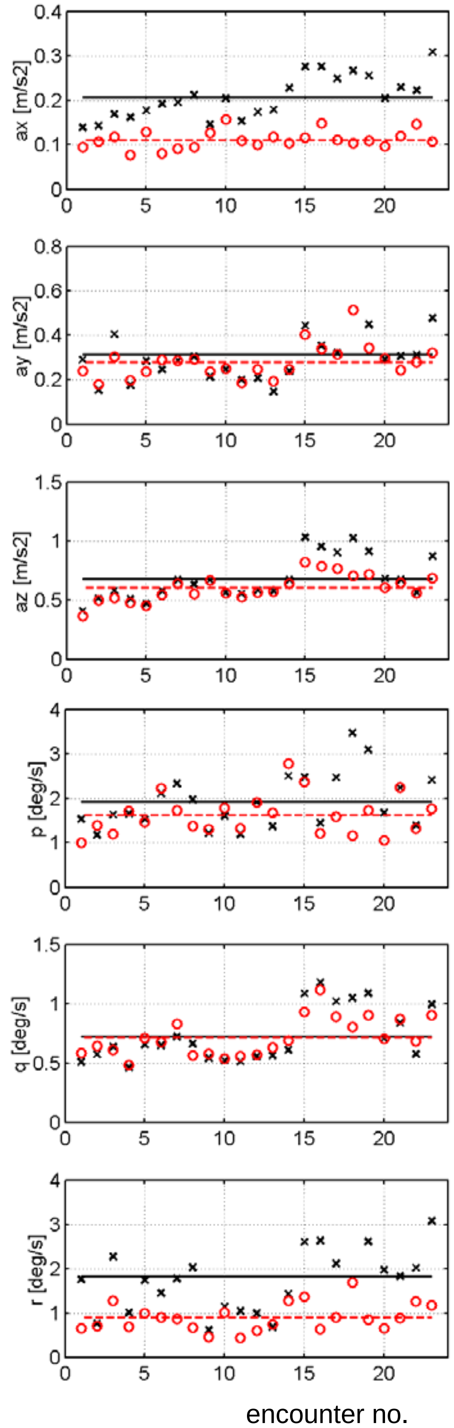

Fig.18 Model improvements for 23 wake encounter simulations: standard deviations of the errors between model outputs and the corresponding flight test data; without (**x**) and with (**o**) wing and fuselage drag effects; the lines give the *mean* error standard deviation of all 23 encounters

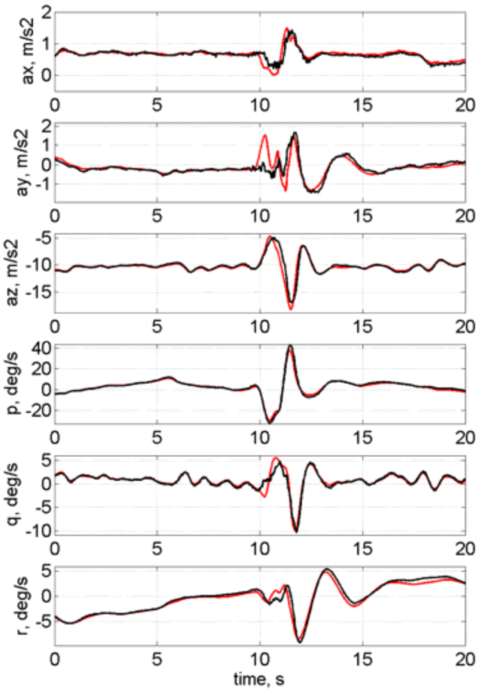

Fig.19 Do128 lateral wake fly-through: simulation output with wing and fuselage drag modelling (———) compared to flight test data (———)

Fig. 19 shows the Fig. 16 example, now applying the described model extensions. Despite some discrepancies in the lateral motion, a considerable improvement in the longitudinal axis (ax) and the yawing motion (r) is seen. The initial contrary model reaction in the yawing motion now is largely eliminated. However, one constraint is evident: no general formulation was found for the semi-empirical drag derivatives. Suitable values can be determined from flight test data applying the method described in this paper. If those flight test data are not available, the value of 0.8 may be taken in an empirical manner, but the validity of this has still to be proven for other aircraft.

8 Summary and Outlook

How good are nowadays wake vortex encounter models used for simulation and hazard assessments? A method was presented to analyse the quality by comparing the model outputs to corresponding wake encounter flight test data. The method consists of an elaborate procedure which requires several inputs: (a) suitable encounter flight test data, (b) a high precision flight path reconstruction, (c) suitable parameters of an analytical vortex model (e.g. *Burnham-Hallock*), and (d) a high quality *basic* aerodynamic model. Having all these data available, the encounter model quality can be assessed and analysed. The model used in the present case study is the *Strip Model*, which is based on lifting line theory. It describes the forces and moments acting on an aircraft in a wake as increments in addition to the basic aerodynamics in five degrees-of-freedom (drag effects are neglected).

Analyzing 23 wake encounters, it could be shown that the Strip Model is capable of reproducing the most important inputs into wake hazard assessment tools, *the vertical and roll degree-of-freedom*, in high quality. This is an excellent result for the widely linear model structure, which is achieved by applying the elaborate validation procedure including sensor calibration, wake identification and basic model inaccuracies. The pitching motion is represented also with sufficient quality. However, the quality of the yawing motion is rated more unfavourable: in many encounters the model dynamics is found *contrary* to what the flight test shows.

Analysing the yaw degree of freedom, a clear correlation between longitudinal model deficiencies (drag neglect) and the yawing motion was found. A simple model extension for drag effects was derived, keeping the idea untouched, that the strip model should have an incremental structure, independent from the basic aero model. Moreover, the strip model was extended for fuselage effects. Doing the validation step again, a considerable model improvement regarding the mean error standard deviations was achieved for all 23 encounters: about 50% in the yaw and in the longitudinal axis, and also further improvements in roll (16%), the lateral axis (10%) and in the vertical axis (11%) can be achieved.

The currently reached simulation quality is considered to be close to the maximum of what is achievable using a linear strip model structure which can be treated independently from the aircraft's basic aero model. However, the validity of the presented model and its extensions to account for drag and fuselage effects should be validated for other aircraft configurations. This is a present topic in the DLR project *Wetter & Fliegen:* encounter flight tests will be performed with a swept wing configuration (Falcon) flying into the wake of a typical transport aircraft (A320 ATRA). The tests are scheduled to start end of 2010.

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