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STRUCTURAL AIRCRAFT DESIGN – WAKE PENETRATION EFFECTS ON DYNAMIC LOADS

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ABSTRACT

The effects on the structural design of military and civil aircraft caused by dynamic loads resulting from the flight through high wake velocities which are generated by different types of aircraft have not been sufficiently investigated in the past. Military aircraft might experience this impact during formation or squadron flight or during combat maneuvers. Civil aircraft could be affected during start and cruise through wakes from other aircraft.

Passing through the wake the safety of the aircraft might be critical by wrong guidance, uncontrolled movements or by induced dynamic loads which might cause failure of structure or structural fatigue. The design of aircraft structure accounting for wakes is not state of the art. The standard design includes dynamic loads from PSD gust analysis and buffet or tuned gust analysis, where the intensities of the gust velocities are defined by military or civil specifications and buffet intensities are defined from wind tunnel test results (Ref. 1).

Predictions by analysis of wake velocity fields of different aircraft indicate however that the known maximum gust velocities are exceeded and the time history of the velocities experienced by the affected aircraft during penetration is different for example to the 1-cos gust in the discrete analysis. Moreover flight test results of the dynamic aircraft response during wake penetration produced evidence for its criticality in several flight regimes.

This contribution concentrates on military aircraft and demonstrates several examples of predicted critical wake fields and results from calculated dynamic response during different kind of penetration. Also examples from flight dynamic responses are discussed.
Finally some recommendations for future research and activities are given which should lead to a wake and wake penetration specification for military and civil aircraft required for future structural design and clearance.

The conventional approach for store separation wind tunnel testing consisted of testing the store in proximity to the aircraft at various store and aircraft positions and attitudes. These tests were conducted at specified Mach numbers, usually in the transonic speed range. This paper demonstrates the mistake of using a pre-selected range of Mach numbers for the wind tunnel testing, and describes the advantages of using the Mach sweep approach.

INTRODUCTION

Wake penetration can endanger the aircraft safety by resulting uncontrolled aircraft movements or motions, loss of control or by induced static and dynamic loads which might cause failure of structure or structural fatigue. A number of accidents are known from military and civil aircraft. One severe accident of a civil aircraft shall demonstrate as an example the present situation, Ref. 4. American

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Airlines and aircraft manufacturer Airbus have reportedly blamed each other for a 2001 crash that killed 265 people in New York. American Airlines flight AA-0587 crashed on November 12th 2001 a few minutes after takeoff from New York's John F. Kennedy Airport. The Airbus A300-600 aircraft was carrying 260 people when it passed through two wakes generated by a Japan Airlines aircraft that had departed from the same runway two minutes earlier. About 85 seconds into the flight the aircraft reportedly carried out two quick rudder swings to the right and then one all the way left. About five seconds later the rudder movements, the aircraft fin broke off, causing the flight to crash in New York Queens. The tail fin and rudder were discovered about half a mile from the wreckage in Jamaica Bay. Five people were killed on the ground. The airline has blamed the crash on the aircraft's flight control system, while Airbus said the pilot was improperly trained.

In general a number of regulations or instructions exist to avoid penetration into safety critical wake environment during take-off and cruise. The regulations on ground describe especially the time between the take-off of the proceeding aircraft, where the time is depending of the type of the proceeding aircraft, in flight the regulation describe the horizontal and vertical distance to the proceeding aircraft as function of aircraft type, for example Ref. 3. In addition flight safety technologies are under development especially for civil aircraft (Ref. 4, 5), for example an Aircraft Wake Safety Management (AWSM) system, Ref. 4 has been tested using SOCRATES and LIDAR sensors. The Aircraft Wake Safety Management (AWSM) system is being developed to provide a total airport system solution to the need for increased airport capacity with enhanced safety. SOCRATES is an airport based laser acoustic wake vortex sensor for the detection and tracking of wake vortex turbulence. UNICORN is an airborne radar for collision avoidance using state of the art components to achieve low cost, small size.

For military fighter aircraft it would be of benefit for aircraft safety to design the aircraft structure such that in flight wake encounters of maximum wake velocities from all possible wake generating aircraft are covered for possible short distances. This contribution should highlight only the problems for structural design and not the guidance problems.

WAKE DESCRIPTION

Wake turbulence, see definition from Ref. 2, is turbulence that forms behind an aircraft or helicopter as it passes through the air. This turbulence includes various components, the most important of which are wingtip vortices and jet-wash. Jet-wash refers simply to the rapidly moving gasses expelled from a jet engine; it is extremely turbulent, but of short duration. Wingtip vortices, on the other hand, are much more stable and can remain in the air for up to three minutes after the passage of an aircraft. Wingtip vortices make up the primary and most dangerous component of wake turbulence.

Wake turbulence is especially hazardous during the landing and takeoff phases of flight, for three reasons. The first is that during take-off and landing, aircraft operate at low speeds and high angle of attack. This flight altitude maximizes the formation of dangerous wingtip vortices. Secondly, takeoff and landing are the times when a plane is operating closest to its stall speed and to the ground - meaning there is little margin for recovery in the event of encountering another aircraft's wake turbulence. Thirdly, these phases of flight put aircraft closest together and along the same flight path, maximizing the chance of encountering the phenomenon.

Wing tip trailing vortices behind an aircraft see Figure 1 have many parallels in nature, in very small as well as in very large scales. For examples: The well-known galaxies in astronomy and the hurricanes and tornados in the meteorology.

One major characteristic for the description of the vortex flow is its tangential velocity which decreases with the distance from the core or centre. At or near the centre, the tangential velocity changes the sign. Depending on the total diameter of the vortex, there is a region inside the core (singularity) with undefined (zero) velocity. In the case of a hurricane, the typical diameter of the eye is in the order of 10 to 100 km, while it is in the order of one meter only for tornadoes. For wing tip vortices, it depends on the distance behind the aircraft, the speed, the size (mass, span) and type (wing sweep angle, taper ratio) of the aircraft, starting in the order of mm's only to 100 m's, see Figure 2.

Figure 1: Formation flight and maneuvering of military aircraft and vortex generation by different transport aircraft – Boeing 757, 777, 747, Ref. 10

Analytical Prediction

Dynamic load predictions due to uncertainty in aerodynamics are described in detail in Ref. 1. The analytical prediction of wake velocity profiles can be performed using classical approaches or modern numerical aerodynamic CFD tools. For example a classical approach is described in Ref. 2 and 3.

In the references the distribution of vortex induced velocities is described by analytical vortex models for known circulation and core radius. From flight measurements it was concluded that for the description of the tangential velocity V_t of a single vortex the formulation of BURNHAM-HALLOCK leads to reasonable results as illustrated in the figure below.

For example Ref. 8 documents wake vortex advanced prediction. A number of predictions treat the far field vortex location and decay. Simple models for the prediction of trajectories and decay of the wake vortices have been investigated. These have been implemented into wake warning systems. Large eddy simulation of wake vortices has been developed. Advanced numerical computational models and algorithms exist to study the effect of various atmospheric conditions on wake vortex motion and decay.

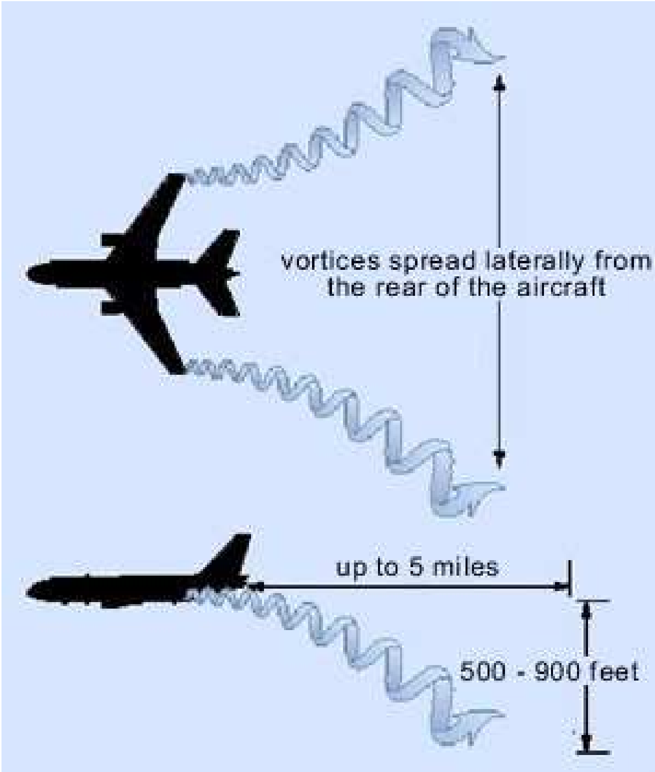


Figure 2: *Wake vortex development, from Ref. 10*

Verification of Predicted Wake Velocities by Different Analytical Approaches and Flight Test

The predicted results of wake velocity profiles as function of aircraft configuration, flight condition (Mach number, altitude, angle of attack, etc.) may be verified by comparison to predictions of different aerodynamic approaches and by comparison to flight measured flow sensor signals.

An example of the comparison of predicted and flight measured results of vortex induced velocities from Ref. 2 is shown below in the Figure 3. More evidence of the validity of other analytical predictions is however required for different configurations and flight conditions.

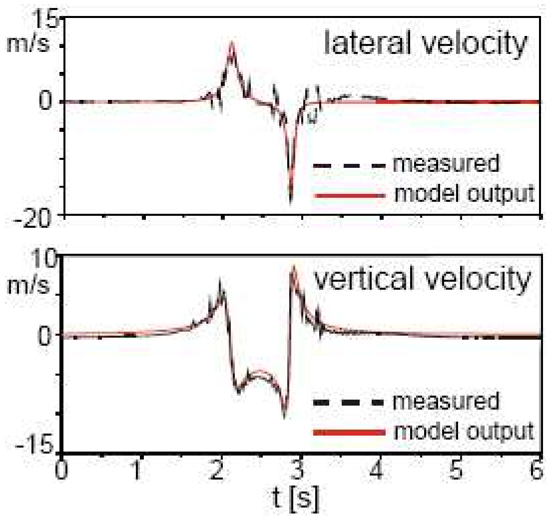


Figure 3: *Vortex induced velocity distribution, from Ref. 2*

WAKE PENETRATION DESCRIPTION

The wake profile behind a generating aircraft is characterized by up-wash and downwash areas in span wise direction. These up- and downwash areas can be penetrated in arbitrary manner. The wake velocity field can be crossed in perpendicular way to the path of the wake generating aircraft or in direction of the proceeding wake of the generating aircraft by different heading angles, Figure 4

Thus the structural load factor, the altitude and climb/sink rate and the roll angle and roll rate of the following aircraft may change and vibrations of the elastic aircraft can occur which produce dynamic loads. The wake induced effects can result in degradation or loss of aircraft guidance and the high structural vibrations will lead to corresponding high dynamic loads or even to structural failure.

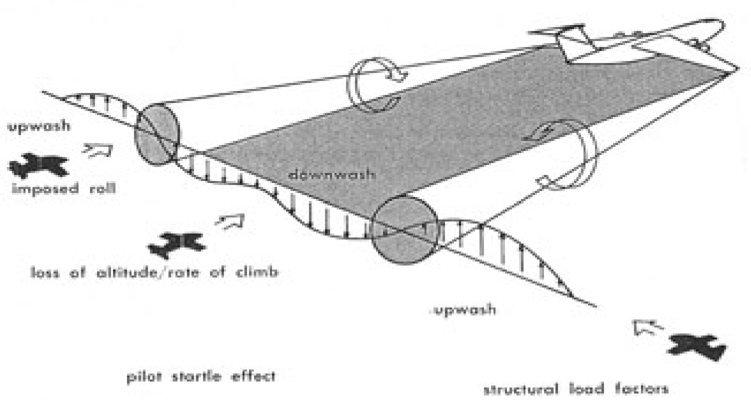


Figure 4: *Wake profile behind generating aircraft (Ref. 9)*

ANALYTICAL PREDICTION OF AIRCRAFT RESPONSE

The analytical prediction of aircraft response and dynamic loads is possible through the prediction of wake velocities by wake generating aircraft followed by an analytical dynamic response calculation and dynamic load calculation of the wake receiving following elastic aircraft using a flexible aircraft model.

The wake generating aircraft produces a wake profile, which depends on the flight condition of the generating aircraft and the distance to the wake receiving following aircraft and its heading position, see Figure 5 below.

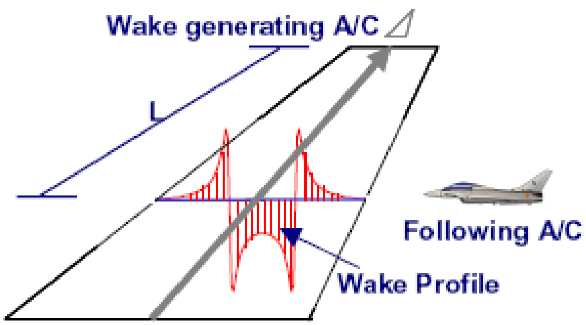


Figure 5: *Wake profile from wake generating aircraft, from Ref. 11*

Analytical Prediction of Wake Velocities for further Aircraft Response Analysis

Wake velocities have been analytically predicted for further flexible aircraft response calculations. The wake velocities generated by fighter aircraft and a civil aircraft VFW 614 have been derived at a distance of 800 ft between the two Aircraft. The flight conditions of the wake generating aircraft are described in the table 1 below.

		Profile #1: Fighter Type	Profile #2: Tanker Type
V	[KCAS]	350	116
h	[ft]	10 000	10 000
AoA	[°]	20	-
Nz	[-]	-	1

Table 1: *Flight Condition of Wake generating Aircraft, from Ref. 11*

The generated wake velocity by Commuter VFW614, by Fighter Aircraft and by Airbus A310 at a distance of 800 ft is shown in Figures 6, 7 and 8. Maximum speed for VFW614 wake velocity is 14 m/sec for Fighter Aircraft 55 m/s and Airbus A310 42 m/s. A comparison of wake by VFW614 and Fighter Aircraft to the maximum gust velocity applied by the discrete gust analysis has been, demonstrates that the wake velocities are higher than the gust velocities.
In the structural dynamics analysis the term "discrete gust analysis" is used. The discrete gust analysis is defined in the time domain by the (1-cos) gust. If the gust length varies the analysis is called "tuned gust analysis". In the design process the maximum gust velocity is defined by 66 ft/s, whereas the maximum wake velocity is

- 187 ft/s with Fighter Aircraft as generating A/C
- 138 ft/s with Airbus A310 as generating A/C
- 46 ft/s with the commuter A/C VFW614 as generating A/C

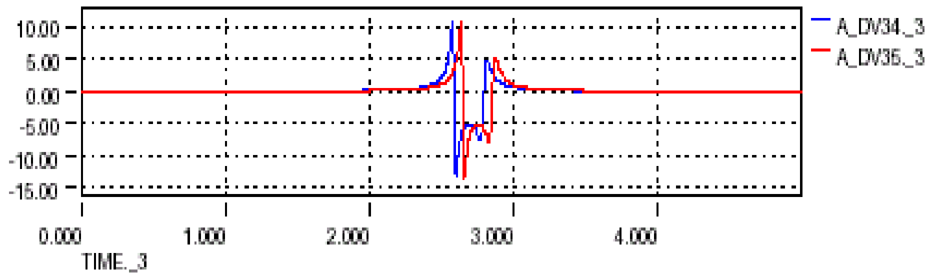


Figure 6: *VFW 614 wake prediction; VFW614 speed: (Mach 07; 10 kft), 116KCAS*

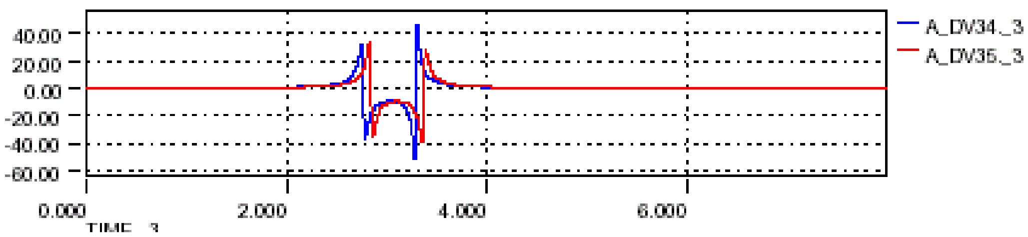


Figure 8: *Airbus A310 wake prediction max vertical velocity 42 m/s; generating aircraft A310 Speed: 325 KCAS*

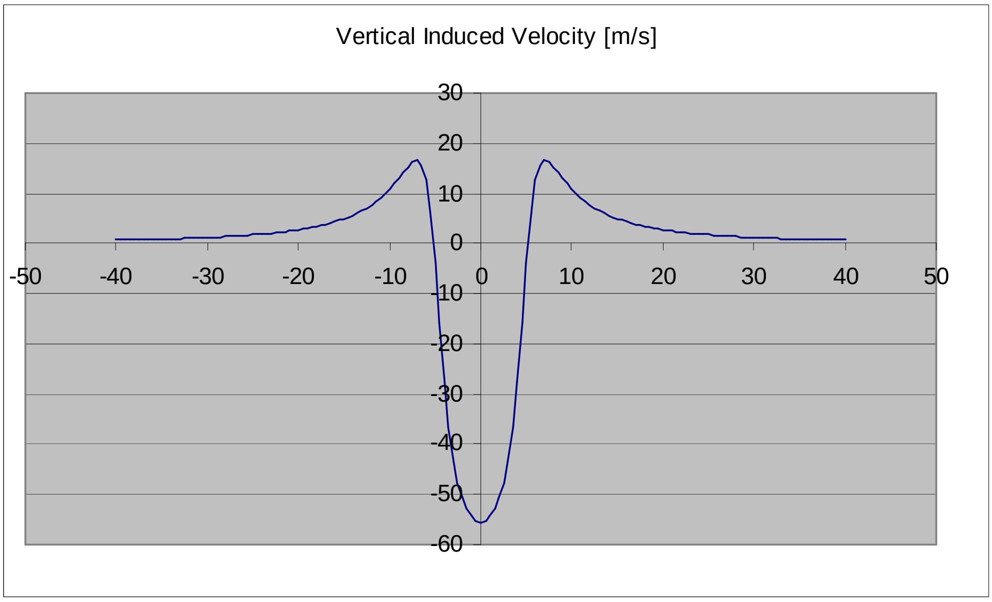


Figure 7: *Calculated wake generation by FighterAircraft 350 KCAS, 20 deg. AoA; 10 000 ft a distance of 800 ft for further dynamic response calculation of flexible A/*C

Analytical Predictions of Dynamic Response and Loads

The dynamic response of the Fighter Aircraft in the wake of the VFW614/ATTAS and in the wake of a Fighter Aircraft has been calculated (Ref. 11). This activity was initiated in order to derive advice for the flight test with respect to the distance to the wake generating aircraft and the speed of the wake receiving aircraft.

The conditions for the prediction of the wake receiving aircraft crossing speed is 350 KCAS, altitude = 10000 ft, Mach 0.64, Nz = 6 at a distance to the wake generating aircraft of 800 ft.

The accelerations of the forward, centre and rear tip pod station, the forward and rear station of the foreplane and two fuselage stations, the location of which are demonstrated in Figure 10, had been predicted. The acceleration reaches an almost critical high value of

- 69.6g at the rear tip pod station
- 87.6g at the rear foreplane station and
- 20.6g at the front fuselage

The loads obtained at the different monitoring stations of the aircraft are inside the allowable loads envelopes for the wake profile of VFW614. For the fighter wake profile the loads exceed the allowable loads envelopes at some of the wing and foreplane monitoring stations.

From the calculated dynamic responses and loads it was concluded, that for flight test the distance of 800 ft had to be increased to a distance > 1500 ft at 350 KEAS and 10000 ft.
The influence of the heading angle of the wake crossing aircraft was found to be not very significant due to the short wake wave length.

It can be concluded that the requirements for the structural design using the discrete gust specifications do not cover the wake environment produced by military fighter aircraft at high speed and high g levels for distances below 1500 ft. Since during dog fight the speeds of wake producing and wake receiving aircraft might be higher than 350 KEAS and distances to the wake receiving aircraft can be lower than 1500 ft.
Therefore during future design of military aircraft structure it would be beneficial to include requirements for dynamic loads from wake velocities.

EXAMPLES OF FLIGHT TEST RESULTS

Flight test results are available from a wake receiving military Fighter aircraft due to the wake generation by a Fighter Aircraft and a VFW 614. Analytical predictions of wake velocities are available from wake generating aircraft see Figures 5 to 7 for a distance of 800 ft, i.e. an Fighter Aircraft, a VFW614 and a tanker Airbus A310, configurations see Figure 9 below.

The flight test results of the wake receiving aircraft are local acceleration signals at different locations, wing tip stations, outer foreplane stations and fuselage stations.

Figure 9*: Wake producing aircraft Military Fighter, VFW 614 and Airbus 310*

The wake penetration flight tests have been performed recently. The wake penetration was performed by the application of different maneuvers which are described in Figures 11 and 12. Maneuver 1 consists in a 1g straight and level flight, maneuver 2 is a horizontal crossing in a g-turn and maneuver 3 is a vertical crossing. The response of a Fighter aircraft was tested due to the wake generated also by an Fighter Aircraft and due to the wake of a transport type VFW614 aircraft. The flight test results have been analyzed w. r. t. local accelerations on foreplane, outer wing, (the location of which is described in Figure 10), and on fin.

It was intended to investigate the flight test data to have a preliminary rough estimate of the maximum local accelerations by extrapolation of flight tested data and by application of wake predictions for VFW614 and AIRBUS A310. A310 wake predictions besides the Fighter Aircraft predictions have been applied to derive maximum wake conditions.

The present evaluation of flight test results performed for 250 KCAS and a distance of 2500 ft shows already high levels of accelerations in terms of foreplane acceleration (90g) and wing tip acceleration (30g) for the flight tested conditions. Since the flight tests have performed at moderate wake velocity conditions at distances > 1500 ft, it is expected that the mentioned values of acceleration will increase significantly with reduced distances to the wake generating aircraft and higher speeds of the receiving aircraft.

Therefore the existing flight test data have been extrapolated to the maximum possible wake velocities. Aerodynamic models are available which are able to predict the maximum velocities in terms of v and w.

For the further evaluation of the flight test results w. r. t. maximum condition

- the velocities v and w due to wake used in flight simulation for the flight conditions of existing flight tests (for example Fighter against Fighter) and

- the maximum velocities due to wake at the aircraft points used in flight simulation have to be calculated.

Manoeuvres for Wake producing and Wake receiving Aircraft

Different flight maneuvers had been defined for the wake penetration flight tests. In Figure 11 the flight maneuver 1 is illustrated, both the lead and the following test aircraft, the wake receiving aircraft, are in 1g straight level flight condition. Results of test 16 of table 2 are discussed in the following chapter 5.2.

Figure 12 demonstrates the maneuver 2 which is characterized by horizontal crossing in a g-turn. Maneuver 3 is not shown here, but it is the vertical crossing of the wake receiving aircraft.

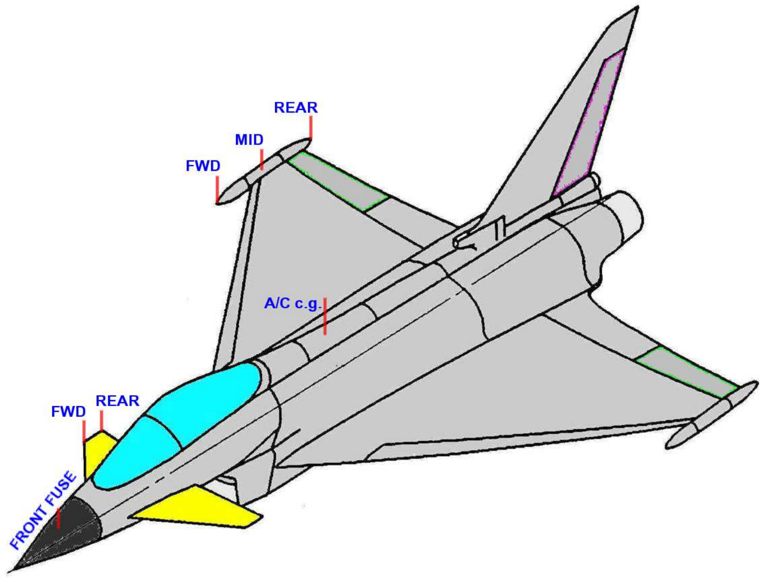


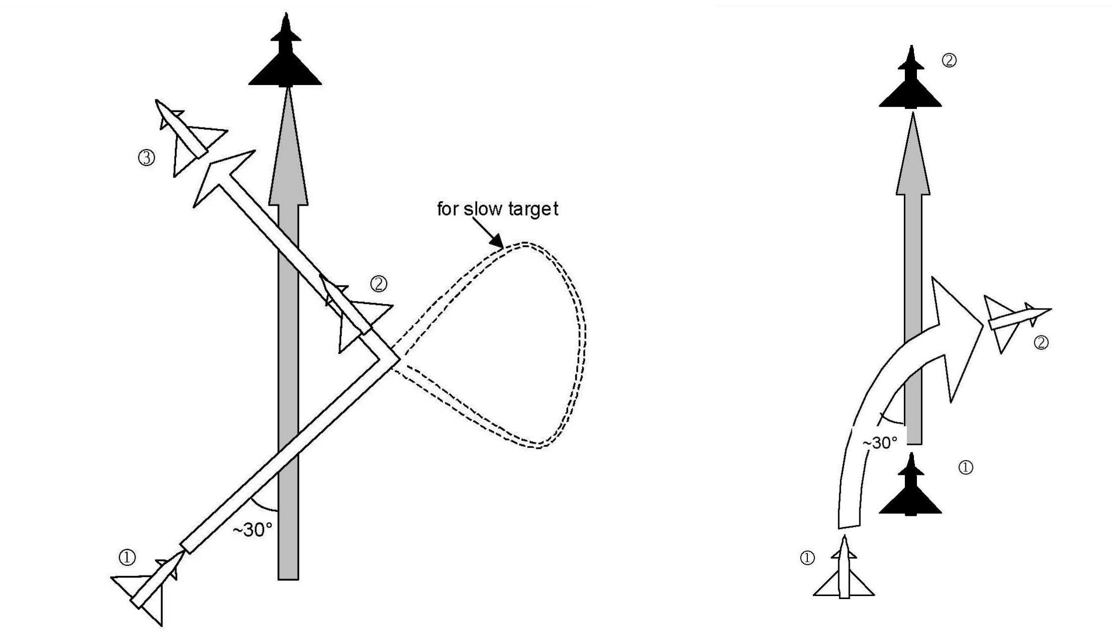
Figure 10: *Accelerometer installation for flight test*

Number	Start	Stop	Distance	Speed	nz/AoA	Flight condition of
	[sec]	[sec]	[ft]	[KCAS]	[g/deg]	Wake generating aircraft
1	53650	53660	1500	180	1g	**1g, 180KCAS of Euro fighter**
2	53690	53720	500	180	1g	
3	**54010**	**54020**	**3000**	**180**	**20**	**20AoA, 180KCAS of Euro fighter**
4	54090	54100	1500	180	20	
5	54170	54180	1000	180	20	
6	**54300**	**54310**	**3000**	**300**	**3g**	**3g, 300KCAS of Euro fighter**
7	54390	54403	2000	300	3g	
8	54540	54550	1200	300	3g	
9	**54655**	**54665**	**5000**	**250**	**1g**	**max g-turn, 400KCAS of Euro fighter**
10	54804	54814	4500	250	1g	
11	54934	54944	3000	250	1g	
12	55106	55116	3500	250	1g	
13	55215	55224	3000	250	1g	
14	55300	55310	2500	250	1g	
15	55456	55466	2000	250	1g	
16	55544	55555	2500	250	1g	

Table 2: *Flight conditions of wake receiving Fighter Aircraft*

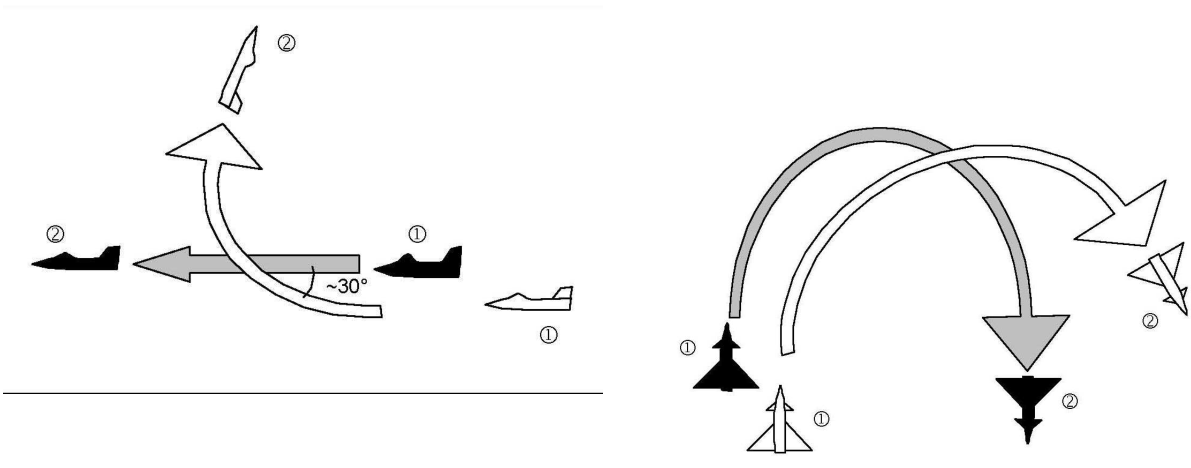
Time histories of flight measured dynamic responses on Fighter due to wake generation by Fighter and by VFW614 (tanker- transport type aircraft)

Time histories of the responses at Fighter Aircraft due to Fighter Aircraft wake generation are described in the Figures 13 to 18. The flight condition for wake generating Fighter Aircraft at maximum g-turn was 400 KCAS, the flight condition of the wake receiving Fighter was 250 KCAS at 1g at a distance of 2500 ft. In figure 19 the Fighter response due the wake velocities generated by the VFW614 is demonstrated.



Straight and Level 1g **AoA/nz (vertical)**

Figure 11: *Maneuver for wake penetration flight tests from ref. 7*



AoA/nz (horizontal) **Horizontal crossing in g-turn**

Figure 12: *Maneuver for wake penetration flight tests from ref. 7*

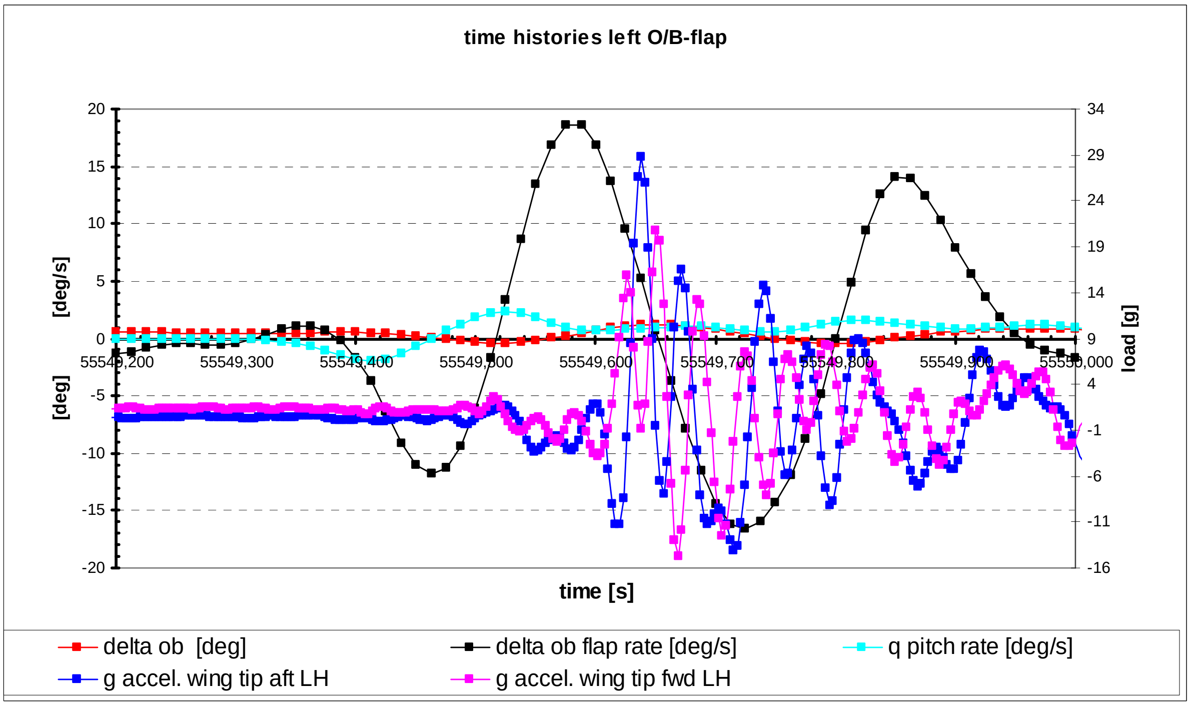


Figure 13: *Left O/B flap angles and rate; q and acceleration of fwd wing tip*

The right y-axis belongs to the g-acceleration loads and the left one to the other states - flight test results of the receiving aircraft at 250 KCAS, distance 2500 ft, 1g, Fighter as wake generating aircraft (400KCAS at max turn rate)

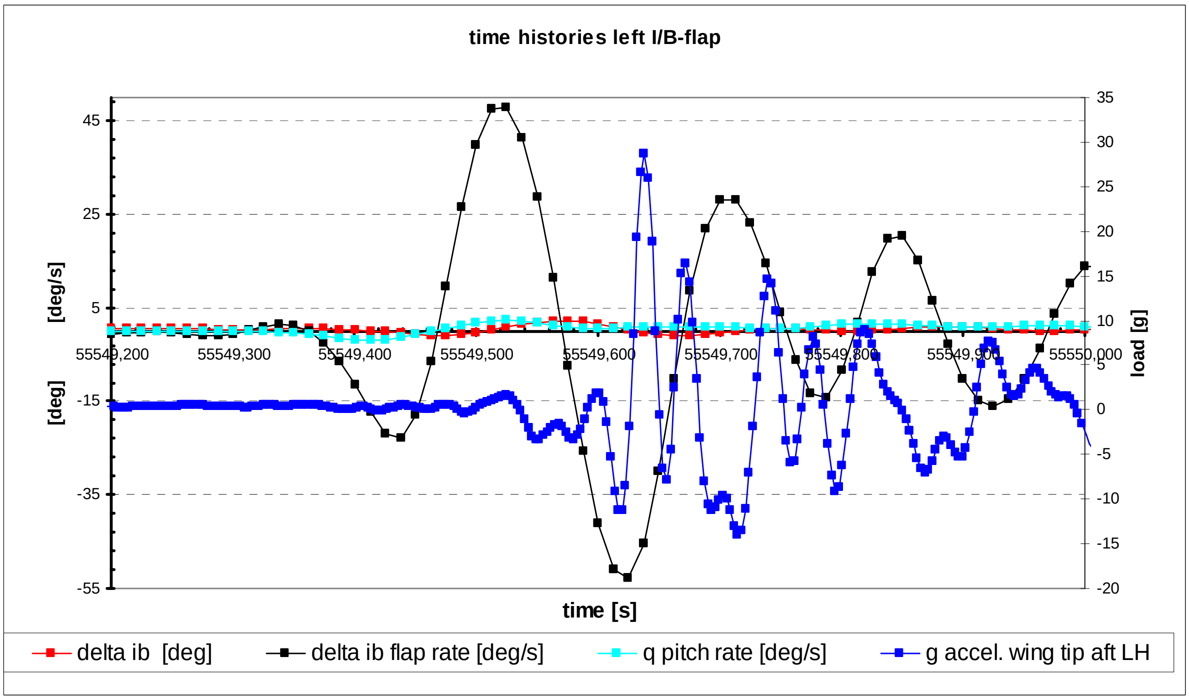


Figure 14: *Left I/B flap angles and rate; q and acceleration of aft wing tip*

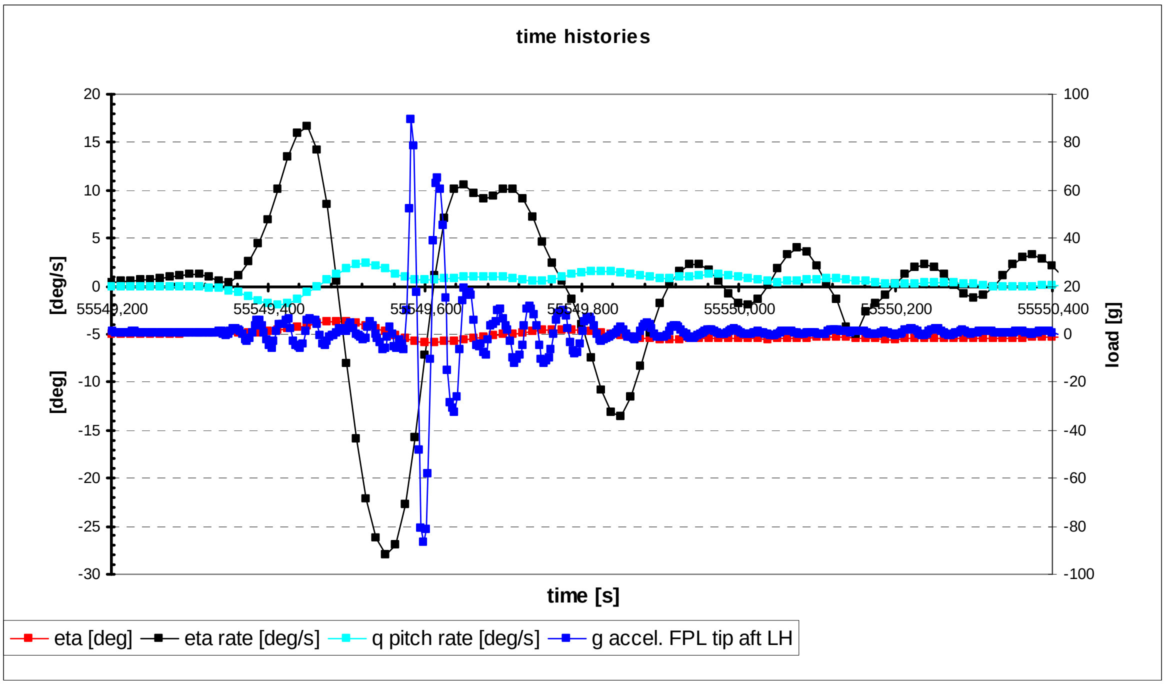


Figure 15: *Left foreplane angle and rate; acceleration of foreplane tip*;

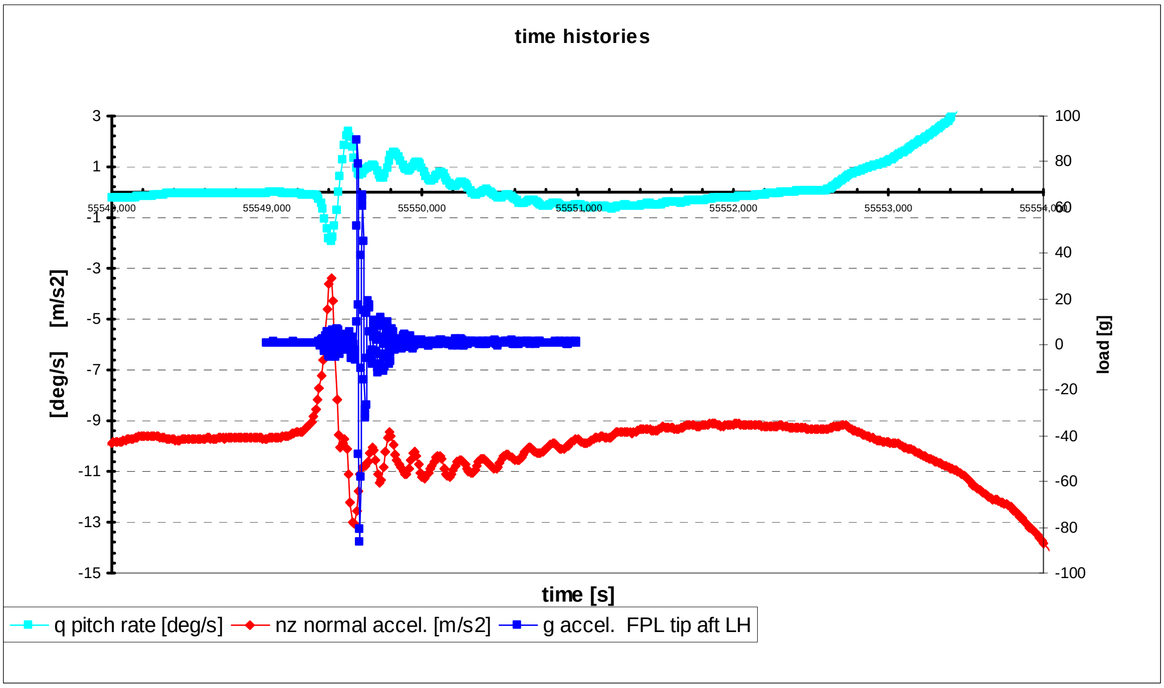


Figure 16: *Time history of q and n_Z and acceleration of foreplane tip*

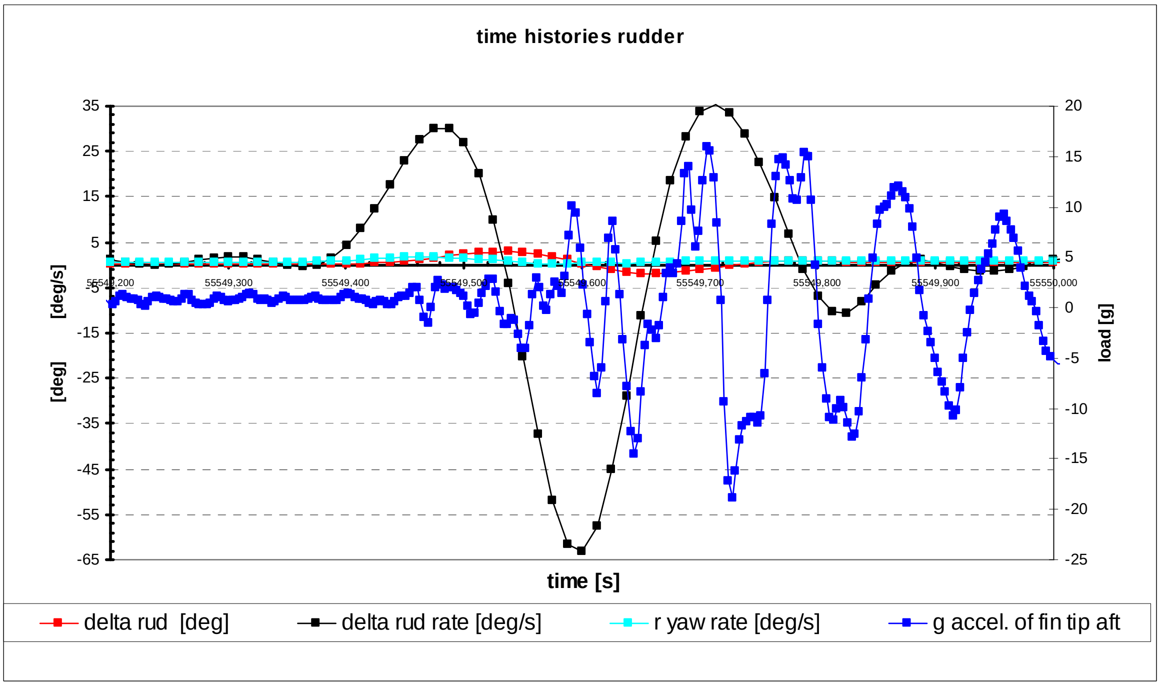


Figure 17: *Rudder angle and rate; acceleration of fin tip*

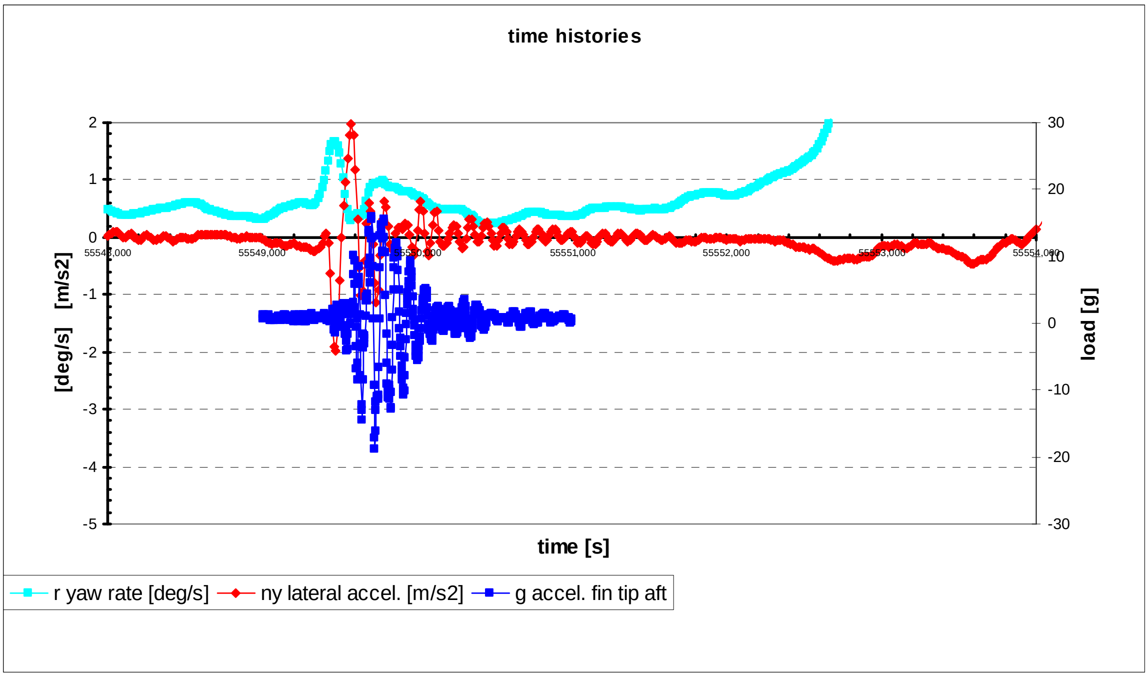


Figure 18: *Time history of yaw rate, lateral n_Y and acceleration of fin tip due Fighter wake*

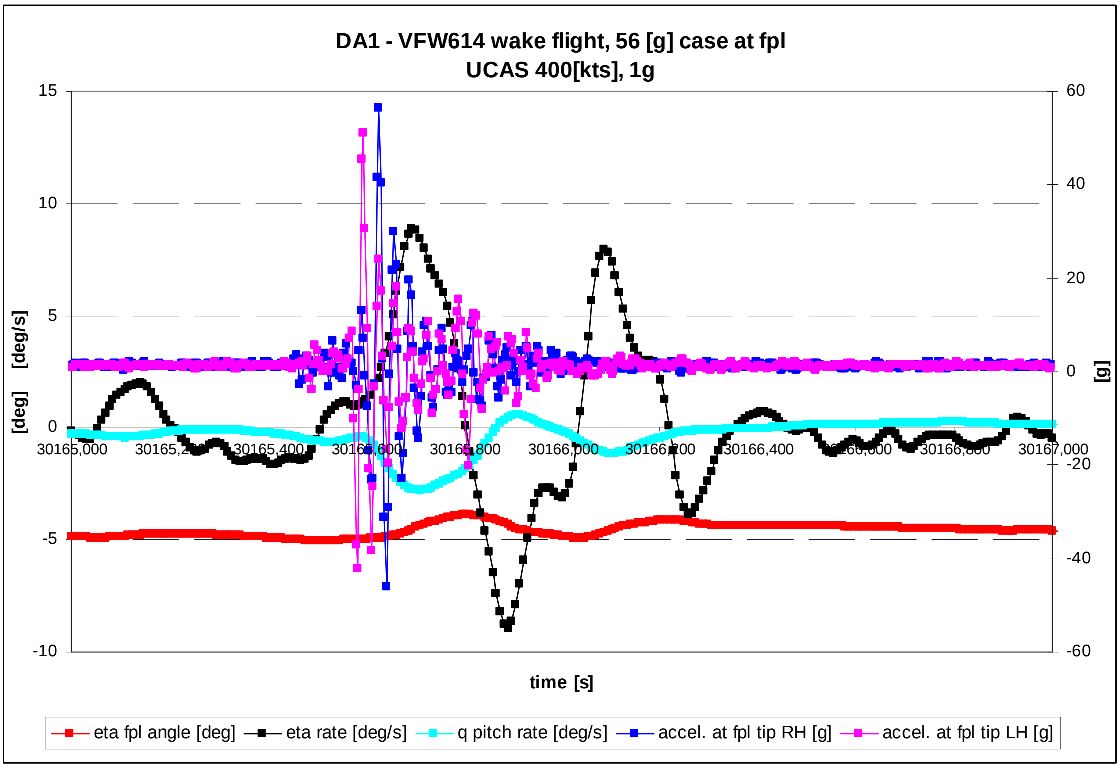


Figure 19: *Foreplane angle and rate; acceleration of foreplane tip LH/RH*

Comparison to Predicted Responses

<u>Evaluation of the flight test results Fighter against Fighter</u>

The flight test results of Fighter Aircraft flight with another Fighter as wake generating aircraft have been evaluated for the flight condition 250 KCAS, distance 2500 ft, 1g (see table 2). The wake generating Fighter Aircraft was operating at maximum speed.
Time histories of Fighter Aircraft responses due to Fighter Aircraftas wake generator have been analyzed.
The following evaluation was carried out for flight case 16 (highlighted in Table 2), since for that time period the maximum loads were observed compared to the other flight cases.
In Figure 17 the time history of the vertical acceleration of the LH rear and forward wing, the corresponding outboard flap deflection in degree and the outboard flap rate are shown together with the pitch rate.
The LH outer wing acceleration reaches a maximum value of 30 g at rear wing and 21.5g at the forward position, resulting from the response of the first wing bending mode (6.7 Hz) and the wing torsion mode around 30 Hz.
The damped pitch rate response q shows a 6.7 Hz vibration due to wing bending mode response at the IMU station. Also the outboard flap and flap rate response shows the motion due to first wing bending mode due to feedback of notch filtered pitch rate.

In Figure 14 the vertical acceleration of the LH rear wing, the corresponding LH inboard flap deflection in degree and the LH inboard flap rate are shown together with the pitch rate.
The LH outer wing acceleration reaches a maximum value of 30g as shown in Figure 13 and 14, resulting from the response of the first wing bending mode (6.7 Hz) and the wing torsion mode around 30 Hz. The damped pitch rate q response shows a 6.7 Hz vibration due to wing bending mode response at the IMU station. Also the inboard flap and flap rate response shows the motion due to first wing bending mode due to feedback of notch filtered pitch rate.
In Figure 15 and 16 the vertical acceleration of the foreplane, the corresponding foreplane deflection in deg. and the foreplane rate are shown together with the aircraft pitch rate.

The foreplane acceleration reaches a maximum value of 90 g, resulting from the response of the foreplane bending mode response. The damped pitch rate q response shows a 6.7 Hz vibration due to wing bending mode response at the IMU station. The foreplane deflection and foreplane rate response shows the motion due to first foreplane bending mode at around 30 Hz due to feedback of notch filtered pitch rate. Figure 17 shows the time history of N_z. In Figure 22 the lateral fin tip acceleration, the corresponding rudder deflection in deg. and the rudder rate is depicted. The fin tip acceleration reaches a max value of 18 g, resulting from the response of the fin bending mode response at around 13 Hz. Since the wake receiving aircraft was flying at 1g and did not perform a roll maneuver, the lateral acceleration is believed to be not fully representative for maximum combat conditions w. r. t. wake induced accelerations.
From the comparison of vertical and lateral predicted velocities w and v, it could be detected, that the deviations in w and v are not very high, therefore the actual fin acceleration would reach similar values for instance at a bank angle of 90 degrees. Figure 18 shows the yaw rate and lateral acceleration.

Conclusion of the test results of wake generating Fighter Aircraft against wake receiving Fighter Aircraft.
The outer wing acceleration and therefore corresponding dynamic loads and the foreplane response is quite high at the evaluated moderate wake flight test results and will reach significant higher values for maximum wake velocities and higher dynamic pressure and shorter distances < 2500 ft to the generating aircraft.

The Fighter Aircraft wake chosen for the evaluation was at maximum turn rate at 400 KCAS. Therefore the maximum lift coefficient C_A was reached at a near maximum speed of a combat maneuver. Consequently the extrapolated response according to the extrapolation to maximum possible speed described below is only dependent on the ratio of dynamic pressure and on angle of attack due to the wake velocity w.

At constant Mach number the response is proportional to the rate of the dynamic pressure $\frac{\rho}{2}V^2$ for maximum velocity and dynamic pressure of flight test and proportional to ratio of angle of attack α at max. velocity and of angle of attack α for flight test velocity of the receiving aircraft due to wake w_{wake} of the generating aircraft, which produces an angle of attack at the receiving aircraft $\alpha_{receiving\ aircraft}$ due to the w_{wake} of the generating aircraft (i.e. the enemy), therefore

$\alpha_{receive-AC} = \frac{w_{wake-gener-AC}}{V_{receive-AC}}$ and $\alpha_{wake} = \frac{w_{wake}}{V}$; w_{wake} is proportional to $V \cdot c_A(\alpha, Mach)$

of the wake generating aircraft. Therefore the factor for extrapolation of flight tested responses (for example accelerations) is:

$$\frac{V_{\max-receive-AC} \cdot w_{wake-gener-AC}}{V_{flight-test-recieve-AC} \cdot w_{flight-test-gener-AC}}$$

For example for the receiving Fighter aircraft at 250 KCAS, 1g and the generating Fighter aircraft in flight conditions for max turn rate and 400 KCAS, assuming that maximum conditions are already reached with max turn rate and 400 KCAS (i.e. flight test w generated is equal to max w), then the extrapolation is performed with the ratio of the maximum and flight tested velocities of the receiving aircraft.
Assuming a maximum velocity of the receiving aircraft of 500 KCAS (flight test 250 KCAS), then the max outer wing acceleration would be 60 g and the max foreplane acceleration would be 180 g.
These results already indicate the criticality of the wake penetration effects on flexible aircraft response. Even if the speed of the receiving aircraft would be 400 KCAS the outer wing dynamic loads might become critical, dynamic load assessment have therefore to be performed.
This first preliminary guess of aircraft wake penetration dynamic response of flexible aircraft has to be confirmed / updated with further more detailed investigations which should be based upon detailed wake velocity information and refined assumptions of maximum wake conditions and flexible aircraft dynamic load calculations.

Evaluation of flight test results of Fighter due to generating aircraft VFW614.

Data for the foreplane are presented in Figure 19 showing foreplane deflection and rate and LH/RH foreplane tip acceleration. The maximum value of acceleration was 56 g at RH fore-plane tip. The receiving Fighter speed was 400 KCAS

Extrapolation of these data can be performed using predicted velocities. Preliminary extrapolation of existing Fighter accelerations using wake information of ATAS/VFW614 and of maximum wake definition for A310.

VFW614 speed was at Mach 07, 10 kft KCAS=116; for A310 the maximum predicted vertical wake velocity of 42 m/s exceeds the maximum discrete gust speed of 66 ft/s by about a factor of 2. However the development of the wake impulse with time is different to the 1-cos gust shape and the duration smaller than a 3c discrete gust. Therefore only high frequency elastic modes will be excited which would lead to different dynamic loads compared to discrete gust design conditions.

The ratio of max vertical LH wing wake velocity (from A310, ca. Mach 0.85, 30kft) to ratio of max vertical LH wing wake velocity about 42/12

The extrapolation factor for wing acceleration by $\dfrac{V_{\max-receive-AC} \cdot w_{wake-gener-AC}}{V_{flight-test-recieve-AC} \cdot w_{flight-test-gener-AC}}$

can only be generated if the wing tip data are available.

SAFE FLIGHT IN WAKE ENVIROMENT

Safe flight in wake environment may be achieved through the determination of safe distances and additional consideration of wake velocity profiles during the design and clearance of new air vehicles.

Definition of Distance from generating to receiving Aircraft

An example is presented in Figure 20 below, demonstrating the variation of wake velocity with longitudinal x and lateral distance y as function of incidence for the Fighter.

The decrease of wake velocity in x-direction can be used as indicator for the safe distance definition, if the aircraft is designed by the application of dynamic local loads from tuned gust analysis using a 66 ft/sec gust velocity, the safe distance for wake penetration shall be derived from the extrapolated wake velocity diagram w versus x- distance.

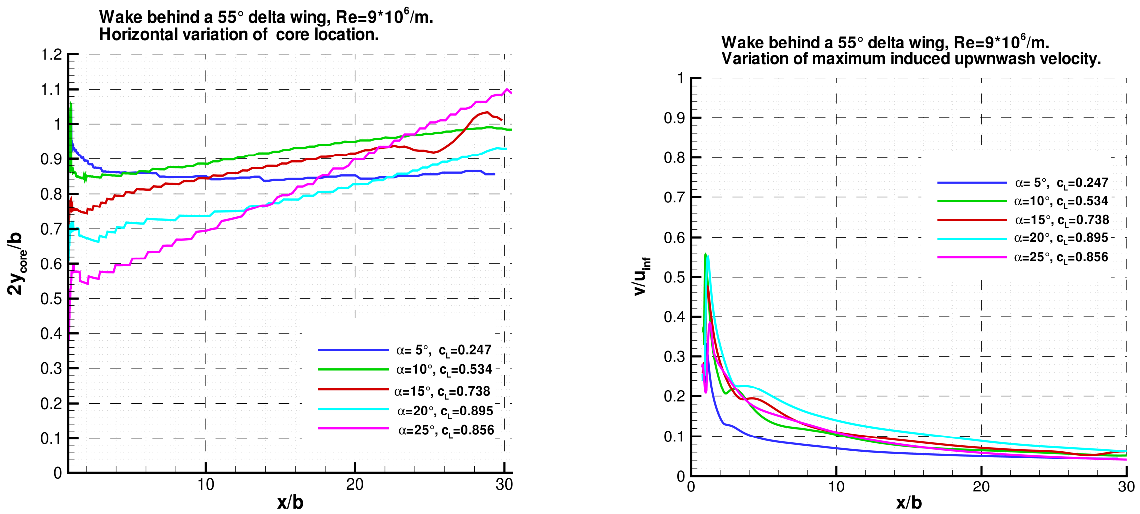


Figure 20: *Wake velocity behind Fighter*

Calculation for static and dynamic loads for wake penetration

The static loads due to wake penetration shall be based upon the dynamic response of the rigid aircraft with flight control system using the flight dynamic model of the aircraft generated by the wake excitation.

The dynamic loads on arbitrary local aircraft monitoring stations shall be calculated using the analytical model of the flexible aircraft. The derivation of local inertia and unsteady aerodynamic forces of the vibration modes together with the wake induced unsteady aerodynamic forces form the dynamic wake induced loads.

Definition of allowable loads envelopes for Design and clearance

For the design and clearance allowable load envelopes at local structure monitor stations have to be defined which include:

- Manoeuvre loads
- Dynamic gust loads from tuned gust analysis
- Dynamic buffet loads
- Dynamic impact loads
- Landing loads
- Wake penetration loads

The local load envelopes in terms of shear force F_z versus torque My and bending moment M_x versus torque M_y have to be defined. To prove that the structure withstand the gust and buffet loads as well as the wake penetration loads, the actual calculated or measured loads must be inside the Ale's (Allowable Loads Envelope).

CONCLUSION

The results of the first preliminary assessment of flexible aircraft dynamic response from wake penetration flight tests already indicate the criticality of the wake penetration effects on flexible aircraft wing, fuselage and fin dynamic loads. The dynamic loads of the wake receiving aircraft should always include buffet loads from high angle of attack manoeuvres.

The first preliminary guess of aircraft wake penetration dynamic response of flexible aircraft for assumed max conditions has to be confirmed / updated with further more detailed investigations which should be based upon detailed wake velocity information and refined assumptions of maximum wake conditions.

The following future actions are recommended:

- Comparison of predicted accelerations and dynamic loads from wake penetration and from discrete tuned gust for a representative set of military aircraft
- Refined investigation of max. dynamic response using detailed wake velocity information for a number military aircraft as wake generators
- Definition of wake velocities from existing wake penetration flight testing (for example DLR VFW614 and Fighter aircraft) and other military aircraft
- Clear definition of predicted max. wake velocities of generating aircraft
- Definition of max flight conditions of attacking aircraft in wake condition during combat maneuvers in terms of speed, Mach number , g- conditions
- Preparation of an analytical flexible aircraft model calculations to treat wake penetration using wake information from
- Performance of analytical dynamic response calculations for the generation of sectional dynamic loads on aircraft monitoring stations for comparison to Ale's.

- Definition of times spent in high, medium and low wake velocity conditions of a different military aircraft in 600 flight hours (wake – combat maneuver correlation for fatigue life prediction).
- Performance of fatigue life assessments for outer wing, fin and foreplane based on the definition above

RECOMMENDATION

Finally some recommendations for future research and activities are given which should lead to a wake and wake penetration specification for military and civil aircraft required for the structural design and clearance.

Future Aerodynamic Research

Although a big variety of analytical investigations are available from past aerodynamic research, as for instance documented in Ref. 1-3 and 8 it is recommended in order to establish safe aerodynamic predictions to perform intensive aerodynamic wake vortex research campaigns also including results of comparisons of different CFD tools and validations using wind tunnel and in flight measured wake velocities for the validation of the tools.

Future Flight Test Programs of Wake Penetration of Different Aircraft

The knowledge of flight tested wake characteristics of different civil and military aircraft with respect to velocity intensities as function of speed, Mach number, altitude and AoA and n_z of the wake generating aircraft and the distance to the aircraft is very limited. Flight test programs should therefore be initiated in order to establish a sufficient broad data basis for future validation of analytical wake velocity predictions and for definitions of aircraft design requirements followed by the formulation of corresponding design and clearance specifications. The data acquisition shall be performed by a wake receiving aircraft equipped with flow sensors.

In addition to the flight measurement of wake vortex velocity characteristic also the dynamic response at different locations of the tested aircraft shall be measured for future validation of analytical dynamic response calculations which should include the flight measured wake velocities.

Verification of wake predictions

The verification of the analytical wake velocity predictions shall be performed through comparison with flight measured characteristics.

The verification of the analytical dynamic response predictions shall be performed through the comparison of flight measured local aircraft accelerations.

Definition of Guidelines for Safe Flights in Wake Environment

From the results of the proposed investigations on wake penetration guidelines with respect to aircraft structural aspects shall be summarized for the safe flight of military and also civil aircraft in wake environment.

The guidelines shall be part of military and civil specifications for static and dynamic loads and vibrations for aircraft design and flight clearance of aircraft structure and equipment.

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