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REALTIME-SIMULATION OF AIRCRAFT BEHAVIOUR IN WAKE VORTICES WITH RESPECT TO FLIGHT SAFETY

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Abstract

Even nowadays wake turbulence plays an important role concerning flight safety so that preventive actions are necessary to inhibit incidents. To investigate the interaction between aircraft and the vortex flow both a realistic, if possible realtime capable vortex model and an aircraft simulation with an aerodynamic lifting surface/lifting line algorithm for determination of the vortex induced forces and moments on an encountering aircraft is required. Both is presented in this paper. The realtime capable vortex model is based on the results of a single vortex simulation and describes the development of the vortex flow from it's generation at the wing trailing edge up to it's decay. The parameters of the vortex model consider the influence of the vortex generating aircraft and the influence of atmospheric turbulence on vortex aging. Based on this vortex model computations of aerodynamic forces and moments on an aircraft encountering the vortex flow have been carried out. The influence of parameters like

- encounter angle
- wing span of the encountering aircraft in relation to the vortex core extension
- weight and size of generating and encountering aircraft

has been investigated. Aircraft simulations with fixed controls showed the influence of the encounter angle between flight path and vortex axis on the aircraft movement. By application of a simple flight control system the behaviour of a controlled aircraft under the influence of wake vortices is demonstrated. In contrast to that, simulation results of a manually flown landing approach into a wake vortex show the severe problems, the pilot has to control the aircraft.

Introduction

The wake vortex is a well known phenomenon since the first days of aviation $^{(1)}$. Already at the beginning of this century it was found that a lifting surface like an aircraft wing produces two counterrotating vortices at the wing tips (fig. 1). The fact that wake vortices can have an impact on flight safety was first noted in the seventies when the first heavy jet aircraft entered into service. Those aircraft produce very strong vortices which may lead to hazardous situations for following aircraft. The most dangerous situation is given in the flight segments 'take off' and 'landing approach' due to the relativ small distances between the aircraft, which additionally all move on similar flight paths. As a consequence the Federal Aviation Administration introduced a separation rule, the wake turbulence classification (tab. 1) which orders definite minimum separation distances between two aircraft. Due to the growth in air traffic this separation rule meanwhile restricts the economic operation of the big airports so that there is great interest to reduce the ordered separation distances. To investigate the possibility to meet this requirement, detailed knowledge concerning the vortex and about the interaction between aircraft and vortex flow is needed.

In the present paper simulation results of aircraft behaviour in wake vortices are presented. The investigations have been carried out on a six degree-of-freedom fixed base flight simulator. For a realistic description of the time dependent vortex flow field a wake vortex model has been developed $^{(2)}$. This model which is based on the use of single discrete vortex elements, includes the whole life cycle of a vortex from its generation through its decay. The main model parameters are the weight, the geometric dimensions of the vortex generating aircraft, the atmospheric condition and the vortex age. To produce realistic simulation conditions, the minimum separation distances due to the wake turbulence classification have been considered to determine the distances between the vortex generating and the encountering aircraft. This, of course, defines the vortex age at the point of encountering.

Nomenclature

$A_1 - A_4$	: parameter of the vortex model
b	: wing span
C_l	: rolling moment coefficient
F	: failure function
H	: altitude
k	: parameter of KUTTA JOUKOWSKY's law
N	: number of inducing points
r	: radial coordinate
r_c	: vortex core radius
s	: wing span
s'	: distance between vortices after roll-up
t	: time, vortex age
V	: airspeed
V_t	: tangential velocity of the vortex flow
W	: weight
Δx	: distance between vortex generating and encountering aircraft
Δy	: lateral displacement between aircraft and vortex flow
Γ	: total vorticity
γ	: flight path angle
η_o	: nondimensional lateral displacement between aircraft and vortex flow
π	: 3.14159...
ρ	: air density
σ	: standard deviation of turbulence velocity
Φ	: bank angle
Ψ	: encounter angle
ξ	: aileron deflection
a/c	: aircraft
max	: maximum
NM	: nautical miles
ref	: reference
to	: tons

The Vortex Flow

A lifting surface, such as an aircraft wing produces two counterrotating vortices which develop in the downstream direction. The strength of the vortices is determined by the wing lift, the aircraft velocity, the air density and the wing span according to the law of KUTTA JOUKOWSKY

$$\Gamma = \frac{L}{\rho\ b\ V\ k} \tag{1}$$

The parameter k depends upon the lift distribution along the wing span. The generation of the vortex flow corresponds to the differences in pressure on the upper and lower surface of a finite span wing. This leads to a lateral flow from the lower side to the upper side of the wing. As a consequence the pressure varies in the lateral direction. As the local pressure difference is proportional to the local lift force, this difference corresponds to the spanwise lift distribution, which, in turn corresponds to the distribution of circulation. At the wing trailing edge the counterwise oriented lateral flows on the upper and lower side of the wing mix, resulting in a sheet of vorticity behind the wing, which tends to roll up in the downstream direction resulting in the generation of the vortex flow. At the end of the roll up process stands a vortex flow with an antimetrical distribution in tangential velocity. As an viscid phenomenon the vortex flow field shows a viscid core region with a nearly linear increase in tangential velocity and an inviscid outer flow with a hyperbolic decrease in velocity (fig. 2). After roll up the vortices have the smallest vortex core radii and the highest vortex core velocities. Due to friction effects the core radii begin to increase and the core velocities decrease following a law of similarity (fig. 3). This process is called 'vortex aging'.

Vortex core radius and core velocity are the main characteristic parameters. For modelling the time dependent vortex development these parameters have to be described as a function of time.

The roll up of the sheet can be determined by a numerical simulation where the wing flow is described by a set of single vortices$^{(3)}$. While the single boung vortices describe the bound circulation distribution along the wing span, the single free vortices describe the circulation distribution in the vorticity sheet. Due to the mutual induced velocities of the single vortex system the sheet begins to roll up into two counterrotating spirals (fig. 4).

The computation of this roll up process enables a complete determination of the vortex flow field. fig. 5 and fig. 6 show two examples for a clean and a flapped wing. For the clean wing the typical vortex flow field with an upwind zone outside and a downwind zone within the vortex cores can be seen. For the flapped wing three discrete vortex cores develop in the flow which stand for the wing tip vortex (1) and the counterrotating flap vortex pair (2) and (3). These three vortex cores in turn rotate around each other and finally mix resulting in one common vortex flow.

As the results of the single vortex simulation showed good accordance with measured data$^{(4)}$ they were taken as a basis for a realtime capable wake vortex model$^{(2)}$

$$V_t(r,t,\sigma) = \frac{\Gamma}{2\pi r} * \left(1 - e^{-\frac{r^2}{A_1{}^2}}\right) * A_2\left(\operatorname{atan}(A_3 \cdot r) + A_4\right) * e^{-0.4\frac{\sigma t}{s'}} \tag{2}$$

which can be seen as modified OSEEN[6] vortex. The model parameters A_1 ... A_4 are time dependent and aircraft specific. Values for the model parameters for aircraft of the light, medium and heavy category are found in [2].

The influence of atmospheric turbulence is considered by an algorithm found by DONALDSON[5] ($e^{-0.4 \frac{\sigma t}{s'}}$) which shows a decrease in tangential velocity with time t following an exponential function. Additional parameters influencing the vortex aging are the standard deviation of the turbulence velocity σ and the distance between the vortex cores after roll-up s'. According to Eq.(2) a stable stratified atmosphere with small turbulence velocities leads to a slow decay of the vortex flow. So the atmospheric condition is an important parameter influencing the hazard of a vortex flow with respect to flight safety. The second model parameter s' is aircraft specific and corresponds to the wing span ($s' = \pi/4 * s$ for an elliptic bound circulation distribution) of the vortex generating aircraft. From Eq.(2) it can be stated that the vortex flows especially of large aircraft with a great wing span pose a hazard because of their slow decay resulting in long vortex life times.

fig. 7 shows the development of the characterisic vortex parameters 'core radius' and 'core velocity' versus time for three different aircraft which, according to the wake turbulence classification belong to three different weight categories

a/c A => weight category 'light'
a/c B => weight category 'medium'
a/c C => weight category 'heavy'

While the core radii are nearly aircraft independent, the influence of the vortex generating aircraft can significantly be seen in the core velocities. Here the 'heavy' aircraft as expected produces the highest velocities, which even at life times of three minutes show considerable values of about 5 m/s. So the hazard associated with vortex flows of heavy aircraft is caused by two reasons

- these aircraft produce the strongest vortex flows
- the vortex life times are greatest, due a slow aging process.

Influence of Wake Vortices on Aircraft Behaviour

The investigations concerning the interaction between vortex flow and aircraft are divided into two parts

- stationary computations of the vortex induced lift forces and rolling moments
- dynamic simulations of aircraft encountering wake turbulence

In both cases the wake vortex model described by Eq. (2) was used. The aerodynamic forces and moments were calculated with a simplified lifting line/lifting surface model according to the vortex induced velocity distributions along the wing and tailplane span.

The precision of the computation of aerodynamic forces and moments directly corresponds to the number of reference points along the span where the local velocity is considered. The required number of reference points for a precise computation in turn corresponds to the geometric dimension of the flow field in relation to the aircraft dimensions. For low frequent, wind shear like flow fields with a nearly linear velocity distribution four points are sufficient (hatched region in fig. 8) to consider the velocity distribution over the aircraft surface. For small sized flow fields with geometric dimensions within or less than the wing span of the encountering aircraft the simplification of a linear velocity distribution is no more valid (see fig. 8). Here more reference points along the wing span are required to satisfy a sufficient precision. fig. 9 shows the relative failure in rolling moment

$$F = \frac{C_{lref} - C_l}{C_{lref}} \qquad (3)$$

versus the number of points and the vortex age (C_{lref} is a reference value, calculated with hundred points). As expected the failure decreases with an increasing number of points. As the numerical expense for the aerodynamic computation corresponds to the number of points, a compromise between expense and precision has to be found. For vortex flows with geometric dimensions of only a few meters (see core radii in fig. 7) a minimum of 30 points is required to achieve a maximum failure of about 10%.

On this premise the induced rolling moments of a wing positioned in the vortex center is calculated for different wing spans. fig. 10 shows a nonlinear distribution with considerable increases in rolling moment with decreasing wing span. So the vortex induced forces and moments are at maximum for small aircraft with a wing span in the magnitude of the vortex core diameter. Due to their relativ small forces and moments of inertia, those aircraft additionally show a quick response to external disturbances, so that the pilot of an encountering aircraft has only few time to react and to control the situation. In comparison with large and heavy aircraft, small and light aircraft are considerably more endangered in an encounter situation. This is in accordance with statistics of vortex caused accidents, showing the greatest danger for small aircraft following heavy aircraft.

Another signicant parameter is the encounter angle Ψ between the aircraft's flight path and the vortex axis. fig. 11 shows the vortex induced rolling moments versus the lateral displacement η_0 between aircraft and vortex axis and versus the lateral encounter angle. For a flight path parallel to the vortex axis ($\Psi=0$) the maximum values occur if the aircraft is positioned in the vortex center. With increasing lateral displacement the sign of the induced rolling moment changes. For the pilot of an encountering aircraft this may lead to a disinterpretation of the situation concerning his position relative to the vortex axis and the sense of rotation of the vortex flow. fig. 12 points out the problem. The pilot of an aircraft encountering the left rotating vortex left from the vortex axis may believe, that he has hit the center of a right rotating vortex. This misinterpretation can cause a wrong pilot's reaction probably resulting in a hazardous situation even if the vortex induced forces can be controlled with the aircraft's control surfaces.

fig. 11 additionally shows a significant increase in rolling moment with increasing encounter angle. This phenomenon is caused by the increase of the vortex geometric dimensions in relation to the wing span with increasing encounter angle. In an aircraft fixed coordinate system, the vortex core radius changes with

$$r_{cf} = \frac{r_c(\Psi=0)}{\cos \Psi} \quad . \tag{4}$$

According to the aircraft behaviour this fictive increase in geometric extension of the vortex flow has no significant influence as the aircraft crosses the vortex flow the faster, the greater the encounter angle is (see fig. 14).

Concerning aircraft operation it is most important how aircraft specific parameters both of the vortex generating and of the encountering aircraft influence the hazard of a vortex encounter.

The characteristic parameters of the vortex generating aircraft are the weight and the wing span which both determine the vortex strength according to Eq.(1). The wing span additionally influences the aging process (see s' in Eq. (2)) in a way that an increasing wing span leads to a slower decay of the vortex flow. For the encountering aircraft the wing span also is a characteristic factor influencing the vortex induced forces and moments (see fig. 10).

fig. 13 shows the rolling moment induction for different combinations of vortex generating and encountering aircraft ($\eta_0=0$, $\Psi=0$) versus the vortex age, which in this case is determined by the relation of the distance between the aircraft and the airspeed. For the computations a stable stratified atmosphere with a turbulence velocity of 0.3 m/s was assumed. Three different aircraft as vortex generator and encountering aircraft belonging to different weight categories were used.

Generating a/c	Encountering a/c	Weight Categorie
A	D	'light'
B	E	'medium'
C	F	'heavy'

In the case of a/c A as vortex generator the induced rolling moments for all three following aircraft are relative small and can easily be controlled by pilot's action, so that a light aircraft as vortex generator in any case can be regarded as 'not dangerous'. For a/c B as vortex generator, the vortex influence is significantly greater. If the minimum separation distances according to the wake turbulence classification are considered, an aileron deflection of about 50% of the maximum roll control capability is required to compensate the vortex induced rolling moments. As expected the 'heavy' aircraft as vortex generator is most dangerous. Here for all three encountering aircraft full aileron deflection is required for compensating the vortex induced disturbances. This shows, that hazardous situations can occur even if the wake turbulence classification is considered.

Besides these stationary investigations dynamic simulations have been carried out, to show the influence of wake vortices on aircraft behaviour. fig. 14 shows simulation results of a vortex encounter with fixed controls for different encounter angles. The initial position of the aircraft is determined by the condition, that the flight path in any case should cross the vortex core to enable comparisons of the different cases under similar conditions. The simulation results show that, despite increasing vortex induced forces and moments (see fig. 11) the influence of the vortex flow is the smaller, the greater the encounter angle is. Responsible for that is the time period the aircraft needs to cross the vortex flow. The greater the encounter angle is, the shorter is the time of influence of the vortex flow on the aircraft. At encounter angles of 10 deg the influence of the vortex flow on the maximum bank angle for example is reduced by 80% compared to a parallel encounter. At 20 deg encounter angle no significant influence on aircraft behaviour can be observed. So landing on crossing runways can be an efficient measure to reduce the hazard of vortex encounters.

Another possible way to increase flight safety may be the application of a flight control system. fig. 15 shows simulation results of a vortex encounter of an aircraft with a simple flight control system controlling bank angle, flight path angle and track. The results demonstrate the good efficiency of the control system. For a separation distance according to the wake turbulence classification ($\Delta x = 11\,120\,m$), the deviations in bank angle and flight path angle are negligible. To investigate the possibility of reducing the ordered separation distances without an impact on flight safety, vortex encounters were simulated for different separation distances down to 4 km. The results show a definite increase in bank angle and flight path angle deviations as well as lateral displacements, without however reaching critical values ($\Delta\gamma = +/-1.5$ deg, $\Delta\Phi = 2.5$ deg, $\Delta y = 7\,m$). Efficient flight control systems as they are more and more implemented in modern fly-by-wire aircraft may lead to a considerable improvement towards a reduction of the separation distances while maintaining the level of flight safety. The essential requirement for the flight control system is the ability of a complete automatic landing for the hazard of a vortex encounter is greatest in proximity to the ground shortly before touch down. Compared to this automatically controlled encounter, fig. 16 shows simulation results$^{(7)}$ of a manually flown landing approach into a vortex flow, where the vortex was hit near the center, just as in fig. 14. At the point of encountering a positive rolling moment is induced, which due to a lateral displacement of the aircraft turns into negative (see fig. 12). The bank angle is about 10 deg and the pilot commands 50 deg of aileron deflection for compensation. The changes in heading are about 6 deg with fast oscillations. After climbing up to 50 m the pilot tries to touch down again and encounters the flow for a second time. Here the rolling moments are even stronger and the pilot has to command about 70 deg of aileron deflection. Facing those severe problems the pilot decided to perform a go-aroung manoeuver. This simulation shows the considereable influence of the pilots reaction on aircraft behaviour. Especially the combination of rolling moment and vertical movement makes this situation difficult to control.

Conclusions

Wake turbulence is a significant parameter concerning flight safety. Especially large and heavy aircraft produce strong vortex flows inducing considerable aerodynamic forces and moments on an encountering aircraft which at worst can lead to a hazardous situation. To increase flight safety the wake turbulence classification has been introduced ordering minimum separation distances between two aircraft. As the aircraft weight is an important parameter influencing the strength of the vortices on the one hand and the response of the encountering aircraft on the other hand, both generating and encountering aircraft are classified in the weight categories 'light', 'medium' and 'heavy'.

Investigations of the vortex development show a strong rotating flow after it's generation at the wing trailing edge. Friction effects lead to a slow but steady decay of the vortex with time, resulting in an increase in core radius and a decrease in maximum tangential velocity. With a core radius being nearly aircraft independent, the influence of the generating aircraft type is dominant in the induced tangential velocities. Especially the vortex flows of large and heavy aircraft can produce considerable disturbances on a following aircraft even for a vortex age of three minutes and more, according to a distance of 6 NM for an average approach speed of 140 kts.

Investigations of the interaction between aircraft and vortex flow show that the relation between wing span of the encountering aircraft and the vortex core diameter plays an important role. Especially small aircraft with wing spans in the same magnitude as the vortex core region are most endangered. Here the induced rolling moments are significantly greater compared to large wing span aircraft. Encounter situations for different combinations of generating and encountering aircraft concerning aircraft weight verified, that especially 'heavy' aircraft as vortex generator are most dangerous. Here in adverse conditions full control surface deflections are required to compensate the vortex induced disturbances even if the wake turbulence classification is considered. In contrast to that, 'light' aircraft as vortex generator in any case are not critical. Aircraft of the 'medium' categorie produce vortices with a considerable but controllable influence on following aircraft. Here the pilot's reaction plays an important role.

Simulation investigations of the dynamic behaviour of an encountering aircraft show, that crossing the vortex flow even at small angles leads to a significant alleviation of the vortex influence. At an encounter angle of only 20 deg no significant deviations in bank angle and flight path angle were observed, although the aircraft was simulated with fixed controls. Simulations of an aircraft equipped with a simple flight control system show, that a control system is an effective measure to compensate the vortex induced disturbances even at distances, which were only 30% of the ordered reference separation distance. In contrast to that a manually flown landing approach under similar conditions demonstrates, that a pilot has severe problems to control the aircraft.

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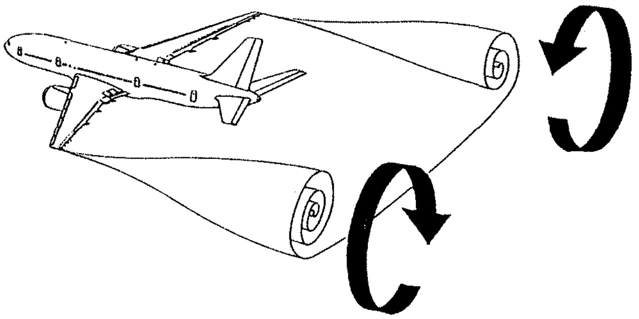


fig 1: Generation of Wake Vortices

	Encountering Aircraft		
Vortex Generating Aircraft	Heavy	Medium	Light
Heavy	4	5	6
Medium	3	3	5
Light	3	3	3
	Minimum Distances in NM		

(Heavy: W > 136 to, Medium: 136 to > W > 7 to, Light: W < 7 to)

tab 1: Wake Turbulence Classification

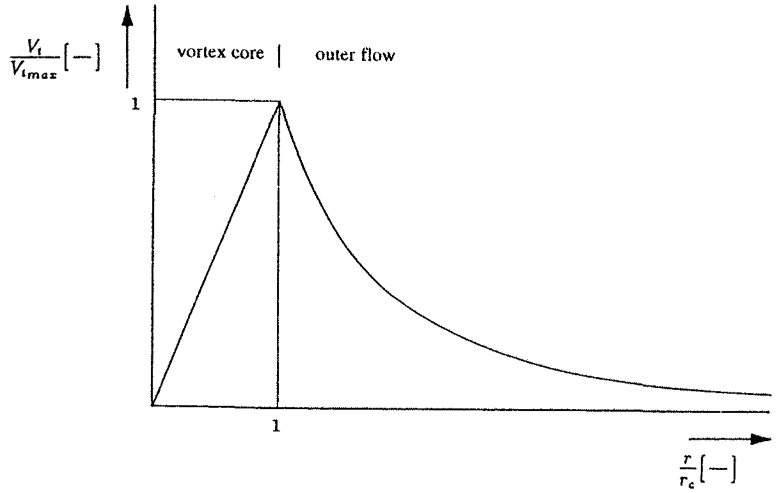


fig 2: Tangential Velocity in a Viscid Vortex Flow

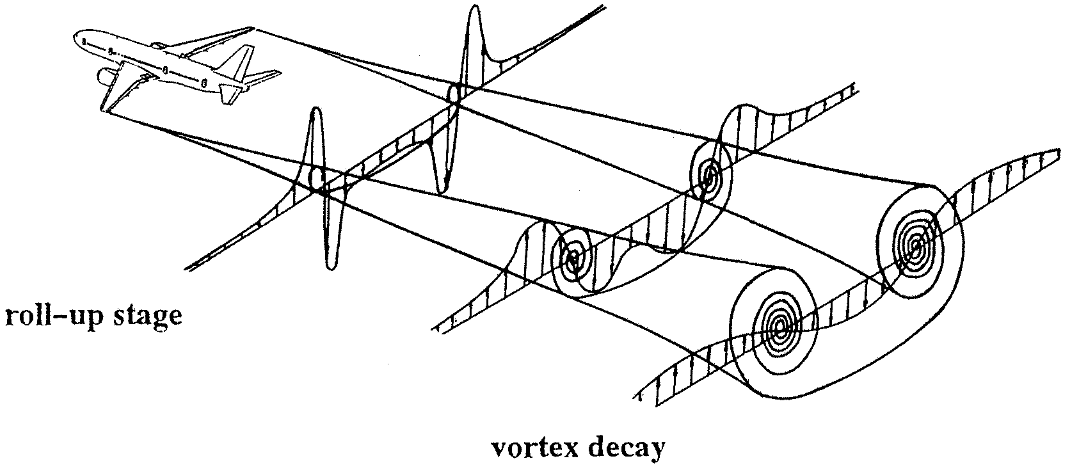


fig 3: Vortex Stages

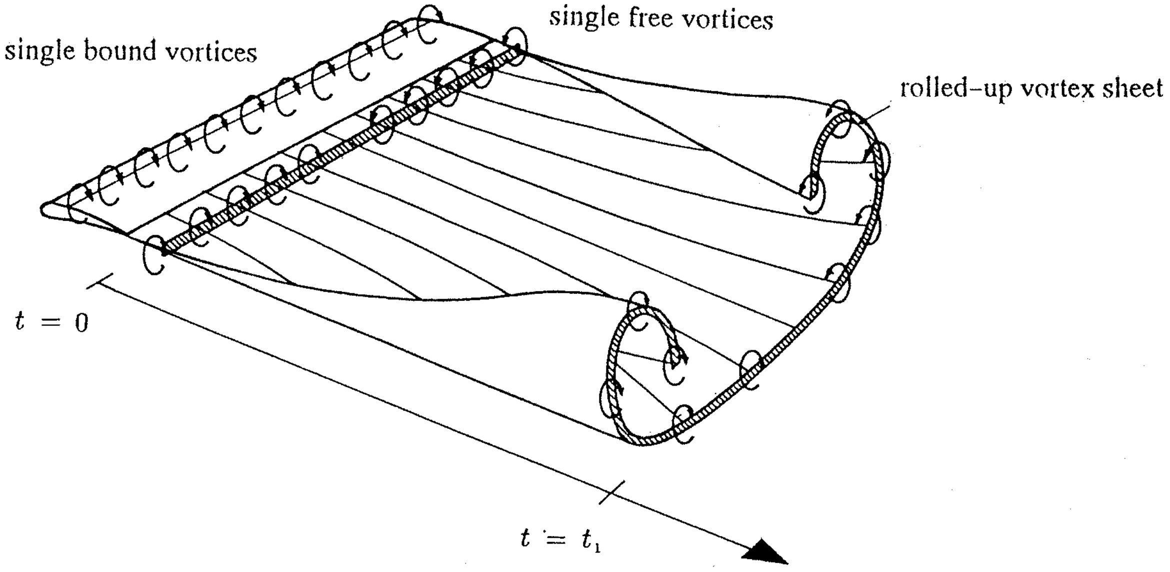


fig 4: Roll-Up of the Vortex Sheet

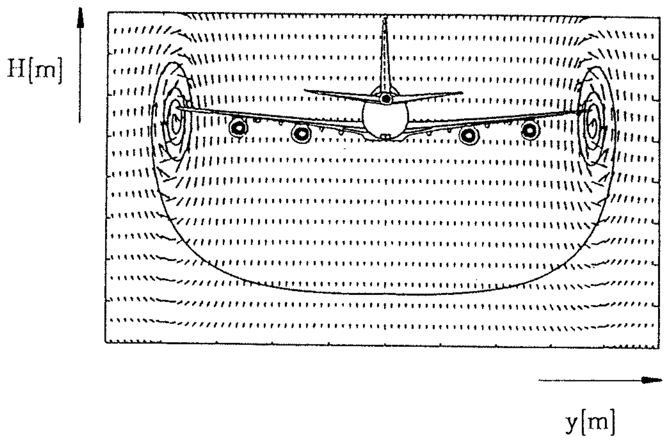


fig 5: Vortex Flow Field (Clean Wing)

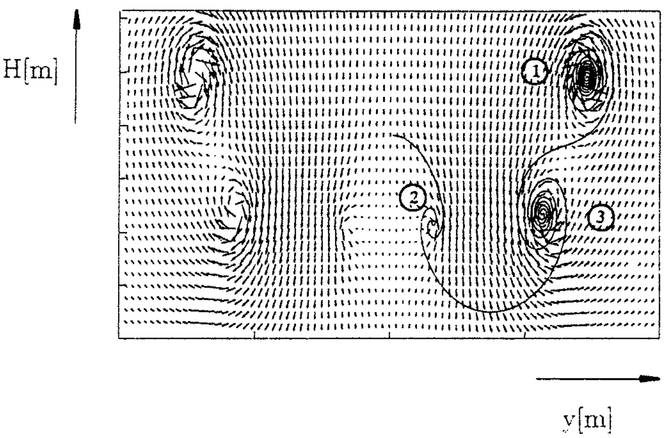


fig 6: Vortex Flow Field (Flapped Wing)

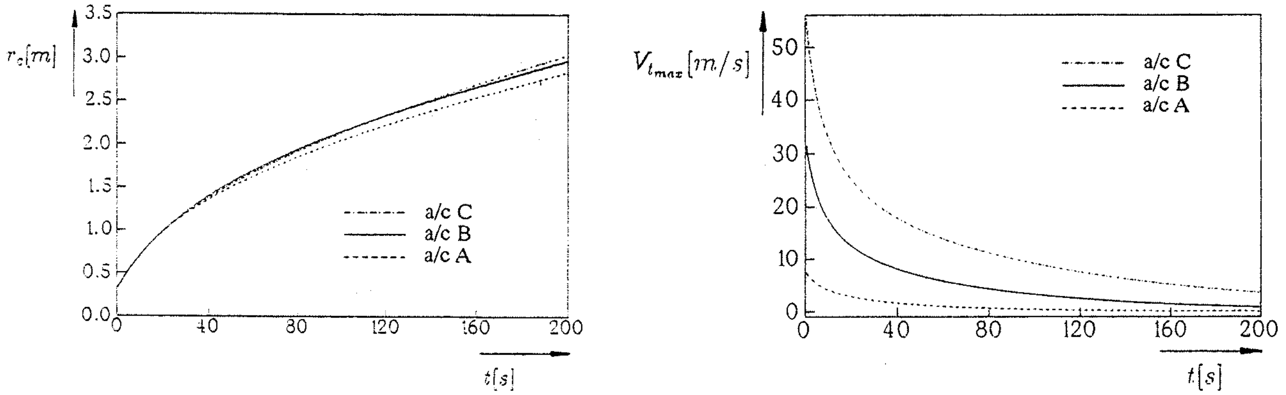


fig 7: Influence of Vortex Aging on Core Radius and Maximum Tangential Velocity

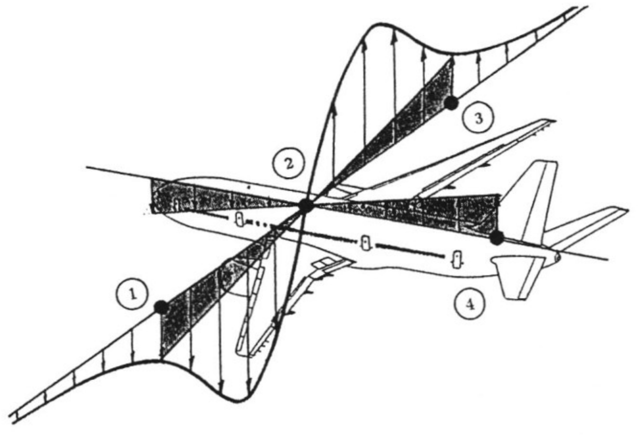


fig 8: Four Point Model

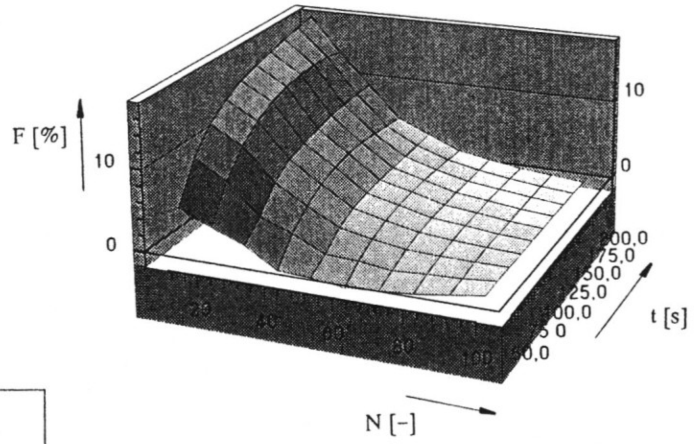


fig 9: Failure in Rolling Moment due to Number of Inducing Points

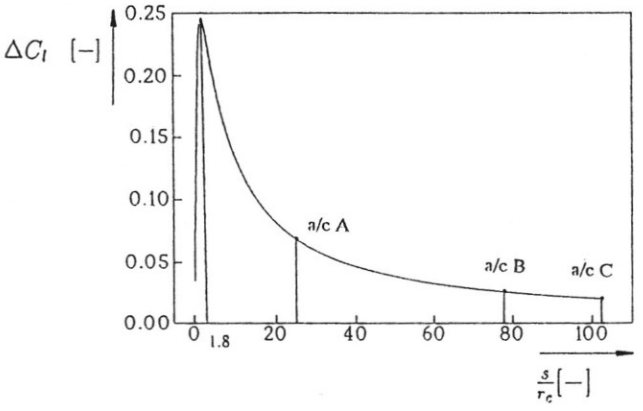


fig 10: Influence of Wing Span on Rolling Moment Induction

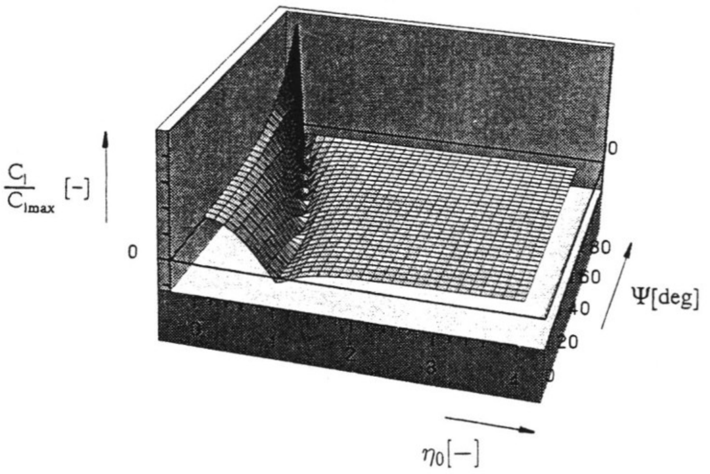


fig 11 : Rolling Moment for Different Encounter Angles

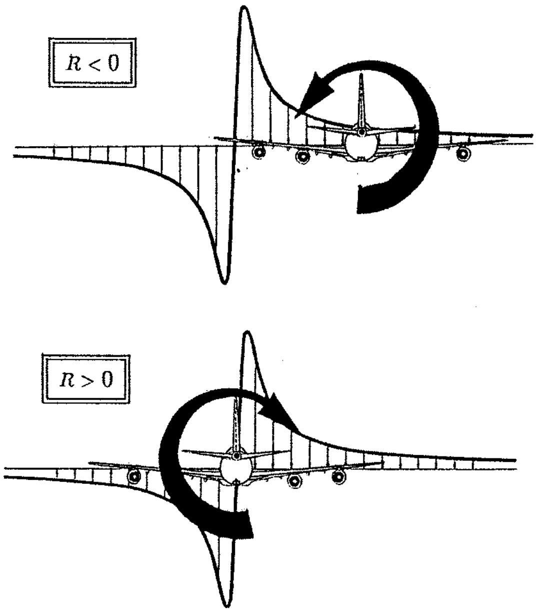


fig 12 : Change in Rotation sign for Lateral Displacement

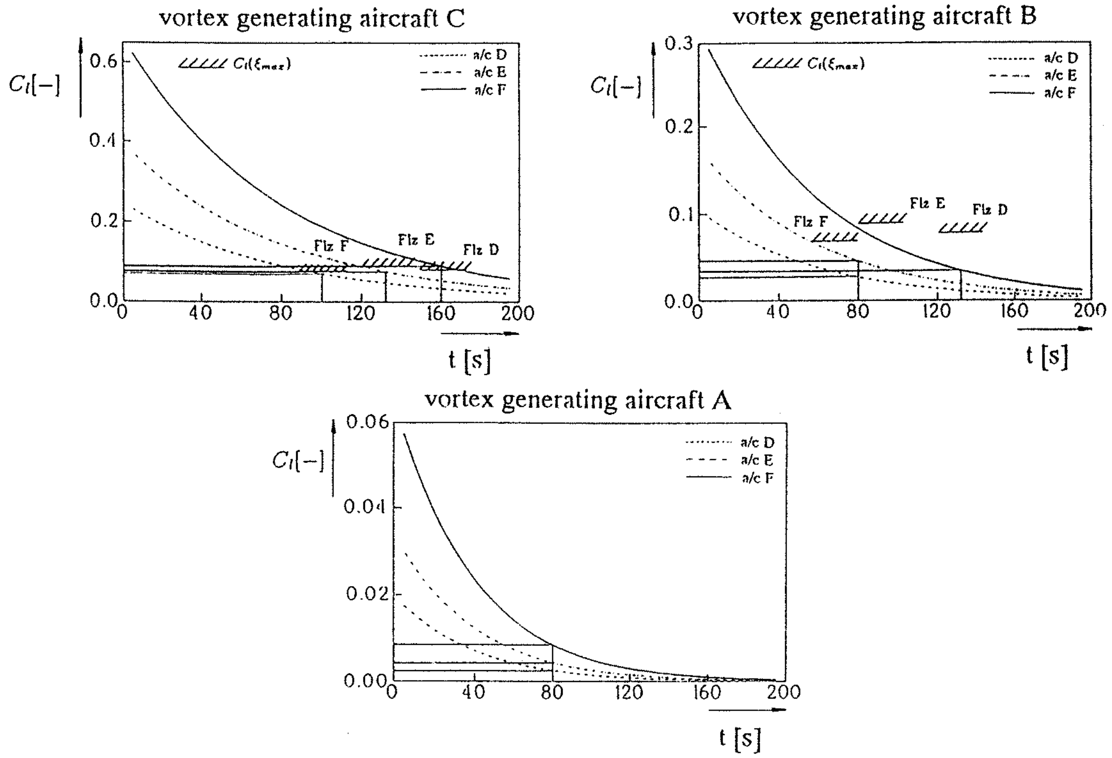


fig 13 : Rolling Moments for Different Aircraft Combinations

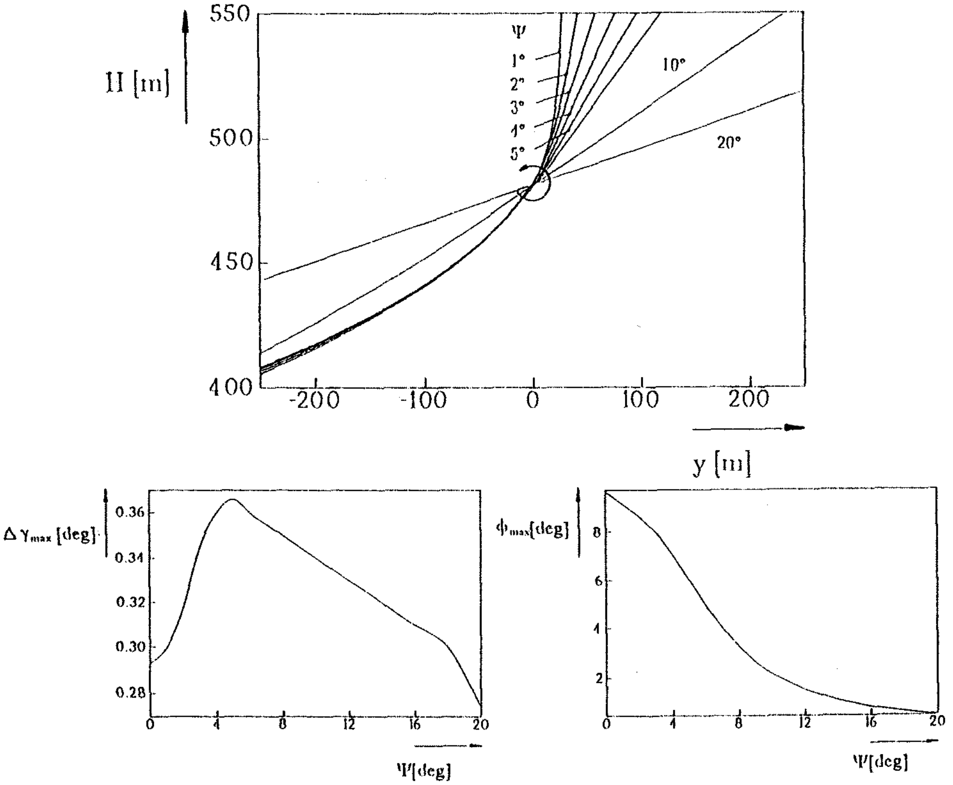


fig 14 : Aircraft Behaviour for Different Encounter Angles

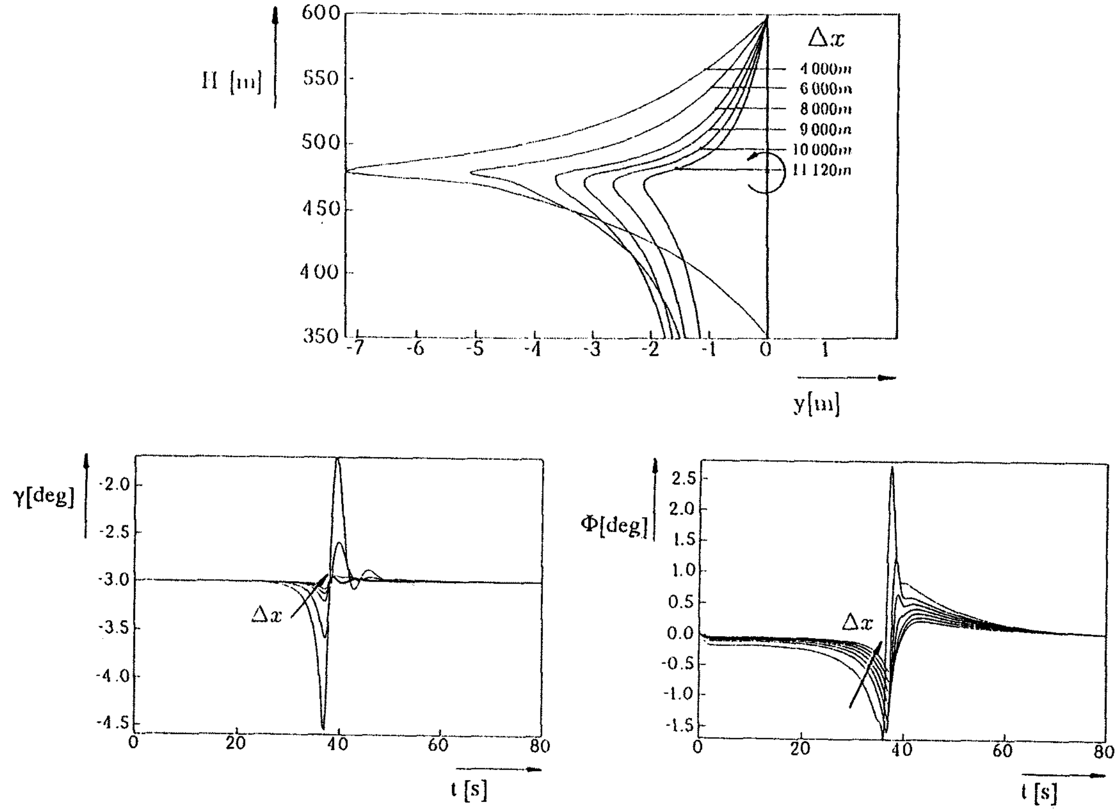
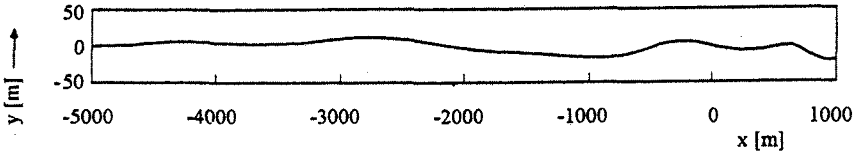
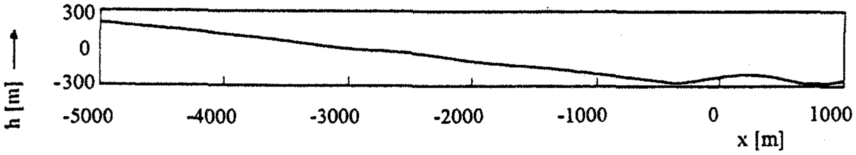


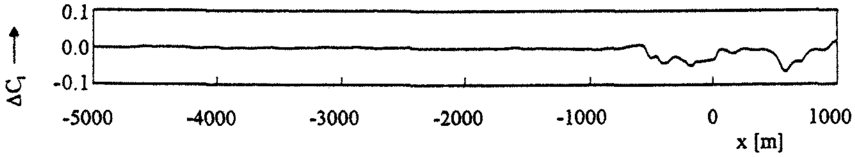
fig 15 : Vortex Encounter of an Aircraft with a Flight Control System



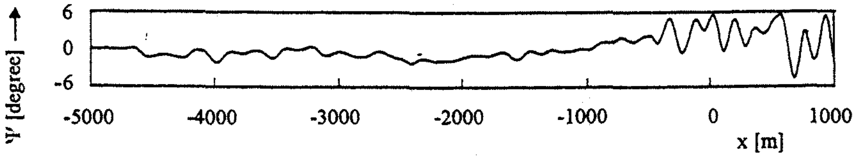
groundtrack



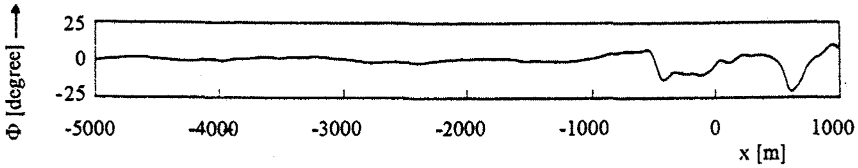
height



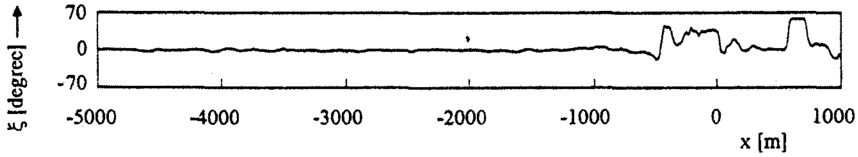
vortex induced rolling moment



heading



bank angle



aileron lever deflection

fig 16 : Simulation Results of a Manual Landing Approach