

WAKE VORTEX ENCOUNTER SEVERITY FOR ROTORCRAFT IN APPROACH AND LANDING

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Abstract

The Advisory Council for Aeronautics Research in Europe predicts that European air traffic may nearly triple by 2020. The growth in air traffic is already an increasing problem with capacity at some airports becoming limited due to congestion. This could be alleviated by providing additional passenger capacity at hubs through the introduction of rotorcraft using new IFR procedures and operating simultaneously but independently of the fixed-wing traffic. These Simultaneous Non-Interfering operations (SNI Ops) will be enabled by a 'reconfiguration' of the airspace, taking advantage of new navigational and air traffic management systems. SNI Ops raise critical safety questions for rotorcraft wake vortex encounters (WVE's) and will require consideration of the longitudinal and lateral aircraft separation and the locations of the rotorcraft FATO's (Final Approach and Take-Off areas). This paper presents analysis from work carried out as part of the Framework 6 project 'OPTIMAL' including the development of predictive methodology and analysis for rotorcraft WVE's, using a severity rating scale. In particular, scenarios are considered where the rotorcraft is following precision glideslopes of up to 12° in both good and degraded visual conditions. Handling qualities criteria have already been found to be well suited to investigating severity issues, by evaluating the pilot's perception of their ability to overcome the effects of an encounter. Within this framework, draft boundaries are proposed for the acceptable severity of an encounter. Furthermore, a pilot may be able to recover from an encounter, but the question of whether the required navigational precision would be compromised and a go-around required is also addressed.

List of Symbols and Abbreviations

$\dot{p}, \dot{q}, \dot{r}$	Roll, pitch and yawing body-axes angular accelerations
a_x, a_y, a_z	X, Y, Z body-axes accelerations
ACP	Aerodynamic Computation Point
AGL	Above Ground Level
ATM	Air Traffic Management
B	Vortex generating aircraft wingspan
c.g.	Centre of gravity
C_D	Drag Coefficient
C_L	Lift Coefficient
C_M	Pitching Moment Coefficient
DVE	Degraded Visual Environment

FATO	Final Approach and Take-Off area
g	Acceleration due to gravity
GVE	Good Visual Environment
H_{lat}	FATO distance from runway/taxiway
HQR	Handling Qualities Rating
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules
ILS	Instrument landing System
IP	Integrated Project
LIDAR	Light Detection And Ranging system
M	Aircraft Mass
MDH	Minimum Decision Height
MTE	Mission Task Element
MTOW	Maximum Take-Off Weight
r	Radial position in vortex
r_c	Vortex core radius
RVR	Runway Visual Range
s	Scaling parameter of initial vortex spacing
SNI Ops	Simultaneous Non-Interfering Operations
V_c	Vortex core tangential velocity
V_{MINI}	Minimum speed for IFR flight
VMC	Visual Meteorological Conditions
VSR	Vortex Severity Rating
V_T	Vortex tangential velocity
V_X	Body X-axis Velocity
XI	Inertial X position
YI	Inertial Y position
ZI	Inertial Z position
Γ_0	Average vortex circulation
γ_h	Rotorcraft horizontal flightpath angle
Γ_r	Vortex circulation at a radial position r
ρ	Density of air

Introduction

OPTIMAL The OPTIMAL project is part of the European Commission's Framework 6 Programme. It is an Integrated Project (IP) covering a wide range of technical areas through a consortium of 24 partners. The OPTIMAL project is an air-ground cooperative program that is aiming to define and validate innovative approach and landing procedures for fixed and rotary wing aircraft in a pre-operational environment (website: www.optimal.isdefe.es).

The need for these developments is identified by ICAO forecasts of 5% growth per annum of world air traffic (www.icao.int). Based on recent experience This estimate is likely to be conservative for the European theatre of operations. Taking into account the variations in

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growth in the types of traffic (i.e. commuter over long-haul), ACARE's Vision 2020 (Ref. 1) is expecting European air traffic to potentially triple over the 2002-2020 timeframe. The impact of this will be increased airport congestion and the associated safety, efficiency and environmental effects unless additional measures are taken.

In response, it is proposed that a re-design of the airspace structure, division, categorisation and the Air Traffic Management (ATM) procedures, exploiting improved aircraft performance and new navigation technologies/capabilities, be undertaken. From this, four key aspects for European commercial air operations will be addressed: capacity, efficiency, safety, and reduced noise exposure.

Overall, the expected outcomes of the OPTIMAL project will be a validated set of approach and landing procedures, support systems and technologies achievable from 2010 as one part of a first step to the ACARE 2020 vision.

New Rotorcraft Procedures The University of Liverpool is working within the OPTIMAL work package that is developing new rotorcraft procedures, paying special attention to the context of airports allowing **Simultaneous Non Interfering (SNI)**, IFR (Instrument Flight Rules) rotorcraft operations. The new SNI procedures for rotorcraft are aimed at incorporating steep and/or curved and segmented trajectories. The benefit of these is the smaller noise footprints resulting from the higher altitudes of flights over population zones adjacent to airports and also the lower noise emissions of rotorcraft in steep approaches (greater than 6°). Important for the development of future SNI operations are the safety issues associated with interactions between rotorcraft and fixed-wing wake vortices in these new scenarios.

The University of Liverpool is contributing to the project by building upon past research in the modelling and simulation of rotorcraft vortex wake encounters. It is developing methods that will eventually allow the definition of the safety boundaries in terms of where rotorcraft SNI operations can take place and for defining the flight envelopes for different rotorcraft types. The important factors for such a study will include the wind speed and direction, the vortex generating aircraft (e.g., Airbus 310, Boeing 737), the encountering rotorcraft type and the rotorcraft's trajectory (approach, hover, take-off).

Wake Vortices: Their Characteristics and Risks

Wake vortices are generated by the lifting surfaces of all aircraft. Typically, the vortices that are shed by the wing along its span eventually

roll-up to form two counter-rotating vortices of swirling air. The strength of the vortices, Γ_0 , is directly linked to the lift (C_L) generated by the wing and is related to the wake generating aircraft's weight through the following relationship:

$$\Gamma_0 = \frac{Mg}{\rho sBV} \quad (1)$$

Clearly, the heavier the aircraft, the stronger the circulation Γ_0 . The correlation of the circulation with the velocity flow-field can be seen through the 'Dispersion' model for a vortex Ref. 2. This model expresses the tangential velocity, V_T , as function of the local circulation Γ , the radial location, r and the vortex core radius, r_c .

$$V_T = \frac{\Gamma_r}{2\pi(r^2 + r_c^2)} \quad (2)$$

As equation (2) shows, the tangential velocity is directly proportional to the circulation and thus to the aircraft weight via equation (1).

These parameters can be used to describe the basic characteristics of vortices and Table 1 shows some best fit parameters of vortices for current commercial transport aircraft. Also included are parameters for an alternative vortex model known as the 'Burnham' (Ref. 3) model which is used in this research and will be discussed later in the paper.

Aircraft	"Burnham" model		"Dispersion" model		
	r_c (m)	V_c (m s ⁻¹)	Γ (m ² s ⁻¹)	r_c (m)	V_c (m s ⁻¹)
B747	2.4	14.9	612	3.2	15.2
B757	<0.8	>21.2	251	<0.9	>22
A340	2.0	11.4	385	2.5	12.2
A310	<1.0	>20	283	<1.0	>22

Table 1 Best fit parameter values to LIDAR velocity profiles for the Burnham and Dispersion models (Ref. 3)

Once generated, the wing-tip vortices interact with each other, the atmosphere, and, if low enough, have a complex interaction with the ground. Extensive research has been conducted in trying to understand these phenomena using a variety of methods including LIDAR (Ref. 2) and acoustic measurements (Ref. 4) as well as numerical methods to model the vortices (Ref. 5 and Ref. 6). These methods try to capture the characteristic behaviour of vortices such as the self-induced sink-rate, their decay, and how they are 'transported' by the prevailing winds.

Typically, wake vortices descend at around 300-500 ft/min and can last for several minutes at near full strength in the right atmospheric conditions. It should be highlighted that wake vortices are sensitive to the atmospheric conditions. For example, strong or turbulent winds or strong density stratification (Ref. 7), caused by temperature gradients, are known to accelerate the decay and dispersion of wake vortices.

It is well known that these vortices are a potential risk to conventional fixed-wing traffic but what are the risks to rotorcraft? Longitudinal separation rules have been in place for conventional traffic on the same approach path for many years but what about simultaneous, laterally separated rotorcraft traffic? These questions raise even more fundamental questions related to the SNI concept for rotorcraft.

- What is the 'severity' when meeting a vortex of a given strength in a number of varying scenarios?
- What is the probability of encountering a wake vortex for different regions of a given airport and what will its strength be?

The work required to answer these questions represents a significant undertaking, especially b) which relies heavily on being able to predict the complex motion and decay of the vortices after they are generated. Part a) also requires a further breakdown, as the question of measuring severity of an encounter has yet to be defined. In addition, the question arises to whether the severity of an encounter and the ability to overcome an encounter can be linked to the handling qualities of the encountering rotorcraft.

All of these factors can be combined to form a framework to assess and quantify the severity of an encounter. One objective (see Figure 1) is to establish safety margins for the positioning of rotorcraft approach trajectories and the FATO (Final Approach and Take-Off area). The current criteria for VMC rotorcraft operations near to a runway are from Ref. 8 and are shown in Table 2. Consider a scenario of a light crosswind of 4-5 knots, a wind not strong enough to cause significant dispersion of a vortex. For a period of 4 minutes, (which is possible for a vortex lifetime) the vortex could travel over 490 metres if it moved at the speed of the prevailing wind. This is a fairly crude approximation, but even with an error of $\pm 50\%$, this calculation would put the vortex near to the FATO at the separation margin for the largest category of aircraft in Table 2. This simple example demonstrates that separation both laterally and longitudinally is an important factor for simultaneous, independent rotorcraft operations.

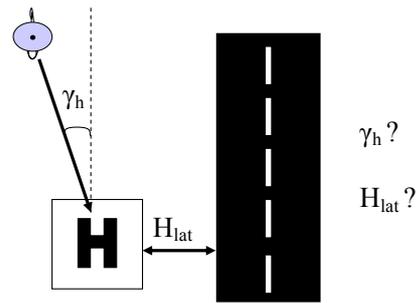


Figure 1. Helicopter FATO and approach trajectory separation distances from Runways

If aeroplane and/or helicopter mass are	Distance between FATO edge and runway or taxiway edge
up to but not including 2,720 kg	60 m
2,720 kg up to but not including 5,760 kg	120m
5,760 kg up to but not including 100,000 kg	180m
100,000 kg and over	250m

Table 2 ICAO Annex 14, Vol II – helicopter FATO separation distances from Runways

The potential hazard has been identified but how is the risk assessed? Simulation is the key here as recreating enough scenarios in flight-test of sufficient variety and severity would be unfeasible logistically and potentially dangerous.

By using the concept of vortex severity it is proposed that the risk for regions around a runway can be defined by combining severity data with vortex transport and decay data. Through this approach, recommendations for the approach corridors and FATO separations could be made.

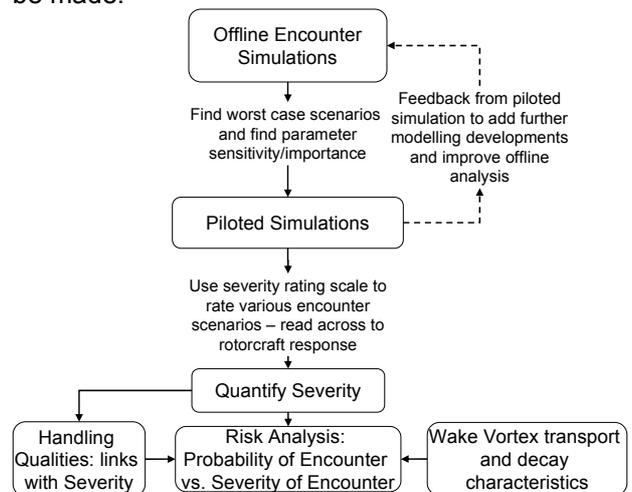


Figure 2 Roadmap to Wake Vortex Encounter risk analysis

A roadmap to achieving this goal is shown in Figure 2. The process begins with offline analyses that identify critical scenarios i.e. the worst cases as well as providing an environment where prescribed trajectories can be used to analyse the effect of an encounter. In conjunction with this process are the piloted simulations which focus on developing and using the vortex severity rating scale to acquire a measure of severity for a particular encounter. The objective here is to correlate the rotorcraft dynamic response or a particular encounter scenario to the perceived 'severity' according to the pilot. The outcome of this analysis feeds into two areas - the correlation of severity with a particular flight condition and the likely nature of a vortex's strength, geometry and location to give an overall wake vortex encounter risk. Finally, this data could be fed into a probabilistic model that features the vortex generating aircraft and encountering rotorcraft as well as the vortex transport and decay. An alternative approach to this could be to develop a contour map of a generic runway showing areas of graded 'risk' based on the severity of the vortices in that location. Either solution will have to be able to consider different wind conditions and various spatial or temporal separations.

Modelling and Simulation

Rotorcraft Modelling The rotorcraft simulation used for the research reported in this paper is a model of the Eurocopter AS365N1 Dauphin helicopter. The Dauphin (Figure 3) is a medium-weight multipurpose twin-engine helicopter that features a four blade main rotor and a 'FENESTRON' ducted fan tail rotor.



Figure 3 AS365N Dauphin Helicopter

The main technical specifications of the Dauphin are as follows:

- MTOW = 4250 kg
- Main rotor radius = 5.695m
- Main rotor nominal RPM = 350 rpm
- Tail rotor radius = 0.447 m
- Tail rotor nominal RPM = 4626 rpm

The Dauphin simulation was created using FLIGHTLAB (Ref. 9), which is an advanced software package that uses a multi-body dynamic approach to modelling flight vehicles. A modular

approach is used where the rotor, fuselage, empennage, fin, engines and flight control system are individual subsystems made up of 'components'. Each component is a modelling primitive, i.e. airfoil, hinge, mass, translate and by connecting these together, complex dynamic systems can be rapidly generated.

The Dauphin FLIGHTLAB model is currently a medium fidelity model with the following features:

- 5 segment, 4 blade, blade-element main rotor
- Quasi-steady, non-linear C_L , C_D and C_M data for each blade segment
- Separate Fuselage, Fin and Empennage subsystem models
- 3-state dynamic inflow model
- 3-axis rate stabilising SAS
- 'Simple' engine model
- Ducted fan tail rotor model

Wake Vortex Model a number of empirical models have been used to describe the flow-field of a vortex, including such models as the Dispersion model, Burnham, Rankine and Lamb-Oseen models (Ref. 5) For this study the wake vortex model used is the 'Burnham' model (Ref. 3), which takes the form:

$$V_T(r) = \frac{V_c [1 + \ln(r/r_c)]}{r/r_c}, \quad |r| > r_c \quad (3)$$

$$V_T(r) = V_c \left(\frac{r}{r_c} \right)^b, \quad |r| < r_c \quad (4)$$

Here, V_T is the tangential velocity which has different behaviour depending on the relative position to the vortex core. Inside the core, that is where the radial position r , is less than core radius, r_c , equation 3 is valid. Outside the core, equation 4 is used, and this models the attenuation of the velocities as the distance from the core is increased.

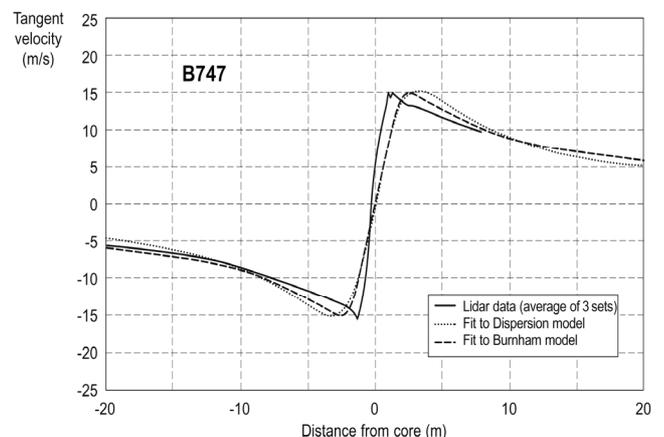


Figure 4 Velocity distribution in Boeing 747 Wake Vortex

Figure 4 (Ref. 2) shows that a reasonably good match can be achieved using a Burnham model representation of vortex with a Boeing 747 wake measured using LIDAR (Coherent Laser Radar). From Figure 4 the peak tangential velocity at the core radius has a magnitude of 51.45ft/s (15.68m/s), appropriate for a full strength 747 wake vortex.

In the simulations the velocities in this model are 'frozen' with no decay and the vortex was placed in a fixed location on the runway centreline, extending back from the threshold. This represents the worse case scenario i.e. full-strength. In order to investigate the effect of the reducing the strength of the vortices, encounters were also made with vortices with their velocities scaled to 66% and 33% of the full strength velocities.

Vortex Interaction Modelling The FLIGHTLAB Dauphin helicopter simulation interacts with the vortex through a number aerodynamic computation points or ACP's. In total there are 24 distributed locations on the model which 'see' the flow velocities of the wake vortex. These consist of 5 aerodynamic points on the four rotor blades, one for the tail rotor at the hub, one each for the fin and empennage, and one at the fuselage ACP. The vortex velocities are added to the inertial velocities and any induced inflow and/or interference velocities at each ACP. This is one of the fundamental simplifications for this level of simulation fidelity, whereby the assumption is that the vortex flow-field is unaffected by the rotorcraft downwash and the velocities are simply summed. Clearly, this is not likely to be wholly physically representative, but very little research is available to assess this assumption fully. Ref. 10 reports on a study that uses more advanced computational models. The results suggest that the effect of the vortex is overestimated at low speed using the superposition principle. However, the data in Ref. 10 suggest that the quasi-steady superposition approximation is reasonably valid at speeds of 60kts and above.

Results and Analysis

Offline analysis of Wake Vortex Encounters

In advance of the piloted simulations a method of predicting offline the effect of the vortex flow-field was investigated. This analysis method was based on the FLIGHTLAB Xanalysis 'steady-state' function. The procedure was that the rotorcraft was first trimmed in a particular flight condition (e.g. 70kts, 3deg glideslope, 0deg heading) outside the vortex flow field and then the rotorcraft was placed in the vortex flow field and run to steady state. This function 'freezes'

the rotorcraft body states i.e. positions and attitudes and rates but all the other dynamics are allowed to run to a steady value (such as the rotors). Once complete, the quasi-steady body-fixed accelerations $\dot{p}, \dot{q}, \dot{r}, a_x, a_y, a_z$ are recorded at the rotorcraft c.g. This procedure is repeated over multiple locations within the vortex flow-field and the results were used to form the contour plots shown in Figures 5 and 6. These contours give an indication of the nature of the disturbance and how they change throughout the vortex flow-field. The magnitudes however have to be treated with some care as they represent the quasi-steady acceleration as if the rotorcraft were instantaneously placed in the vortex. In this condition the rotorcraft still has the controls in the trim positions for a location outside the vortex. In reality, as a pilot encounters a vortex the controls would be constantly re-trimmed thus resulting in smaller steps in the accelerations induced.

Figures 5 and 6 show the acceleration contours for two example encounter geometries, a parallel encounter [to the vortex] (0° heading) and a perpendicular interception (90° heading). In both cases the rotorcraft had been trimmed at 70kts and on a 3° glideslope. The area displayed is an 80x80ft square with the 747 wake vortex core (100% strength) at the centre, the view angle is from the south (the vortex runs north-south).

What can be seen is that different regions excite accelerations in different axes. At the centre, in the core, the acceleration is predominately in pitch, this because of the lateral distribution of the normal flow across the main rotor disc. In this situation, the vortex possesses a clockwise rotation, so there is a downwash on the right side and an upwash on the left. Subsequently, the rotor blades are flapped up at the front of the disc, and down to the rear, via the 90 degrees phase shift of a rotor. A pitch up acceleration is induced. For rotorcraft, the direction of this pitching moment is dependent on two factors, 1) the sense of rotation of the vortex and 2) the rotation direction of the main rotor. For the Dauphin, the clockwise rotor induces a nose up pitching moment; a rotorcraft with an anti-clockwise rotor encountering the same vortex would experience a nose down pitching moment.

Also, for the parallel encounters, regions of strong yaw accelerations can be seen just above and below the core. This is due to the lateral components of the flow-field and most likely influences the thrust of the tail rotor. Either side of the core, regions of large vertical translational accelerations can be seen. This is where the rotor is either in the upwash or downwash regions of the vortex.

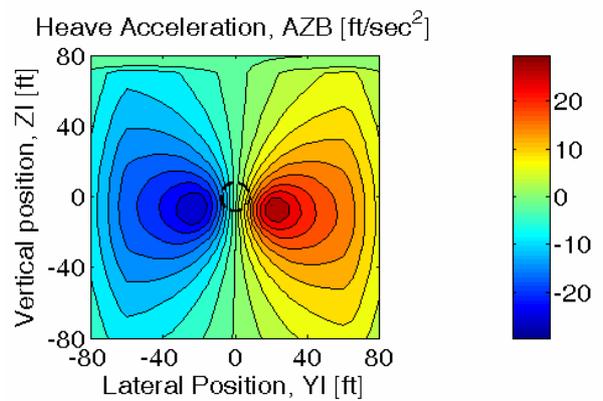
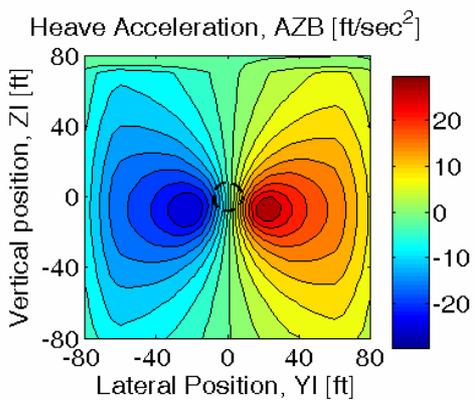
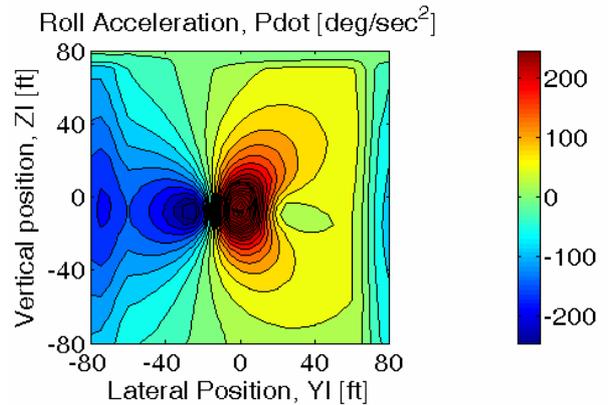
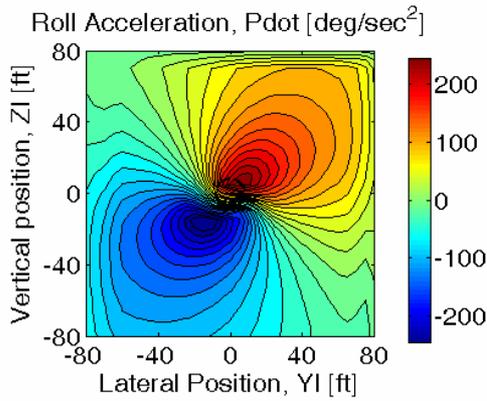
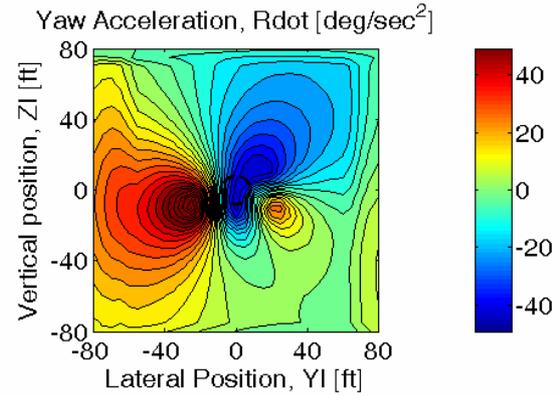
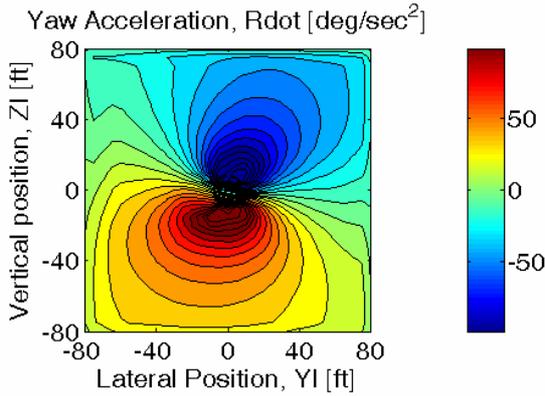
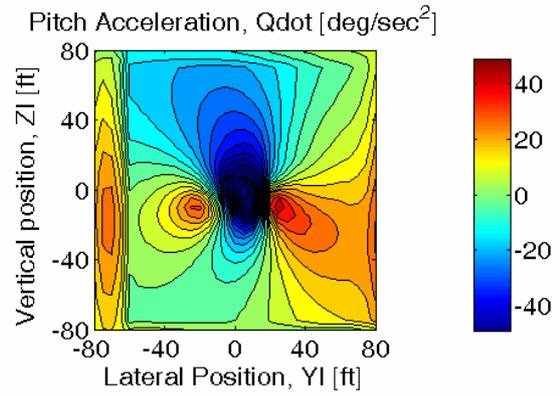
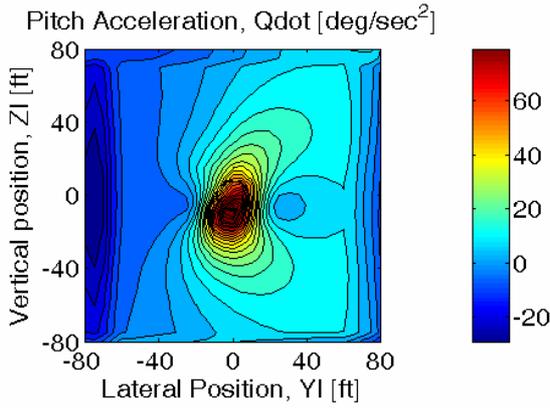


Figure 5 Acceleration contours for 100% 747 vortex (3° Glide slope, 0° Heading intercept, 70kts), (black dashed circle marks vortex core)

Figure 6 Acceleration contours for 100% 747 vortex (3deg Glide slope, 90deg (from left) intercept, 70kts), (black dashed circle marks vortex core)

The perpendicular encounter in Figure 6 shows a different behaviour in the pitch, roll and yaw accelerations. There are regions of high pitch acceleration just above and below the core that mirror the roll acceleration regions in the previous figure. Similarly, in the core, a region of induced roll acceleration can be seen, this is due to the distribution of the flow fore-aft over the rotor disc. For the same flow velocities in Figure 5 the roll accelerations are much higher in fig 6 than the pitch accelerations in the parallel encounter because the roll inertia, I_{XX} , is approximately four times lower than the pitch inertia, I_{YY} .

The analysis using the contour plots have shown that the accelerations induced on rotorcraft are highly dependent on the speed, flightpath angle, attitude and position within the flow-field. The quasi-steady measurements are useful for interpreting the dynamic response of the rotorcraft as it passes through the vortex and can reveal certain combinations of flightpath, attitude,

speed etc. where a potential increase in upset severity may occur.

A number of offline dynamic responses were also run. The tests consisted of trimming the rotorcraft simulation in a particular flight condition near to the vortex and then allowing the rotorcraft to fly into the vortex and recording the open-loop 'free' response. There are difficulties with this method, primarily with keeping the rotorcraft on an intercept course with the vortex core. The vortex flow-field tends to push the rotorcraft away from the critical regions near the core. This is unrealistic in the sense that the pilot, if following a desired course would try to maintain course and would force entry into a vortex core unknowingly. The case where vortex also has a translational velocity and can pass into a rotorcraft's flightpath simultaneously should also be considered. A partial solution to this has been to constrain some of the rotorcraft dynamic states such as the lateral position and heading.

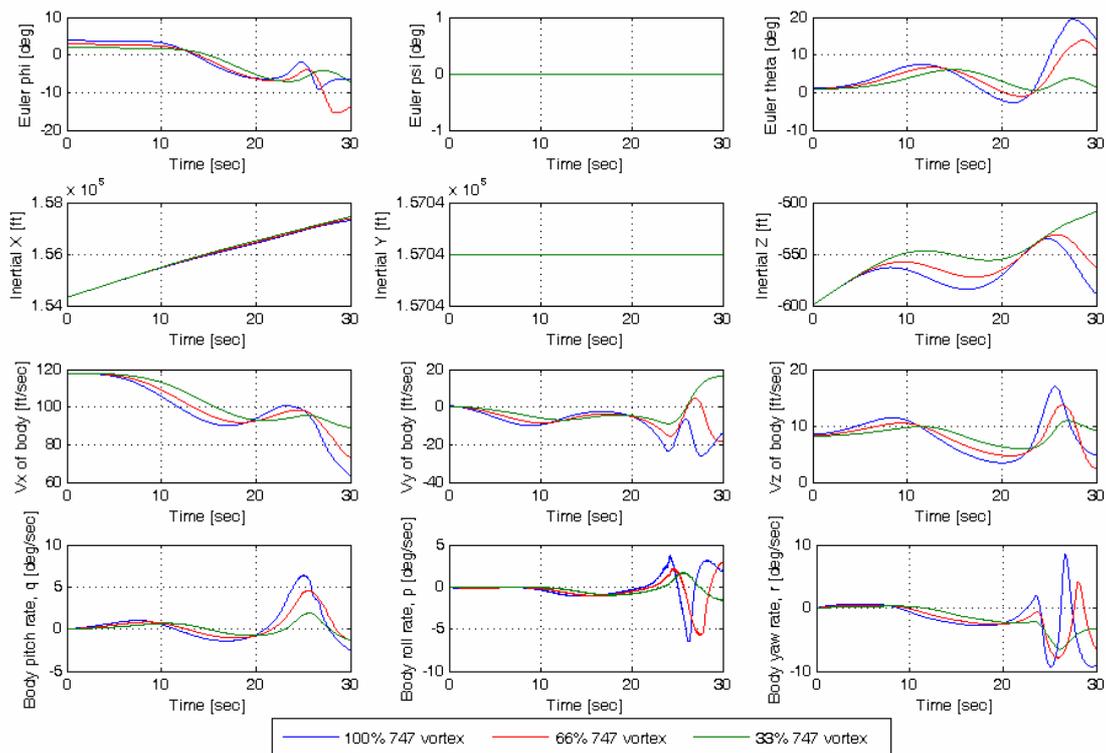


Figure 7 Offline Wake Vortex Encounters, 3° glide slope, 70kts (parallel encounter, 0° Heading)

Figure 7 shows an example of three parallel encounters with different vortex strengths (100%, 66% and 33%). The flight condition is a 3° approach at 70kts and the heading angle (PSI) and lateral position (YI) have been frozen.

The rotorcraft start point in these runs was approximately 70ft above the vortex core; this is near to the edge of the vortex flow-field. Almost immediately the rotorcraft is affected by the vortex causing it to be disturbed both in translation and rotation. The most notable effect

before the core is reached ($T < 25s$) is in the heave axis. In the plot of ZI vs. time, (negative ZI is up) the rotorcraft can be seen to be pushed up and away from the core. The stronger the vortex, the more the rotorcraft was deflected in the vertical axis; however, the rotorcraft did reverse its direction and descend again due to the forward airspeed (V_x) being lost in the climb. At $T = 23-24s$, the rotorcraft reach the vortex core in all three cases; not surprisingly, the 33% vortex encounter shows the smallest disturbances in roll, pitch and yaw.

The 66% encounter shows some interesting behaviour as the rotorcraft underwent a roll attitude disturbance greater than that seen for the 100% encounter. The reason for this seems to be the longer time spent in the vortex core; the lower velocities seen initially in the 66% vortex did not push the aircraft away as rapidly, resulting in the rotorcraft penetrating further into the core, with a consequent greater effect in the rotational axes than in the 100% case.

Clearly, the dynamic response of the rotorcraft occurs in all axes and can rapidly change in direction. The vertical disturbance could be especially critical if the downwash region of the vortex is encountered near to the ground. The limitation with this method is that the constrained dynamics are not fully realistic and that the rotorcraft free response will not be exactly the same as when the pilot is 'in the loop' and trying to minimize the disturbances.

Real-time Piloted Simulation

The objectives of the piloted simulations were to:

- Investigate the flight dynamic response of a rotorcraft in the approach scenarios relevant to the proposed new OPTIMAL procedures
- Develop the use of a Vortex Severity Rating (VSR) scale.

Prior to the experiments, a wide number of experimental factors were identified; to complete the matrix with a full-factorial experimental design would have been unfeasible. From these, four factors were selected for this analysis: The Vortex strength (3 levels), glide slope angle (4 levels), Encounter height (2 levels) and visual conditions (2 levels). The wake strength variation was achieved through scaling the velocities of the B747 wake vortex. Two visual conditions were selected - a Good Visual Environment Day scene (GVE), and a Degraded Visual Environment foggy/cloudy (DVE). The DVE conditions were designed to approximately replicate the worst visual conditions that rotorcraft can currently make approaches in without a coupled auto-pilot, which is equivalent to a CAT I approach with a minimum decision height (MDH) of 200ft. With a full lighting system, a minimum Runway Visual Range (RVR) of 500m is permitted (Ref. 11) and the DVE visual scene approximately replicated this. For the height factor, 2 levels were selected: vortices at either 300ft AGL or 500ft AGL. These heights were above the MDH of 200ft so that the precision guidance could ensure an encounter. The simulation trials used two pilots, both experienced rotorcraft pilots, and both

possessing helicopter instrument approach experience/ratings.

The details of the four approach trajectories are shown in Table 3. The speeds selected are typical for the approach glide slopes shown (Ref. 12; Ref. 13) and ensure that a maximum descent rate of 1000 ft/min is not exceeded.

Glideslope	Speed (knots)	Start Height (AGL)	Length of approach path
3°	70	955ft	3.0 Nm
6°	60	2000ft	3.1 Nm
9°	40	2000ft	2.1 Nm
12°	40	2000ft	1.5 Nm

Table 3 Speed, height and range parameters for various approaches

The procedure for conducting the approaches was based upon the ILS approach MTE (Mission Task Element) in ADS-33E-PRF (Ref. 14) The performance standards for the task are shown in Table 4. The procedure for the approaches was as follows:

Approach MTE description (Fig 8):

- Start manoeuvre in level flight on approach heading.
- Initial speed and altitude are as defined in Table 4.
- On the glideslope the speed was to be held constant whilst maintaining the navigational performance limits (Table 4).
- If a vortex was encountered the pilot was to take corrective action and attempt to continue the approach.
- If the upset was severe enough (based on the pilots judgement) to require a go-around, the pilot was to announce that they are 'going-around' and initiate the go-around procedure.
- The MTE ended when the pilot reached the decision height of 200ft or was 'steady' in control on the go-around climb-out.
- The pilot was then be asked to rate the approach and vortex encounter and recovery task using the pilot Handling Qualities questionnaires and Wake Vortex Severity Rating Scale questionnaire.

	Desired	Adequate
Maintain airspeed of Y knots within $\pm X$ knots	5 knots	10 knots
Glideslope (vertical) error $\pm X$ dots	0.5 dot	1 dot
Horizontal flightpath error $\pm X$ dots	0.5 dot	1 dot

Table 4 Performance standards for Approach MTE's

The approach precision was varied as a function of altitude to give an approach with narrowing performance standards. These are defined in dots, which are markers on a typical aircraft glideslope and localizer display. The 'dots' represent the displacement of the aircraft relative to the desired flightpath, typically, 2 dots is the maximum deflection of the instrument.

Table 5 shows the maximum and minimum values, the intermediate values were linearly interpolated. These values were chosen to give a lateral precision equivalent to the width of runway at the decision height and a vertical precision equivalent to 10% of decision height at the same point. Using relatively tight performance standards helped to ensure a good probability of a wake vortex encounter.

Height (AGL) [ft]	Lateral RNP [ft]	Vertical RNP [ft]
100	100	20
1000	288	100

Table 5 Navigation accuracy prescribed by Pseudo-ILS (1 Dot Values)

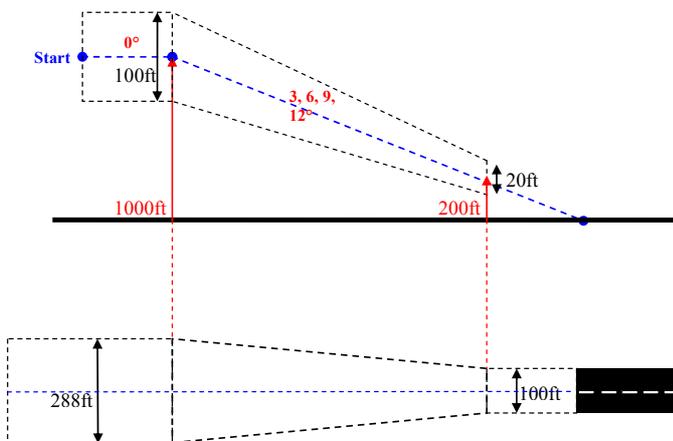


Figure 8 Diagram showing concept for Pseudo-ILS guidance (dashed lines represent 1 dot)

	Pilot 1		Pilot 2	
	GVE	DVE	GVE	DVE
3°	1	4	4	n/a
6°	2	4	4	n/a
9°	2	n/a	4	n/a
12°	2	n/a	4	n/a

Table 6 HQR's for the approaches with no wake vortex encounter ("control" cases)

Before conducting the wake encounter simulations, all of the approaches were flown without vortices present. This enabled the capture of the 'baseline' or 'control' data. From this, the basic workload required to fly the approach manoeuvres could be obtained as well as the initial pilot comment on the suitability of the simulator, helicopter model and the general experimental procedure. Generally speaking, the pilots considered the approaches to be very 'flyable' with the workload increasing for the slower, steeper approaches. Degrading the visual conditions further increased workload but the desired performance was still achieved and representative of the real world.

It is acknowledged that the speeds for the 9° and 12° are lower than V_{MINI} , which is the minimum IFR speed. This parameter is usually defined in a rotorcraft's flight manual and is typically around 60kts. Some rotorcraft can be flown at speeds lower than this in IFR but the crew and aircraft require special certification. However, for this study, the most basic case is being considered first, i.e. manual operations. All the 'control' approaches were flown in zero wind conditions and were rated using the standard Cooper-Harper Handling Qualities Rating (HQR) scale (Ref. 15). The resultant ratings are shown in table 6. However, it was commented by the pilots that their workload would likely be significantly higher if winds, gusts, or turbulence were introduced.

There are some differences between the two pilots, with pilot 1 giving consistently level 1 HQR's for the GVE approaches whereas pilot 2 gave level 2 (HQR 4) for the same. Both pilots were achieving desired performance but pilot 2 commented that all the manual instrument approaches required at least moderate compensation. An initial inspection of the pilot control activity data did reveal that the two pilots used different piloting strategies; however, further analysis is required to understand this trend fully.

The wake vortex approaches were essentially the same task as the 'control' approaches. The pilots had no prior knowledge of whether a vortex was present and the vortex strength; vortex altitude and approach glideslope were varied randomly. The pilots then flew the approaches and were asked to give their ratings via a questionnaire. If the pilot perceived a noticeable disturbance they were also asked to give a Vortex Severity Rating (VSR) (see fig 14) and to give reasons for the go-around if one was initiated.

The encounter test matrix was designed to encompass a fairly broad set of parameters in order to gain an understanding of the sensitivity to each one. Concentrating on the Vortex

severity, Figure 9 shows all the VSR's recorded plotted against the glideslope angle. The colours denote the visual conditions, blue for GVE and red for DVE. Generally speaking, there is some

scatter in the results but there are some rational trends. The worst encounters in terms of VSR were the 100% strength, DVE, 500ft vortex height

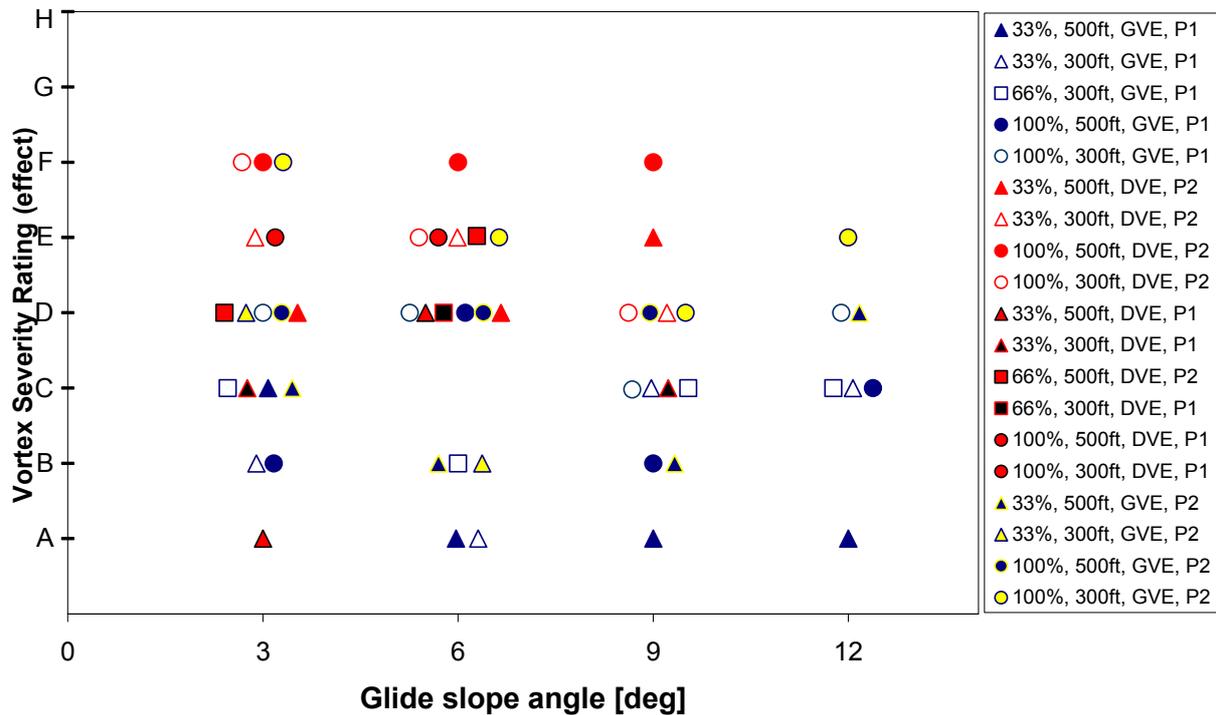


Figure 9 Vortex Severity Ratings for the simulated wake vortex encounters

for most of the approach angles. The correlation with strength is not surprising: the higher the strength, the greater the disturbance. However, the other parameters warrant further description. From Table 8 for GVE conditions, the encounters that led to a go-around all occurred at 300ft, an example is shown in Figure 10 with a number of trajectories shown in Figure 11. Compared to this, the DVE encounters featured go-arounds at both 300ft and 500ft. The likely explanation for this is that for the GVE encounters, the majority of the go-arounds were at the strong vortex strength, these encounters featured the marked attitude disturbances. Therefore the lower altitude of 300ft AGL caused the pilots to perceive a greater level of danger and initiated a go-around. None of the 500ft AGL encounters caused the pilots to go-around in the GVE encounters, indicating that the pilots felt that any disturbance was manageable and of acceptable risk. In DVE, the pilots initiated go-arounds at both altitudes and from Table 9 it can be seen that even the lowest strength vortices sometimes caused a go-around. In addition, the encounters considered acceptable in GVE were deemed more severe with the reduced visual cues, hence the larger number of go-arounds for the lower vortex strengths and higher altitude encounters. Also, for the DVE encounters, some of the encounters at 300ft were considered quite severe and caused quite significant upsets and flight-path deviations but these encounters did not result in

a go-around as the pilots were approaching the 200ft decision height there were enough ground cues such that the pilots switched to visual flying, recovered control and then completed the approach.

Glideslope (deg)	GVE	DVE
3°	5	5
6°	0	3
9°	0	1
12°	1	0

Table 7 Number of go-arounds for varying visual conditions and glideslope

Height of Vortex (ft)	GVE	DVE
300	6	5
500	0	4

Table 8 Number of go-arounds with varying height and visual conditions

Vortex Strength	GVE	DVE
33%	0	2
66%	2	1
100%	4	6

Table 9 Number of go-arounds with varying vortex strength and visual conditions

An interesting result from the DVE runs was that the pilots sometimes complained of difficulty in maintaining track on the localizer. This tended to be more prominent for the weaker vortex strength runs. This raised an alternative problem to the severe upsets from the full strength vortices. In these cases, the pilots did not notice much disturbance as they flew into the vortex flow-field. Subsequently, the nature of the flow tended to be more like a wind shear gradient as the pilot descended through the vortex. The onset of this tended to be quite incipient; the pilots often noticed a drift on their localizer, but only gradually. As a result, their corrective action often was not sufficient, especially as the disturbing flow was changing in strength and direction. The tendency is that the vortex pushes the rotorcraft away from the core and thus divert it from the desired flightpath. This, in turn, forces the rotorcraft into either upwash or downwash areas adjacent to the core. These areas can then cause significant vertical flightpath deviations. Overall in these scenarios, the pilot sometimes had difficulty with both the localizer and glideslope tracking tasks, and because of the visual conditions, lost enough situational awareness such that a go-around is initiated. This incipient

behaviour does not seem to occur with the stronger vortices as the higher velocities are more instantly noticeable when encountered and the pilot takes a more positive action to counter the initial disturbance or drift.

The effect of the glideslope angle on the geometry also has some interesting trends. From Figure 9, the sensitivity of the VSR to the glideslope is small except there is some indication of higher ratings for the 3° cases. However, the 3° approaches certainly caused more go-arounds, which could be for a number of reasons. Firstly, the 3° approach is the flattest trajectory through the vortex thus exposing the rotorcraft to the disturbing velocities for a longer period. Secondly, the 3° approach was flown at 70kts whereas the steeper approaches were flown at lower speeds. The higher speeds could have caused the disturbances to be more pronounced, certainly, at the higher speeds, any flightpath deviations would be larger than at lower speeds. This may explain why the steeper encounters were receiving equivalent VSR's but did not result in a go-around as the pilot could recover with smaller flightpath deviations.

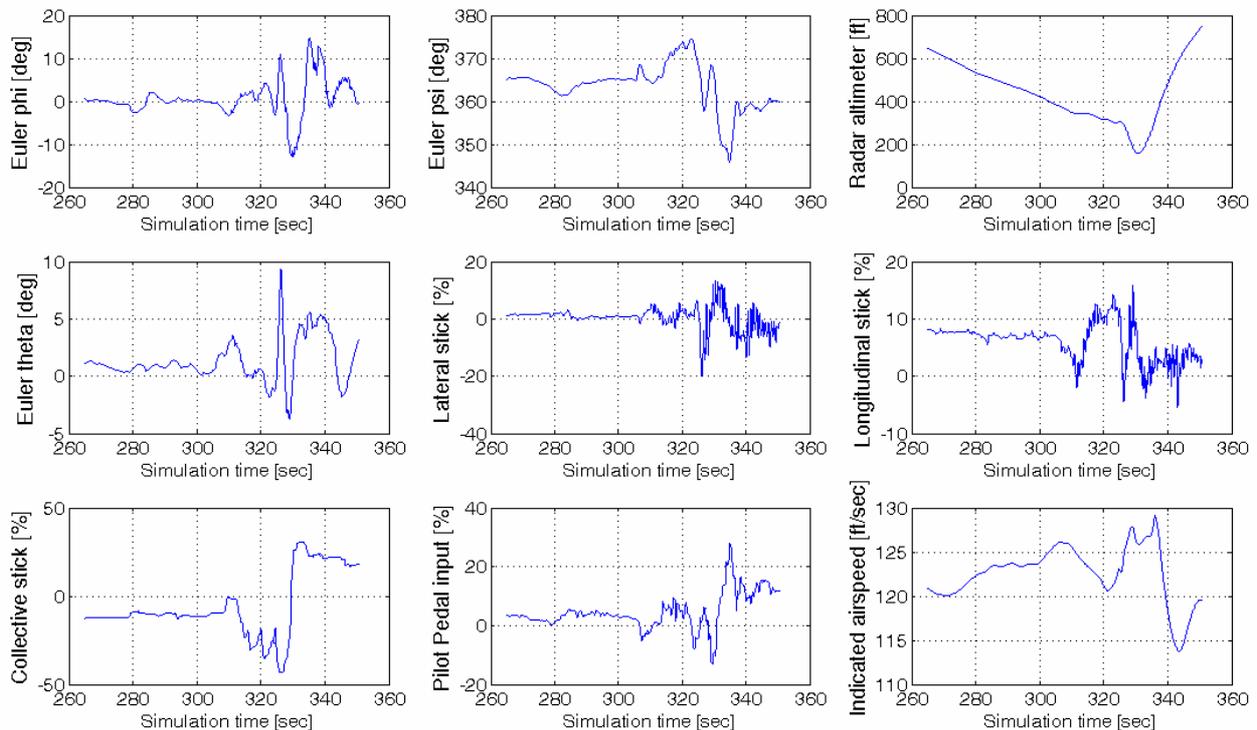


Figure 10 Encounter time history, 3° approach, 100% strength vortex at 300ft, GVE, pilot 1

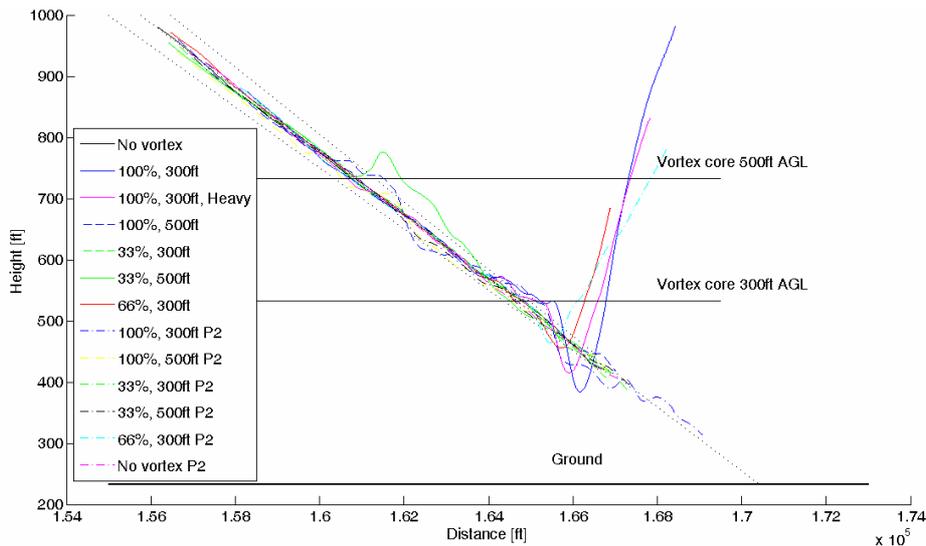


Figure 11 Height vs. Range plot for 3° GVE approaches

As a check, it was investigated whether one approach was more successful in achieving a higher proportion of encounters with the vortex core. The core is an area where the greatest attitude disturbances can be induced so if one approach was more successful, the results could be skewed.

Glideslope (deg)	No of Core Entered	Total No of Runs	%
3	10	21	48%
6	5	20	25%
9	9	15	60%
12	7	14	50%

Table 10 Number of Core encounters (within one rotor radius) for each glideslope

Table 10 shows the summary of the percentages of each glideslope in encountering the vortex core within one rotor radius. There is no large variation with the 3°, 6°, 12° in the region of 50%, however the 6° was lower at 25%.

Vortex Severity Criteria Development

It has been shown how the Vortex Severity Rating scale (Ref. 3) has been used to obtain a subjective measure of the severity for a wide range of encounter scenarios. However, it can potentially also be used to develop severity criteria based on either the dynamic response or the vehicle characteristics. The Vortex Severity Rating scale is based on a rating scale designed for the subjective analysis of the effect of control system failures (Ref. 16). As such, there is a strong analogy with the transient disturbances caused by a vortex. The premise is that the risk assessment is a balance of severity versus the level probability; the catastrophic cases must be 'extremely improbable' or a probability of 10⁻⁹ per

flight hour whereas the minor cases are acceptable at the 'probable' level with a probability of 10⁻³ to 10⁻⁵. Before any probabilistic analysis can be made, through methods such as fast-time or Monte-Carlo simulations, criteria need to be defined for assessing any particular encounter. Continuing the analogy with flight control system failures, ADS-33E-PRF, (Ref. 14) contains criteria relating the transient upset due to a system failure to handling qualities levels. The criteria for these levels are presented in Table 9; they relate the attitude and acceleration perturbations to the handling qualities levels for different phases of flight and pilot intervention times.

LEVEL	FLIGHT CONDITION		
	HOVER AND LOW SPEED	FORWARD FLIGHT	
		NEAR-EARTH	UP-AND-AWAY
1	3° roll, pitch, yaw 0.05g $\dot{\theta}_x, \dot{\theta}_y, \dot{\theta}_z$ No recovery action for 3.0 sec	Both Hover and Low Speed and Forward Flight Up-and-Away requirements apply	Stay within OFE. No recovery action for 10 sec
2	10° attitude change or 0.2g acceleration. No recovery action for 3.0 sec	Both Hover and Low Speed and Forward Flight Up-and-Away requirements apply	Stay within OFE. No recovery action for 5.0 sec
3	24° attitude change or 0.4g acceleration. No recovery action for 3.0 sec	Both Hover and Low Speed and Forward Flight Up-and-Away requirements apply	Stay within OFE. No recovery action for 3.0 sec

Table 11 ADS-33E criteria for transients following a failure

These criteria offer a readily useable framework to assess the disturbances induced by a wake vortex encounter. Figures 12 and 13 show the Vortex Severity ratings plotted against the attitude disturbances. The raw data is presented in Figure 12, which shows the averaged absolute peak values of the roll, pitch and yaw attitudes for each severity rating. Although scattered, the results do indicate a trend of increasing attitude disturbance with increased severity rating. The

reason for averaging the peak attitudes from all axes is to reflect the multi-axis nature of the transient upsets. This is an extension to methods used for severity analysis applied to fixed-wing aircraft encounters with wake vortices which are characterised by the predominant roll attitude disturbances. For example, Ref. 17 has assessed and developed criteria based on the roll attitude disturbance or the ratio of available control power to the roll disturbance induced by the vortex. Via these analyses the authors were able to achieve good levels of prediction for encounters that resulted in go-arounds. A similar methodology has been applied to the rotorcraft encounters, but with more focus on the link to handling qualities levels. Figure 13 shows two possible hypotheses using the data obtained from the baseline trials. The first shows the curve fit of average peak attitude of all three axes, the second is the average absolute peak attitude of the three axes. Both are plotted against the severity rating. The correlation from the curve fits are overlaid on the transient upset criteria from Table 11 which gives a rational agreement between the handling qualities levels and the severity ratings. The lowest level of severity of A is approximately Level 1/2. Increasing the severity to E/F, which is the tolerable/intolerable boundary on the VSR, falls approximately on the Level 2/3 HQ boundary. This is an interesting correlation, as this is where, according to the Cooper-Harper HQ Rating scale (Ref. 18), "Adequate performance not attainable without maximum tolerable pilot compensation, controllability not in question". The final comment in relation to controllability is also important here as none of the encounters were reported as uncontrollable or where controllability was in question. This suggests that for rotorcraft wake vortex encounters, attitude criteria may be sufficient for severity analysis.

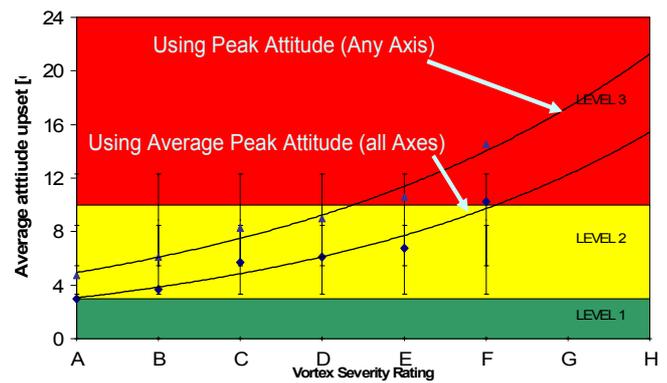


Figure 13 Vortex Severity Ratings versus averaged attitude upsets

Using the results from Figure 13, the Severity Rating Scale can be directly compared to the handling qualities levels, as shown in Figure 14. This reflects that the MINOR cases are Level 1/2, Level 3 equates to HAZARDOUS, and CATASTROPHIC is Level 4. However, the previous figures have combined the data for all effects, including height of encounter and visual effects. By separating the ratings for each visual condition, an argument could be made that perhaps two lines or boundaries are more suitable, one for GVE and one for DVE. In this scheme the GVE line could be much steeper, reflecting a greater tolerance to larger attitude excursions. The DVE trend would be much flatter showing that smaller attitudes are more, or at least as, severe in those conditions. An alternative is that there is a straightforward offset of one or two severity levels for a given level of DVE. In Figure 9, the DVE severity ratings occupy the upper area of the plot with a fairly consistent offset from the GVE ratings. No strong trend was detected for the effect of the height on the attitude vs. severity correlation. This is likely to be because the heights used in these experiments are above a threshold where the attitude vs. severity relationship is fairly constant. Other criteria such as the NASA roll attitude criteria in Ref. 17 have a single boundary for acceptable roll disturbance that reduces with reduced height. It is expected that such a relationship will also exist for rotorcraft at lower heights but with the incorporation of multi-axis disturbances. As discussed earlier, it appears that most of the go-arounds were a result of unacceptable deviations from the desired flightpath. Ref. 17 proposes that these encounters are known as 'navigate' go-arounds because the pilot is uncertain of position, or has lost the instrument tracking task, or it would be dangerous to attempt to re-acquire the flightpath. The alternative is an 'aviate' go-around where the go-around is initiated immediately because the disturbance is excessive. This type is more likely nearer to the ground where the pilot would consider a recovery of control and of the

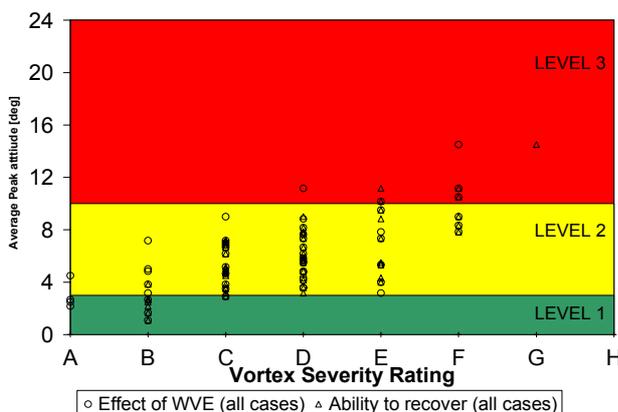


Figure 12 Vortex Severity Ratings against the average of multi-axis peak attitudes

approach flightpath impossible or too dangerous in the time and space available.

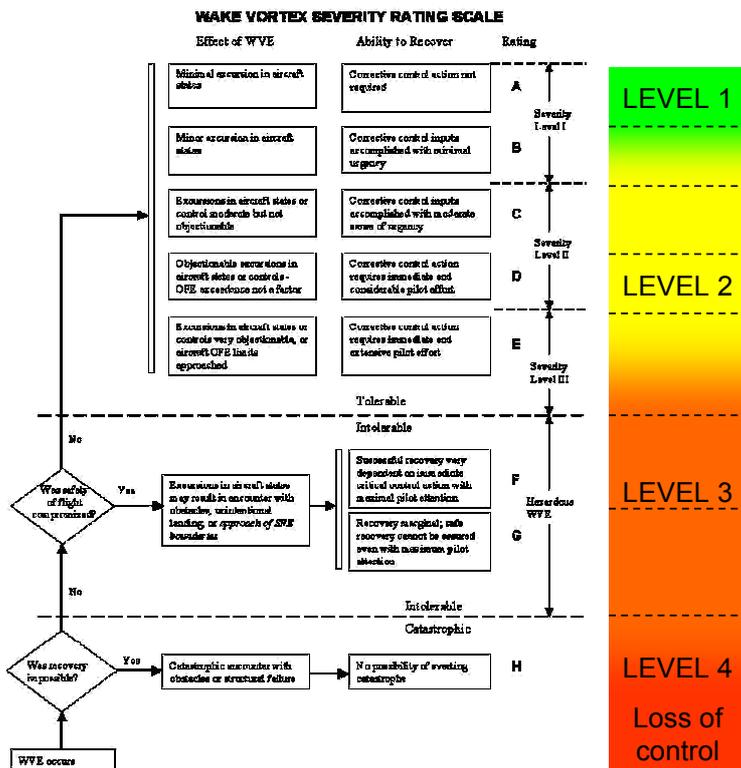


Figure 14 Comparison of Vortex Severity rating scale with Handling Qualities levels

Conclusions

The paper has reported the first results from a study into the interactional impact of fixed wing wake vortices on helicopters, as part of the Framework VI OPTIMAL project. The reported research is addressing the key questions;

- What is the 'severity' when meeting a vortex of a given strength in a number of varying scenarios?
- What is the probability of encountering a wake vortex for different regions of a given airport and what will its strength be?

The research methodology, based on modelling and simulation, involves establishing 'contours' of severity using off-line analysis and using these data to develop a number of safety cases from piloted simulation trials.

The loading contour analysis has shown that the accelerations induced on rotorcraft are significant but highly dependent on the speed, flight-path angle, attitude and position within the vortex flow-field.

A Wake Vortex Severity rating scale has been developed to quantify a subjective measure of the transient disturbances they induce. In the

encounters studied, the pilots never lost control. However, some encounters were rated up to level 'G', which is considered to be intolerable as the 'safety of flight was considered to be compromised'. The trials also included a basic assessment of handling qualities in the steep approaches (6°, 9° and 12°) for a rotorcraft flown manually with a rate-stabilized SAS. The results only represent a small part of the overall picture as they were limited to one vortex type and geometry, and one rotorcraft type. Nevertheless, progress has been achieved in the use of the rating scale and in understanding the issues surrounding encounters in approach scenarios. The main conclusions drawn from the analysis so far are:

- The encounters featured multi-axis disturbances and significant vertical disturbances increasing the complexity compared to fixed-wing analysis which focuses on the roll axis.
- The offline analyses, in particular, the acceleration contour plots, provided useful supporting data on the nature of the attitude upset in different regions within the vortex flow-field. Further work is required to develop this technique by correlating them with the results from the piloted simulations. If this can be achieved, this method would highly useful in rapidly analysing multiple rotorcraft/wake/flightpath combinations.
- The 3° encounters with the 100% strength vortex were given the highest severity ratings. This is due to the increased time spent within the vortex flow field and the greater speed of encounter resulting in the largest flightpath deviations.
- In GVE, lowering the altitude increased the severity rating and increased the go-around probability. In DVE, the picture became less clear as the higher altitude encounters often resulted in go-arounds whereas the same encounters a 300ft did not as the pilot was able to transition to visual flying and recover the approach.
- Degrading the visual conditions increased the severity rating by approximately 1-2 rating levels, with the worst cases being the 3° encounters with the 100% strength vortex, at 500ft in DVE.
- The flightpath angle did not have a strong effect on the vortex severity ratings, but the 3° encounters did cause the most go-arounds. The 12° approaches did indicate some increase in severity as result of increased pilot workload.
- The correlation of the vortex severity rating scale with the ADS-33E transient

upset is encouraging and could provide a method for further links of the severity of wake encounters to the encountering rotorcraft handling qualities characteristics.

The results presented so far build on previous analyses in Refs. 2, 3 and Ref. 19 which considered the effects of encounters in low speed and hovering conditions. Those studies also considered the effect of pilot intervention time to investigate the effect of encounters when the pilot may be in a divided attention operation. This study featured scenarios where the pilots were fully attentive but in a higher workload environment and showed that in such situations the encounters could still reach severity levels that were intolerable. This analysis represents further progress but more work needs to be done. Certainly, the activities presented in this paper need to be repeated for other rotorcraft types both heavier and lighter. Ideally, more pilots need to be included to give greater confidence in the highly subjective ratings. It is the intention to widen the analysis to include these factors; furthermore, other scenarios need to be considered such as oblique and perpendicular encounters. Also encounters at lower altitudes should be considered to reflect encounters nearer to the landing area such as in the hover or hover-taxi phase.

A note should be made on the modelling approach used in this analysis. As stated earlier, the vortex was frozen in position and structure and thus did not interact with the rotor wake. This assumption may not be sufficient and thus must be taken into account when studying these results. However, the correlations made for severity vs. attitude upsets are not directly affected by this effect if it is found to be deficient, but the relationship with a particular vortex strength, age, etc may have to be adjusted accordingly.

The results in this paper have also shown that the pilots seem to judge the need to go-around on flightpath deviations rather than attitude upsets. In these scenarios, the heave axis perturbations feature heavily. Consequently, a measure or criteria based on flightpath may be a helpful adjunct in assessing severity; for fixed-wing wake encounters, steps have been made in this area (Ref. 17) and this method could be adapted for rotorcraft.

To conclude, the research has made useful steps in developing the concept of wake vortex encounter severity for rotorcraft. However, further work incorporating more factors is required before the criteria relating the rotorcraft response and vortex characteristics to severity can be used

with confidence. When completed, the severity criteria will be able to support broader studies that will identify risk levels for various flightpath/FATO positioning to aid the development of SNI procedures.

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