

# A Severity Analysis for Rotorcraft Encounters with Vortex Wakes

Gareth D Padfield  
Professor of Aerospace Engineering  
The University of Liverpool, UK

Binoy Manimala  
Post Doctoral Research Assistant  
The University of Liverpool, UK

Graham P Turner  
Senior Scientist  
QinetiQ, Bedford, UK

## Abstract

Our paper concerns the severity of the response of a rotorcraft encountering the vortex of a fixed-wing aircraft. One of the key questions is whether a rotorcraft designed to meet handling performance standards will have sufficient control margin for the pilot to overcome the effects of a vortex encounter. This question is addressed through an analytical study supported by preliminary piloted simulation tests. The handling criteria are found to be well suited to establishing the severity and associated hazard category of typical encounters. Cases are illustrated where insufficient control margin is available to overcome the effects of the encounter. The pilot intervention time is critical as expected. In risk assessment parlance, an intervention time of 3 seconds leads to hazardous encounters (> Level 3 HQs) while a reduced intervention time of 1.5 seconds is more likely to be major (Level 3 HQs).

## List of Symbols

$p, q, r$	roll, pitch and yaw rates
$q_{pk}$	peak pitch rate
$Q = q_{pk}/\Delta\theta$	pitch attitude quickness
$r$	vortex radial dimension
$r_c$	vortex core radius
$V_T(r)$	vortex tangential velocity
$V_c$	vortex core velocity
$\theta, \phi, \psi$	pitch, roll and yaw angles
$\Gamma$	vortex circulation

## Introduction

This paper presents the results of a study into the development of severity criteria for encounters between rotorcraft and the vortex wakes of fixed wing aircraft. The study continues the theme initially developed during research conducted by DERA (now QinetiQ Ltd) for the UK CAA (NATS) (Refs 1, 2). Based on medium fidelity modelling and simulation, Refs 1 and 2 reported a greater hazard than had previously been predicted. Using constrained simulation techniques, the work also shed light on some of the key physical mechanisms

of encounters and recommended that research should continue into modelling, severity criteria and handling qualities issues. Research is also needed into establishing the probability of encounters and hence the safety risks of situating final approach and take off areas in particular locations relative to the main operating runways. A better understanding of the critical issues affecting rotorcraft-wake-encounters will inform the development of operating procedures for runway independent aircraft. This is seen as crucial to the timely expansion of vertical flight aircraft (helicopters and tilt rotor aircraft) operations to and from busy hubs.

This paper develops the results reported in Refs 1 and 2, focussing on the key issue of defining severity criteria for rotorcraft encounters with vortex wakes. The paper is structured in 4 main sections. First, the proposed hazard severity criteria are presented based on handling qualities engineering practice. A key question here is whether an aircraft designed to meet Level 1 handling performance will have sufficient margin for the pilot to overcome the effects of a vortex encounter. Second, the modelling and simulation activities that support the current work are summarised. Third, the results from the previous studies are combined with new data derived from the FLIGHTLAB generic rotorcraft, and together interpreted in terms of the new severity criteria. Fourth, preliminary results from piloted simulation trials conducted at The University of Liverpool are presented and compared with the off-line analysis. The paper continues with a short discussion section, followed by conclusions and recommendations.

## Hazard Severity Criteria

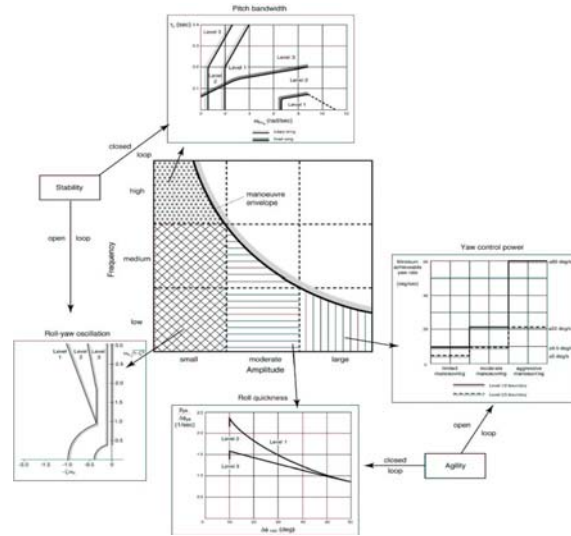
We use the definition of a hazard set out in the SAE's Aerospace Recommended Practice ARP4761 (safety assessment of airborne systems) (Ref 3) – 'a *potentially unsafe condition resulting from failures, malfunctions, external events, errors or a combination thereof*'. In busy airspace, aircraft are regularly exposed to the risk of experiencing an unsafe condition through wake-vortex encounters

(Ref 4). Separation is designed to minimise this risk, but the risk is ever present. The acceptability of this risk is a function of the severity of the disturbance and the probability of occurrence. Generally, severe disturbances must be improbable and as the level of severity decreases, so frequency of occurrence can increase. This critical relationship underpins aviation safety and system design. In this paper our focus is on quantifying severity, but we will return to the relationship with probability and associated risk later, in the discussion Section of the paper.

There are 2 major concerns and related questions regarding disturbance severity:

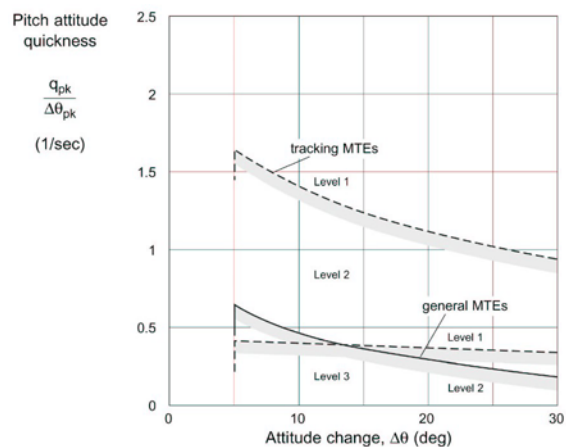
- a) does the disturbed aircraft have sufficient control margin for the pilot to overcome the disturbance?
- b) can the disturbance transient lead to an unsafe flight condition if not checked within a reasonable pilot intervention time, in terms of collision with surfaces, exceedance of flight envelope, risk of pilot disorientation or loss of control?

In a general sense a positive answer to a) combined with a negative answer to b) are required to ensure that the hazard is only minor. The detailed answers to these questions lie in understanding the nature of the response of the aircraft to a vortex disturbance. We address this topic in the next Section. Here, we cast the problem in terms of response and failure transient criteria from handling qualities standards. Fig 1 summarises the dynamic response criteria (taken from Ref 5) in the military handling qualities standard ADS-33 (Ref 6). An aircraft's response is limited in the frequency-amplitude range and the allowable region can be conveniently divided into 4 regions as shown. In response to a vortex encounter disturbance, the regions of immediate interest concern moderate to large amplitude defining the agility of the aircraft. The control power is simply the amount of response achievable with the available control margin. The response quickness is defined by the ratio of peak attitude rate to attitude in a discrete attitude change manoeuvre. This parameter is inversely related to the time to change attitude and will be affected by roll/pitch damping, actuator limits and to an extent, static stability effects. Quickness is also sensitive to nonlinearities in the response and links directly with control power at large amplitude and attitude bandwidth at small amplitude (Ref 5).

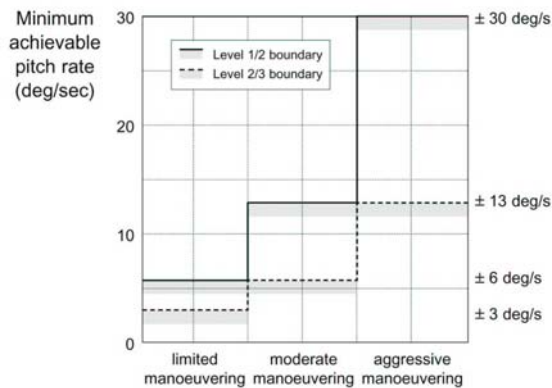


**Fig 1 Dynamic Response Criteria (Ref 5)**

We will address the question of sufficiency of attitude control margin in terms of quickness (for pitch manoeuvres up to 30deg) and control power (for pitch manoeuvres > 30deg). In the present analysis we focus almost exclusively on the pitch axis. Refs 1 and 2 highlighted that the initial disturbance to an encounter with the vortex core, aligned in the same direction as the helicopter, will be in pitch. This is in contrast to the roll disturbance experienced by fixed wing aircraft. For reference, Figs 2 and 3 show the pitch axis quickness and control power criteria boundaries for low speed/hover tasks (Ref 6). Note the manoeuvre and mission-task-element (MTE) dependent nature of the requirements.



**Fig 2 Pitch Axis Quickness (Ref 6)**



**Fig 3 Pitch Axis Control Power (Ref 6)**

In the vertical axis, the corresponding Level 1 response criteria are defined in terms of control power (160ft/min, 1.5 seconds after initiation of rapid displacement of collective control from trim) and vertical rate time constant ( $t_{63\%} < 5$  seconds). These correspond roughly to a hover rate of climb performance of 650 ft/min with a 5% thrust margin.

An aircraft should possess at least the Level 1 performance standards for the pilot to be able to fly moderately aggressive low speed manoeuvres precisely and with minimal compensation. The question arises as to whether an aircraft designed to meet the ADS-33 performance standards will have sufficient margin for the pilot to overcome the effects of a vortex encounter. We return to this question when presenting and discussing the results from modelling and simulation later in the paper.

The second issue listed above concerns the aircraft motion transients in response to the vortex encounter. If we consider the disturbance to be similar to that resulting from a control system failure we can draw on the extensive database of knowledge on failure modes and effects and functional hazard analysis (e.g. Ref 3). Within this framework, ADS-33 sets requirements for the response to system failure transients in the form of Table 1.

Level	Flight condition		
	Hover and low speed	Forward flight	
		Near earth	Up-and-away
1	3 deg roll, pitch, yaw 0.05g nx, ny, nz no recovery action for 3 secs	both hover and low speed & forward flight up-and-away reqts apply	stay within the OFE no recovery action for 10 seconds
2	10 deg roll, pitch, yaw 0.2g nx, ny, nz no recovery action for 3 secs	both hover and low speed & forward flight up-and-away reqts apply	stay within the OFE no recovery action for 5 seconds
3	24 deg roll, pitch, yaw 0.4g nx, ny, nz no recovery action for 3 secs	both hover and low speed & forward flight up-and-away reqts apply	stay within the OFE no recovery action for 3 seconds

**Table 1 Response Transients following Failures (Ref 6)**

Our focus in this study has been the severity of encounters for rotorcraft flying in hover and low speed (<45kts), including low speed climbs. We shall be mainly concerned with the first column in Table 1, and particularly the Level 3 boundary on the basis that this differentiates between safe and unsafe conditions. The Level 3 boundary corresponds to a transient that would result in a displacement of the aircraft of about 20ft (6.1m), velocity of about 20ft/sec (6.1m/sec) and angular rate of 10deg/sec, after 3 seconds. A question that arises when expressing the encounter transients using these criteria are - what should the pilot intervention time be? The 3 seconds in ADS-33 corresponds to a scenario of a single pilot attending to other mission duties while in hover with auto-hover engaged. In the UK Defence Standard (Ref 7) this would correspond to passive hands-on operation. For attentive hands-on operation, the pilot response time is 1.5 seconds in Ref 7, following control system failures. In the civil certification standards (Ref 8), the response time (for hover operations) is set at the normal pilot recognition time (0.5 seconds). However, a strong argument could be made for increasing this to 1.5 seconds in divided attention situations or when operating with auto-hover engaged. An initial exploration of the effect of pilot intervention time on the transient response to disturbances will be described later in the paper.

## Modelling and Simulation

The modelling and simulation environment used in the studies is FLIGHTLAB and the HELIFLIGHT motion simulator at the University of Liverpool (Ref 9). The 2 aircraft featured in the study are the Westland Lynx and FLIGHTLAB Generic Rotorcraft (FGR), configured approximately as a UH-60 Blackhawk. Key configuration parameters of the 2 aircraft are given in Table 2.

	Lynx	FGR
rotor radius	21ft (6.4m)	27ft (8.2m)
weight	11000lbf (4911kgf)	16300lbf (7277kgf)
disc loading	7.9lbf/ft <sup>2</sup> (38.2 kgf/m <sup>2</sup> )	7lbf/ft <sup>2</sup> (34.4kgf/m <sup>2</sup> )
flap hinge offset	12% (equivalent)	5% (actual)
rotorspeed	35 rad/sec	27 rad/sec
hover power margin	21%	34%

Table 2 Helicopter Parameters

The aeromechanics modelling features are summarised in the following:

- blade element rotor with look-up tables of quasi-steady, nonlinear lift, drag and pitching moment as functions of incidence and Mach number (5 equi-annulus segments),
- FGR – 4 rigid blades with offset flap hinge; Lynx – 4 elastic blades with first 3 coupled modes,
- 3-state dynamic inflow model, Bailey disc tail rotor with  $\delta\delta$  coupling,
- 3-state turbo-shaft engine/rotor-speed governor (rotor-speed, torque, fuel flow),
- look-up tables of fuselage and empennage forces and moments as nonlinear functions of incidence and sideslip,
- rudimentary quasi-steady interference between rotor wake and fuselage/empennage,
- basic mechanical control system with mixing unit and actuators plus limited authority stability and control augmentation system (SCAS - rate damping with attitude control characteristics at small attitudes in Lynx),
- rudimentary 3 point undercarriage

This level of modelling is generally regarded as medium fidelity, capable of capturing the primary

trim and on-axis responses within about 10% of test data. Handling qualities parameters are also reasonably well predicted by this modelling standard (Ref 5).

A variety of empirical models have been used to describe the tangential velocity profile of a tip vortex. Two commonly used examples are the "Dispersion" model (Ref 10) and the "Burnham" model (Refs11, 12); the former takes the form:

$$V_T(r) = \frac{\Gamma r}{2\pi(r^2 + r_c^2)} \quad (1)$$

where  $V_T(r)$  is the tangential velocity at a distance  $r$  from the vortex core,  $r_c$  is the core radius (defined as the distance from the centre of the vortex to the peak of the tangential velocity) and  $\Gamma$  is the total circulation around the vortex (with units of  $m^2s^{-1}$ ).

The "Burnham" model takes the form;

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

$$V_T(r) = V_c(r/r_c), \quad |r| > r_c \quad (2)$$

where  $V_T(r)$  and  $r_c$  are as defined previously, and  $V_c$  is the peak velocity i.e. the value of  $V_T(r)$  at  $r = r_c$ . This model has an unphysical discontinuity at  $r = r_c$ , and it does not converge to a finite circulation ( $\Gamma = 2\pi r V_T(r)$ ) as  $r$  tends to infinity. Nevertheless, it was found to give a good match with test data and is used in the present study.

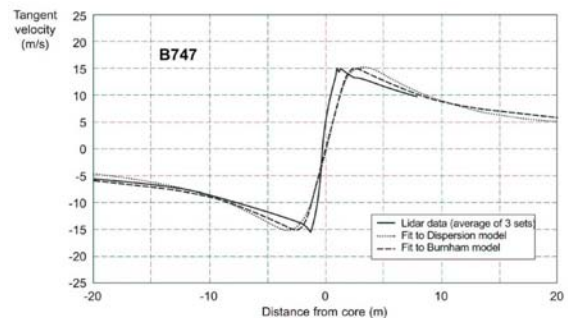


Fig 4 Velocity distribution in Boeing 747 Vortex Wake (Ref 2)

These vortex models are compared to LIDAR measurements of the tangential velocities in the (young) vortex wake of a Boeing 747 in Figure 4 (Ref 2). A best fit was obtained for each of the velocity profiles, and the resulting best-fit

parameters displayed in Table 3; included here are data for 3 other contemporary commercial airliners.

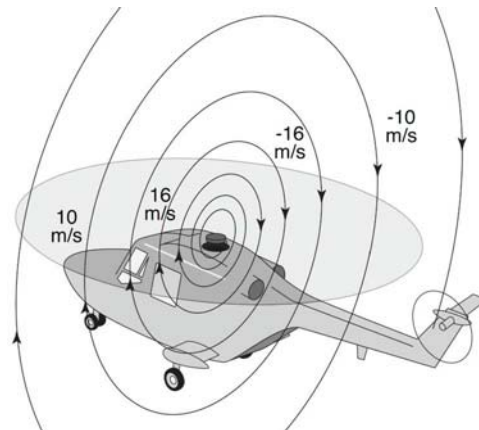
Aircraft	"Burnham" model		"Dispersion" model		
	$r_c$ (m)	$V_c$ ( $m\ s^{-1}$ )	$\Gamma$ ( $m^2\ s^{-1}$ )	$r_c$ (m)	$V_c$ ( $m\ s^{-1}$ )
<b>B747</b>	2.4	14.9	612	3.2	15.2
<b>B757</b>	<0.8	>21.2	251	<0.9	>22
<b>A340</b>	2.0	11.4	385	2.5	12.2
<b>A310</b>	<1.0	>20	283	<1.0	>22

**Table 3 Best fit parameter values to LIDAR velocity profiles for the Burnham and Dispersion models (Ref 2)**

In each case the fit, while not perfect, is considered adequate to give confidence in the validity of using the models in simulations of a vortex encounter. The parameter values for the larger aircraft (Boeing 747, Airbus A340) should be reliable, but the maximum velocities for the medium aircraft (Boeing 757, Airbus A310) are estimates, which will be equal to or less than the true value, as the LIDAR sensitivity is insufficient to detect the peak. The lack of information in the core precludes the extraction of reliable best-fit parameter values for the B757 and A310. It must be stressed that the values in Table 3 relate only to a single data set for each aircraft (average of three in the case of Boeing 747), but these values should nevertheless be broadly representative.

In the current study the encounters occur when the vortex is at the (full) strength given by the preceding Fig 4 and Table 3. Vortices do decay with time of course and the decay rate is a strong function of prevailing wind. The results presented therefore represent clinical worst case scenarios and the encounter effects in a real scenario may differ considerably. We also make the major assumption that the vortex flow-field is unaffected by the rotorcraft and that incidence changes on the rotor are the result of quasi-steady aerodynamic superposition. These assumptions are clearly incorrect but there is little reliable information on the interactional effects and they are likely to be very complex. Once again, we assume a likely worst case scenario and note in passing that research into such interactions is urgently required quantifying the adequacy of the non-interacting model.

The velocity field of a Boeing 747 vortex when centred at the rotor hub is sketched in Fig 5.



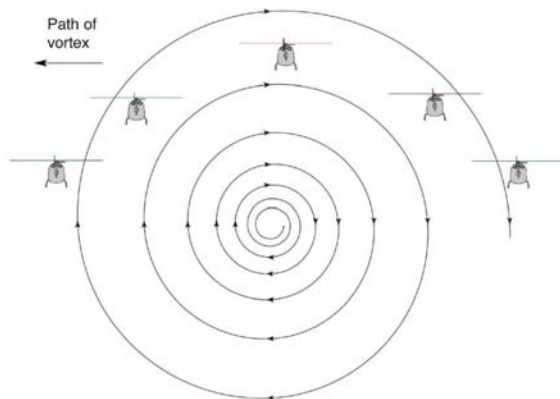
**Fig 5 Velocity flow-field of Boeing 747 vortex around Lynx rotor**

Note that, at the rotor tips, the downwash/upwash is still considerable (10m/s, 33ft/s) and with a rotor tip speed of about 220m/s (720ft/s), the perturbation in incidence is approximately 2.5deg, constant along the radius. This is equivalent to a (longitudinal) cyclic pitch application of the same amount. For the anti-clockwise rotors on the Lynx and FGR, this will result in forward flapping of the rotor blades and a nose down pitch moment.

A similar rationale can be applied to the perturbations in heave velocity. In this case the greatest disturbances are experienced when the rotorcraft is in the vortex tail, close to the core and we find equivalent collective pitch changes similar to the previously described cyclic changes. The amount of cyclic and collective margin available to the pilot to negate the effects of the vortex obviously depends on trim position of the controls.

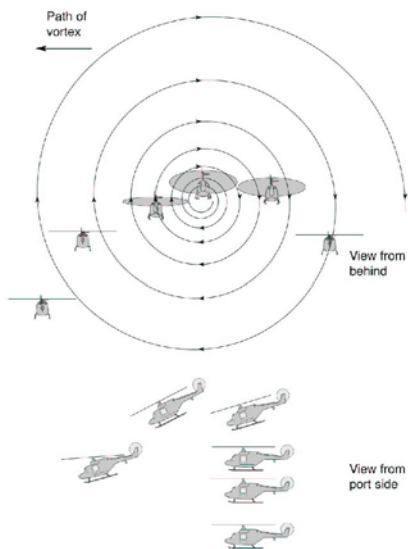
The technique of constrained simulation has been used extensively in these studies to ensure that the rotorcraft-vortex encounters have predictable initial conditions. Also, it has proved more convenient and tractable to fix the position of the vortex in space and move the aircraft laterally at different encounter velocities through the tails and core. With unconstrained simulations (see Ref 1), it was found that as the vortex approached the aircraft at the same height, the aircraft would be lifted up in the approaching tail of the vortex and carried over the top and down in the following tail, as shown in Fig 6.





**Fig 6 Helicopter lifted above vortex core during encounter**

In contrast, Fig 7 illustrates the case when the initial position of the helicopter was such that an encounter with the vortex core was forced to occur. This scenario is not unrealistic as the vortex wakes tend to remain at about a semi-span above the ground (Ref 1). Hence, to avoid the complications of having to set different initial conditions for the different helicopters, vortex wakes and encounter speeds, the constrained simulation approach was adopted. For all cases the initial condition was with the rotorcraft positioned 100ft (30m) to the port side of the vortex, simulating an encounter with a vortex shed from an aircraft taking off to starboard of the rotorcraft.



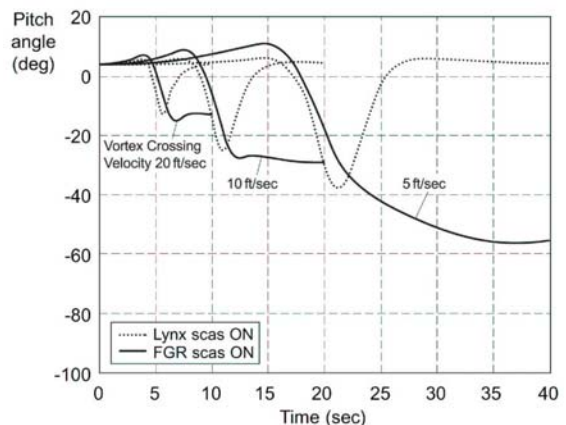
**Fig 7 Helicopter encountering vortex core**

In the following Section we present results for 2 cases: (i) with constrained vertical/forward motion and heading to explore pitch attitude perturbations as the core is encountered, and (ii) with constrained attitude, heading and forward motion to explore heave perturbations as the tails are traversed. Both Lynx and FGR will be investigated, with and without SCAS engaged. Only results for encounters with the vortex wake of the Boeing 747 are presented; Ref 2 presents comparisons of encounters with the different aircraft shown in Table 3.

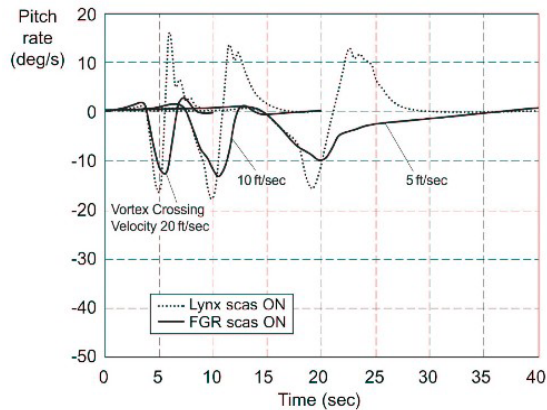
### **Analysis of Encounters**

#### **Attitude Response**

Figures 8 and 9 show the pitch attitude and rate response of the rotorcraft, SCAS engaged, for 3 vortex encounter speeds: 5, 10 and 20 ft/sec (1.5, 3 and 6 m/sec). The attitude transients increase as vortex passing speed decreases as expected. The attitude hold system in the Lynx SCAS returns the aircraft to the hover attitude after the passage of the vortex. This contrasts with the rate damping SCAS in the FGR which leaves the aircraft with the perturbed attitude. The rotorcraft initially pitch up as they pass through the advancing tail of the vortex due to the lateral distribution of inflow through the rotor disc. As the rotor hub encounters the vortex core, the lateral inflow distribution reverses, leading to a much larger flapping and pitch down moment. The attitude perturbations for the 10 and 20ft/sec encounters are similar for both aircraft (25 and 15 deg respectively in 3-4 seconds), while the slower encounter results in a pitch of nearly 40 deg in 5 seconds for the Lynx, and nearly 60deg in 20 seconds for the FGR.

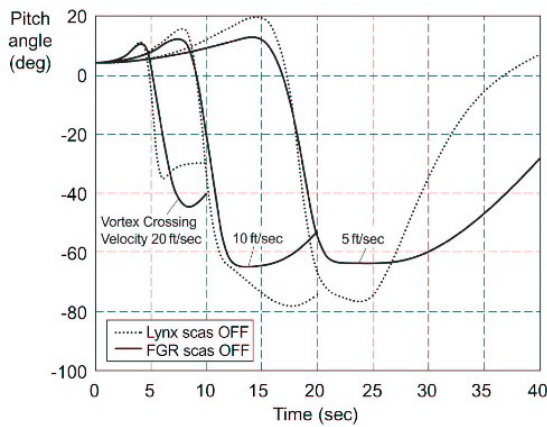


**Fig 8 Pitch attitude response (SCAS on)**

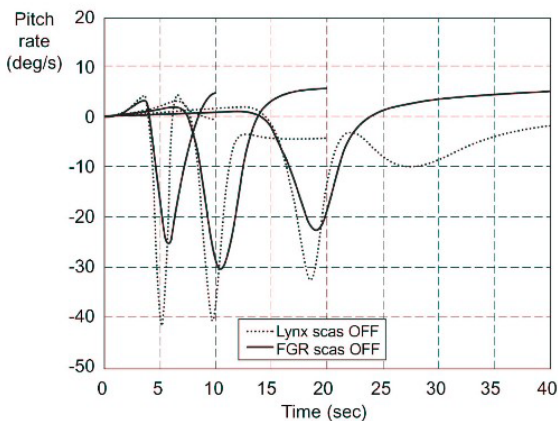


**Fig 9 Pitch rate response (SCAS on)**

The equivalent SCAS off results are shown in Figs 10 and 11.



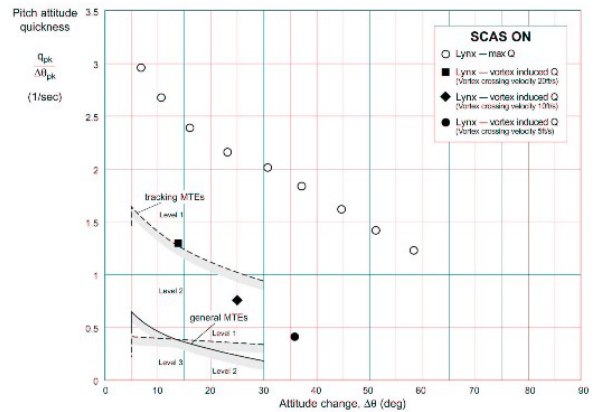
**Fig 10 Pitch attitude response (SCAS off)**



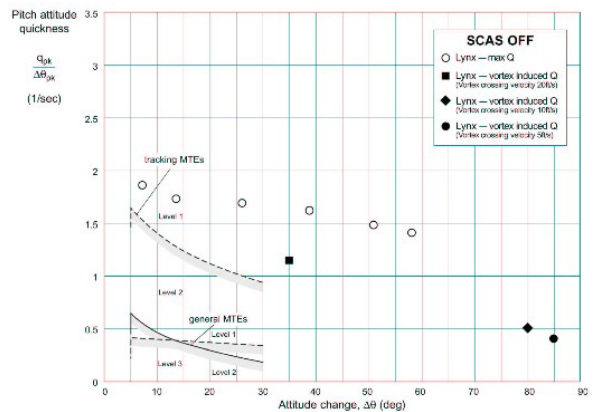
**Fig 11 Pitch rate response (SCAS off)**

Even for the 20ft/sec encounter the pitch attitude changes are greater than 30/40deg for the Lynx/FGR in 3/4 seconds. The pitch moment and corresponding accelerations are much higher on the Lynx with its hingeless rotor system, but interestingly, the FGR is pitched to the higher attitude because the larger rotor is in the vortex for about 30% longer. Note that the pitch response would be reversed for clockwise rotors (e.g. Eurocopter helicopter family)

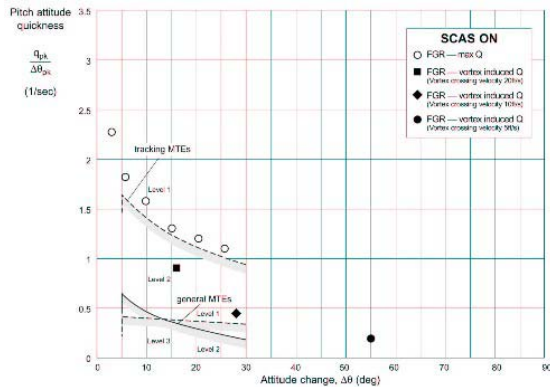
The attitude responses are plotted on the pitch quickness charts in Figs 12 and 13 (Lynx, SCAS on and off) and 14 and 15 (FGR, SCAS on and off). On each chart the maximum quickness is also plotted as a function of attitude derived from applying high amplitude pulse inputs with varying duration. The ADS-33 HQ boundaries are also included from Fig 2.



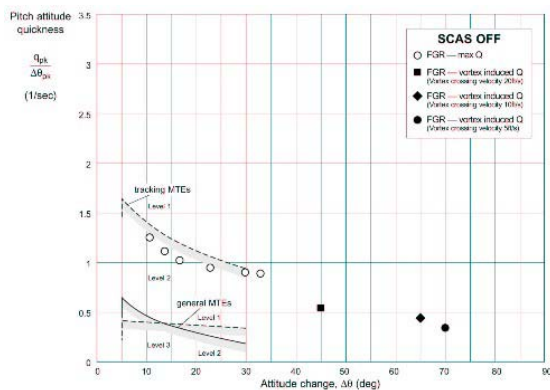
**Fig 12 Pitch Quickness (Lynx - SCAS on)**



**Fig 13 Pitch Quickness (Lynx - SCAS off)**



**Fig 14 Pitch Quickness (FGR - SCAS on)**



**Fig 15 Pitch Quickness (FGR - SCAS off)**

Points to observe in this set of Figures include:

- a) for both aircraft, the SCAS increases the maximum available quickness over the ADS-33 range and reduces the vortex induced quickness,
- b) with SCAS on, both aircraft have significant quickness margin (50-100%) to overcome the vortex up to 30deg pitch attitude change,
- c) satisfying the ADS-33 minimum quickness requirements for tracking tasks (Level 1/2 boundary) gives a significant response margin (50-100%) for 30deg attitude changes with SCAS engaged,
- d) in control power terms, the moderate manoeuvre requirement (13deg/sec) in Fig 3 is barely adequate for the SCAS-on cases; 20deg/sec would give a margin in both aircraft (see Fig 9),
- e) with SCAS-off, the pitch changes are much higher and the ability to negate the effects depends critically on the aft cyclic control

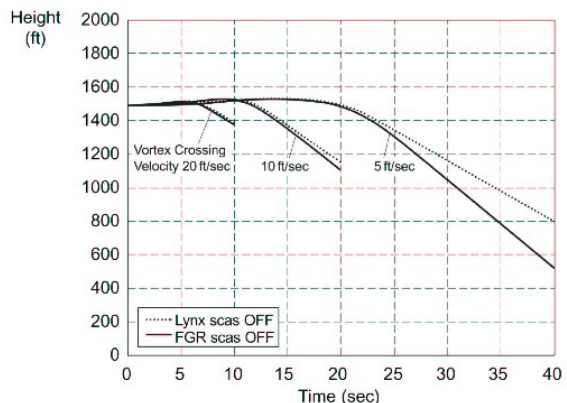
power margin in hover; the ADS-33 control power requirement of 30deg/s appears marginally adequate for the FGR and inadequate for the Lynx,

- f) it should be recognised that the pitch rates discussed above in d) and e) are transient and the nature of encounters is such that the pilot should only need to command these levels of control power momentarily, if at all,
- g) satisfying the minimum Level 1/2 quickness requirements for general MTEs would give wholly inadequate control for counteracting the effects of a vortex encounter.

**Vertical Response**

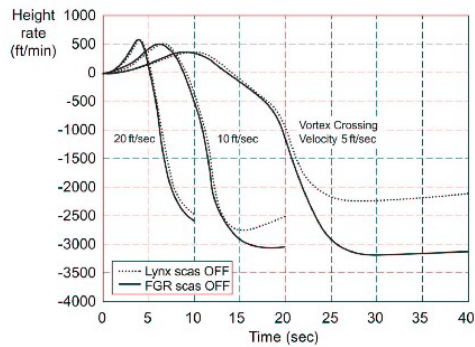
The vertical motions of the rotorcraft during the vortex encounters are illustrated in Figs 16 (height), 17 (height rate) and 18 (vertical acceleration). The effects of SCAS are negligible in most cases, hence we consider SCAS-off only. An exception is the vertical acceleration response of the Lynx, which has a feedback loop from acceleration to collective to improve high speed stability characteristics. The acceleration peaks in Fig 18 are reduced by 20% with SCAS engaged.

An important point to take into account when interpreting these data is that the initial trim of both aircraft is 100ft to port of the clockwise vortex. The collective pitch is therefore lower than the hover value by an amount depending on the rotorspeed and solidity. This results in a descent rate in the receding vortex tail which is considerably higher than that corresponding to the hover collective setting. For the Lynx the reference rate of descent (i.e. the descent rate corresponding to the decreased collective at the initial condition) is about 900ft/min and for the FGR about 1200ft/min.

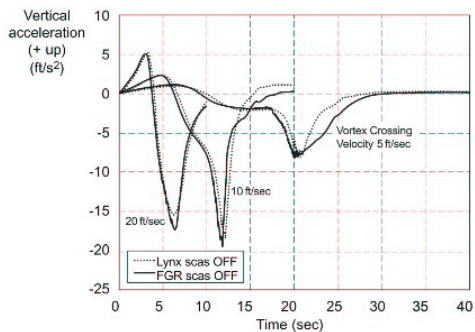


**Fig 16 Height response (SCAS off)**





**Fig 17 Height Rate Response (SCAS off)**



**Fig 18 Vertical Acceleration Response (SCAS off)**

Points to observe in this set of figures include:

- as the rotorcraft approach the vortex core they are lifted up to a max rate of climb of about 500ft/min followed by a reversal to a rapid descent rate of more than 2500 ft/min (more than 1500ft/min relative to reference),
- the response is complicated at low vortex crossing velocities by the passage of the 2 sides of the rotor disc through the vortex,
- The slower the encounter, the greater time is spent in the vortex wakes and the larger height loss. At 20ft/sec encounter, 100ft is lost in about 3 seconds; 10ft/sec, 100ft in 5 seconds; 5ft/sec, 100ft in about 8 seconds,
- The lower disc loading on the FGR result in larger peak accelerations and higher descent rates; at the fastest encounter of 20ft/sec, a bump of about -0.5g is experienced within 3 seconds of a small positive bump,
- The descent rates induced in the vortex tail (1100ft/min – Lynx; 2000ft/min – FGR) are significantly higher than the 650 ft/min

minimum requirement for Level 1 performance defined in ADS-33. This suggests that thrust margins of 10-15% would be required to enable a pilot to completely counteract the effects of vortex encounter.

Handling qualities criteria provide a natural framework within which to set performance margins and quantify severity during upsets caused by vortex encounters. The preceding analysis has demonstrated that an aircraft satisfying minimum Level 1 (tracking) attitude quickness and (aggressive manoeuvring) control power performance should have sufficient control margin to overcome the effects of a full strength vortex. Satisfying the normal minimum performance requirements for general MTEs will not provide adequate margin. A rate SCAS significantly reduces the disturbance, while the addition of the attitude hold function (Lynx) returns the aircraft to the hover attitude, further reducing the upset. In terms of vertical performance, the minimum Level 1 standard, when translated into a margin for climb performance, is insufficient by a large margin to overcome the effects of the downwash in the vortex tail.

The performance criteria indicate what is ultimately achievable but we can gain further insight by comparing the severity of the disturbance against the criteria for the transient response following failures, in ADS-33.

### Severity of Transient Response

In this section, we refer back to Table 1 showing the limits on attitudes and accelerations following a failure. The questions we ask are – can this approach also apply to the response due to external disturbances, and are the same standards applicable? These questions are addressed without regard for the control/response margin. Table 4 presents the approximate pitch attitude transients at 3 seconds. The values are the changes in attitude in Figs 8 and 10 from the maximum pitch up rather than the initial pitch. This method leads to significantly greater transients in some cases, but is justified because although the pilot would not be expected to allow the aircraft to pitch, he or she would have to apply forward cyclic to maintain the hover, which would exacerbate the pitch down as the vortex core was crossed. The bold numbers in Table 4 correspond to the cases where the Level 3 boundary is exceeded.

Aircraft	Encounter velocity			ADS-33 Level 3
	5ft/sec	10ft/sec	20ft/sec	
	<i>Pitch attitude in 3 seconds (deg)</i>			
<b>Lynx scas on</b>	15	<b>30</b>	16	10< $\theta$ <24
<b>Lynx scas off</b>	<b>40</b>	<b>50</b>	<b>45</b>	10< $\theta$ <24
<b>FGR scas on</b>	10	<b>25</b>	22	10< $\theta$ <24
<b>FGR scas off</b>	<b>30</b>	<b>35</b>	<b>50</b>	10< $\theta$ <24

**Table 4 Transient Pitch Attitudes**

Similarly Table 5 lists the 3 second perturbations in vertical acceleration (SCAS-off only data included; SCAS-on does not change Level). In this case the reference conditions in Fig 18 are the points where the larger negative bump begins (e.g. at 17.5 seconds for the FGR with the 5ft/sec crossing).

Aircraft	Encounter velocity			ADS-33 Level 3
	5ft/sec	10ft/sec	20ft/sec	
	<i>Pitch attitude in 3 seconds (deg)</i>			
<b>Lynx scas off</b>	0.16	0.31	<b>0.47</b>	0.2< $n_z$ <0.4
<b>FGR scas off</b>	0.19	0.38	<b>0.53</b>	0.2< $n_z$ <0.4

**Table 5 Transient Vertical Acceleration**

If the intervention time had been set at 1.5 seconds the perturbations would have reduced to less than 50% of those in Tables 4 and 5 (with the possible exception of some SCAS-off cases) and the bold cases would then be within the Level 3 boundary and most other cases would be Level 2. Combining the ADS-33 approach with the hazard categories in Ref 13, we can postulate the following relationship;

- HQ Level 1,2 – hazard category **MINOR** (safety of flight not compromised; slight reduction in safety margin or increase in pilot workload)
- HQ Level 3 – hazard category **MAJOR** (safety of flight compromised; significant reduction in safety margins or increase in crew workload)
- HQ > Level 3 – hazard category **HAZARDOUS** (safety of flight compromised; large reduction in safety margin)

From this classification, and without considering control margins, we can deduce that with a 3 second pilot intervention time the vortex encounter is hazardous and with a 1.5 second intervention time the encounter is a major hazard. Both relate to the disturbance-induced flight path variations and the resulting risk of disorientation or loss of control. As noted above, a possible exception to this, as far as attitude excursions are concerned, are some cases with the SCAS disengaged. Even with the limited authority augmentation in the Lynx and FGR, the 3 second perturbations are halved in magnitude.

To test these hypotheses an exploratory piloted simulation trial was conducted on the HELIFLIGHT facility in the Flight Science and Technology Laboratory at The University of Liverpool.

#### Exploratory Piloted Simulation Studies

The HELIFLIGHT simulator (Fig 19) features 6-axes of motion, 6 visual channels, a variable force-feel system and is harnessed to the FLIGHTLAB simulation environment (Ref 9).

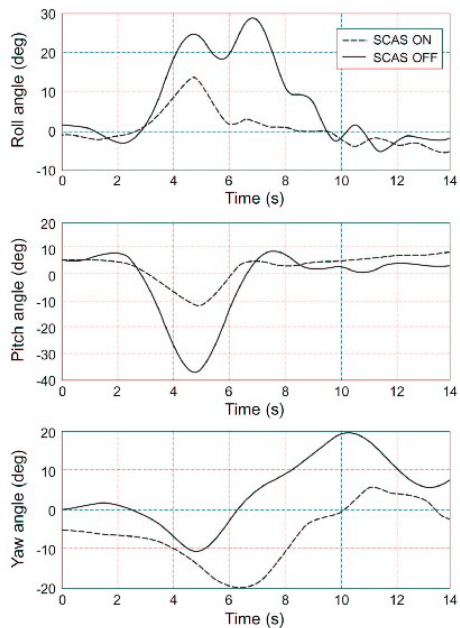


**Fig 19 The HELIFLIGHT Simulator**

During the period Dec 2001 – May 2002, 4 test pilots participated in short exercises to develop a methodology for assessing the effects of vortex encounters. Once again it was found more convenient to fix the vortex in space and fly the helicopter into it. This was far from ideal since, as previously discussed, the vortex tended to lift the helicopter over the top. As the pilot traversed the vortex, the power changes to maintain height were properly captured but rotor/core encounters were rare occurrences. To ensure that encounters between the vortex core and rotor occurred, runs were also made with the helicopter constrained in height as the vortex was traversed. The

FGR/Boeing 747 vortex combination was used in these exploratory investigations. Encounters from left to right and right to left were simulated. The vortex was artificially terminated at 200ft (60m) either side of the core and the helicopter initialized an additional 100ft (30m) outside the outer boundary.

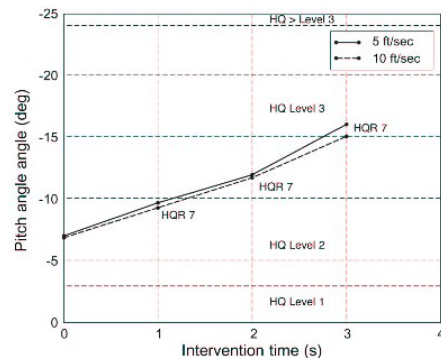
Fig 20 shows the attitude response for typical runs with SCAS on and off, encounter speed of 10ft/sec (3m/sec) and intervention time of about 2 seconds.



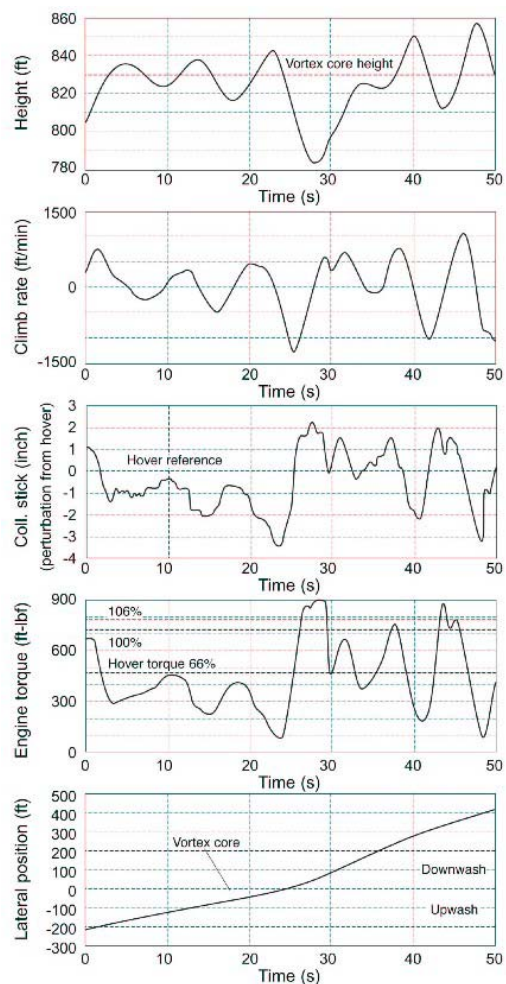
**Fig 20 Attitude response during constrained encounters (FGR)**

With SCAS on, the pilot controls the pitch attitude excursion within about 15deg (compare with 25deg in Table 4). With SCAS off, a nose down pitch of more than the Table 4 value of 35deg is induced; both these peaks occur within 3 seconds. In both cases the helicopter also rolls to starboard and initially yaws to port, couplings that were not allowed in the constrained off-line simulations discussed previously. The roll motion will tend to accelerate the helicopter through the vortex, reducing the attitude excursions.

A preliminary investigation of the effect of intervention time was only accomplished with the SCAS-on configuration and with a single pilot; the results are shown in Fig 21.



**Fig 21 Attitude Excursions as function of pilot intervention time (FGR – SCAS on)**



**Fig 22 Vertical response during encounter (FGR – SCAS on)**

Although they are fairly limited, these data are consistent with the off-line results and the ADS-33 classification in Table 1. The pilot returned a handling qualities rating (HQR, Ref 14) of 7 for all 3 runs based on his perception of the attitude perturbations relative to the Table 1 levels.

Fig 22 shows typical power, collective and vertical changes as the vortex is traversed at a nominal 10ft/sec. Also shown is the lateral track as a function of time with the core and outer boundaries indicated. In the first few seconds the pilot reduces collective as the rotor enters the upwash of the advancing tail. The pilot maintains height within  $\pm 10\text{ft}$  during this phase of flight and reduces collective to command an engine torque less than 20% of the hover setting. At about 25 seconds the vortex core is crossed and as the helicopter passes into the downwash of the retreating tail, a descent rate of more than 1000ft/min builds up in about 5 seconds, arrested by the pilot applying significantly more than the 106% transient torque limit. This transient over-torque limited the height loss to about 50ft. Height and collective excursions during the second phase of the encounter are double those during the advancing phase. The effect of the helicopter being rolled and accelerated to starboard during the core encounter, i.e. pushed out of the vortex, can be seen in the increased slope of the lateral position trace. An HQR of 7 was also awarded for this task on the basis of the torque exceedance and the excursion beyond the adequate height boundary of  $\pm 30\text{ft}$ . Similar results were obtained for (nominal) encounter velocities of 5 and 10ft/sec. The ability to counteract the vertical motion induced by the vortex clearly depends on the available power and thrust margin. We have already seen how the ADS-33 minimum performance for Level 1 HQs is insufficient in this respect.

### **Discussion**

The solution to the vortex encounter or wake turbulence problem with fixed-wing aircraft is to define minimum longitudinal separation distances. The severity of encounters can be catastrophic close to the ground, but the risk is lowered to an acceptable level by reducing the probability of occurrence through separation. When considering runway independent aircraft, and the associated concept of simultaneous, non-interfering operations (SNIOPs), the problem is more complex and lateral separation of approach and departure flight paths also becomes a major issue. At any particular location, the positioning of a helicopter final approach and landing area can be optimised on the basis of prevailing winds and atmospheric

conditions, fixed-wing aircraft landing and take-off points and the nature of the traffic at any particular time. Whether it will ever be acceptable from a traffic control standpoint to operate with this flexibility is another question, but the potential is certainly there for significantly lowering risk.

The results of the current investigations indicate that the severity category is sufficiently high that the risk needs to be carefully managed through flight path constraints. The most concerning result is the potential loss of height due to encounters with the downwash side of a vortex. Interestingly, Ref 15 documents an accident following a suspected encounter of a light helicopter with a vortex, and it was the vertical motion of the aircraft that most disturbed the crew. Helicopters typically operate with fairly low power/thrust margins in hover. Although these may satisfy the handling standards for vertical performance, the results of both off-line and piloted simulations show that they may be wholly inadequate to overcome the effects of a vortex encounter. The situation will improve when some forward velocity has been gained, and when the helicopter has a rate of climb. Nevertheless the severity of the encounter has been shown to be potentially hazardous or even catastrophic and some means of alerting the pilot to the warning signs would seem to be beneficial. In close proximity to the ground, the severity of the attitude disturbances has been judged to be major provided the pilot can react fairly quickly. We have used the ADS-33 near-Earth transient response criteria to classify this level of severity. In practice, the height of the vortex core above the ground is limited but we have seen one effect where the upwash in the advancing tail of the vortex can lift the helicopter into the core. As expected, a SCAS has a significant mitigating effect on the response severity, particularly an attitude-based system which results in a certain amount of self correction.

The study has afforded the opportunity to take a brief look at piloting aspects during encounters in a series of piloted simulation experiments. The results to date are limited but do generally confirm the off-line analysis. One interesting feature that emerged during the piloted tests is the strong coupling into roll and to a lesser extent, yaw. This suggests that roll HQs may need to be assessed in a similar manner to the pitch HQs in this paper. As this paper was being prepared, an initial assessment of the utility of the pilot rating scale for failure transients described in Ref 16 was being conducted. In summary, ratings A to E are tolerable and are awarded for cases where the disturbed excursions range from minimal, requiring no corrective action, to very objectionable,



requiring immediate and intense pilot effort. For cases A->E, safety of flight is judged not to be compromised, and the hazard category is Minor. Safety of flight is compromised with ratings of F->G, with excursions leading to possible encounter with obstacles, unintentional landing or exceedance of flight envelope limits; recovery is marginal and the hazard category is Major (F) or Hazardous (G). A rating of H means that the pilot judged recovery to be impossible; hazard category is catastrophic. The initial impressions are that this scale is more appropriate than the HQR scale for assessing the severity of encounters. The results of the simulation trials using this scale and more realistic encounter conditions will be reported in the future.

Before concluding the paper, it is worth reviewing briefly the key assumption of linear, quasi-steady superposition of the rotorcraft and vortex wakes. The accuracy of this assumption needs to be tested with experimental data. The problem is that the wake interactions and the rotorcraft response represent a coupled, unsteady problem, difficult to simulate experimentally. The assumption is probably most valid when considering interactions with the large scale flows in the vortex tails, and hence when considering severity of vertical motions. Interactions with the vortex core are likely to be considerably more complex and there is an urgent need for special experiments to improve understanding of this effect. At the moment we simply do not know whether such interactions reduce or increase the severity of the rotorcraft response. More sophisticated modelling, including CFD, should also be directed at the problem, but such endeavours do not obviate the need for measurements.

### **Conclusions and Recommendations**

This paper has described a study into the severity of rotorcraft encounters with the wakes of large fixed-wing aircraft. The principal question addressed was - do the minimum handling performance standards give adequate control margin for overcoming the effects of such encounters? The study has been limited to examining the effects of a full strength vortex from a Boeing 747 aircraft with helicopters in the 5-10 tonnes range. The severity of the response has been shown to be critically dependent on the pilot intervention time and nature of the fitted SCAS. The handling qualities standard adopted for assessment was ADS-33, and it has been found that the highest performance boundaries are the more relevant in all cases. The major conclusions are:

1. with SCAS engaged, Level 1 pitch quickness and control power performance standards give a significant response margin,
2. with SCAS disengaged the pitch attitude response is increased to the point where the response margin is small or even negative,
3. descent rates induced in the vortex tail are significantly higher than the minimum requirement for Level 1 performance. This suggests that thrust margins of 10-15% or even higher would be required to enable a pilot to counteract the effects of a vortex encounter,
4. according to the near-Earth transient response severity criteria, a 1.5 second intervention time results in a hazard category of major; with a 3 second intervention time, the severity increases to hazardous,
5. exploratory piloted simulation trials have confirmed the principal results of the off-line analysis but also highlighted the additional complexities of coupled pitch-roll-yaw motions and the high risk of overtorques as the pilot attempts to maintain height.

Handling qualities criteria provide a natural framework within which to set performance margins and quantify severity during upsets caused by vortex encounters. The study has successfully exploited this framework but much remains to be done. In cases where existing limits have been exceeded or performance boundaries challenged, there is a need for more piloted simulation to develop new standards or reposition boundaries. The proposed severity rating scale should prove particularly helpful in this exercise.

Regarding modelling issues, the complexity of the fluid dynamics of the interacting vortex flows warrants specialised experimental work to aid understanding and to define the application limits to the simpler models.

The study also needs to be extended to other types of rotorcraft, including smaller and larger helicopters and tilt rotor aircraft. The latter are particularly important regarding SNIOPs. In the more general context of such runway-independent aircraft, research is needed into establishing the probability of encounters and hence the safety risks of situating final approach and take off areas in particular locations relative to the main operating runways.

### **Acknowledgements**

The results presented from Refs 1 and 2 were produced in a study conducted at DERA (now QinetiQ Ltd), funded by the UK CAA NATS. Grateful thanks to the participating test pilots – Nigel Talbot (CAA), Andy Berryman (BA), Stephane Lignier (DGA) and Geraud Laborie (DGA) – who contributed much to the experimental design and interpretation of results. Thanks also to Andrew Halloway, who conducted a final year BEng project on this topic at The University of Liverpool and helped develop the vortex model and trial methodology.

### **References**

1. Padfield, G.D., Turner, G.P., Helicopter Encounters with aircraft vortex wakes, J. RAeS., Vol 105, No 1043, pp 1-8, Jan 2001
2. Turner, G.P., Padfield, G.D., Harris, M., Encounters with Aircraft Vortex Wakes; the impact on helicopter handling qualities, AIAA paper 9905, to be published in J.of Aircraft, 2002
3. Anon., Guidelines and methods for conducting the safety assessment process on civil airborne systems and equipment, SAE Aerospace Recommended Practice ARP 4761, SAE, 1996-12
4. Kershaw, A., Wake encounters in the London Heathrow area and planned S-Wake studies, proceedings of the 4th WAKENET workshop – 'Wake Vortex Encounter', NLR, Amsterdam, Oct 2000
5. Padfield, G.D., The Making of Helicopter Flying Qualities.; a requirements perspective, J.RAeS, Vol 102, No 1018, pp 409-437, Dec 1998
6. anon, Handling Qualities Requirements for Military Rotorcraft, Performance Specification, ADS-33-PRF, USAAMC, Aviation Engineering Directorate, March 2000
7. anon., UK Defence Standard 00970, Design and Airworthiness Requirements for Service Aircraft, Vol 2, Rotorcraft – Book 1, Defence Procurement Agency, 1988
8. anon., FAA FAR 29, Certification of Transport Rotorcraft, Advisory Circular AC 29-2A
9. Padfield, G.D., White, M.D., Flight Simulation in Academia; HELIFLIGHT in its first year of operation, The Challenge of Realistic Rotorcraft Simulation, RAeS Conference, London, Nov 2001
10. Constant, G., et al., Coherent Laser Radar and the problem of aircraft wake vortices, J. Mod. Opt., 41 2153, 1994
11. Burnham, D.C., B747 vortex alleviation flight tests: ground based sensor measurements, US DOT/FAA report DOT-FAA-RD-81-99 (1982)
12. Hallock, J.M., Burnham, D.C., Decay characteristics of wake vortices from jet transport aircraft, 35th Aerospace Sciences Meeting, AIAA 97-0060, Reno, Nv., 1997
13. Lloyd, E., Tye., Systematic Safety, Civil Aviation Authority, London, July 1982
14. Cooper, G., Harper, R., The use of pilot rating in the evaluation of aircraft handling qualities, NASA TN D-5153, April 1969
15. anon., accident to EC-135, National Transportation Safety Board ref NYC99FA032, Dec 1998; [www.nstb.gov](http://www.nstb.gov)
16. Hindson, W.S., Eshow, M.M., Schroeder, J.A., A pilot rating scale for evaluating failure transients in electronic flight control systems, paper AIAA-90-2827, Atmospheric Flight Mechanics Conference, Portland, Oregon, August 1990