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HELICOPTER ENCOUNTERS WITH AIRCRAFT VORTEX WAKES

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Abstract

This paper presents the results of a study into wake vortex-related safety issues associated with simultaneous rotary and fixed-wing aircraft operations at busy airports. An analysis conducted using both simple conceptual models and high fidelity FLIGHTLAB simulations has considered a helicopter located in the hover above the landing point and during approach and landing. Tip vortices from a Boeing 747 are shed and are assumed to be travelling in a horizontal plane by the time they reach the helicopter. A worst case scenario is simulated, with no vortex ageing or attenuation due to ground effect. Both simple and high fidelity simulations indicate that the rates of climb and descent induced by the vortex tails can be significant. When the helicopter flies through the vortex core, large transient excursions in attitude occur within a few seconds. When the helicopter does not pass through or close to the core, while the flight path perturbations are still significant, the attitude response is shown to be significantly reduced. The predicted cyclic control power required to counteract the vortex-induced hub moments is about 40% of full control, compared with more than 100% for an 'equivalent' fixed-wing aircraft. The control power required in the vertical, collective, axis to overcome the downdraught and updraught in the vortex tails can be as high as 15-20%. While the authors have not tried to make judgements as to whether pilots would find the transients manageable, an approach to quantifying the extent of the hazard has been suggested using the failure transients criteria from the handling qualities performance standard ADS-33. Combined with analysis of the likelihood of such occurrences at particular airports, such response criteria offer a rational approach to developing safety cases for simultaneous operations.

1 Introduction

This paper documents the results of a study into the response of helicopters during encounters with the vortex wakes of fixed-wing aircraft. The results contribute to the analysis of the risks associated with the positioning of helicopter final approach and take-off areas (FATO) for simultaneous operations of fixed and rotary wing aircraft at airports. ICAO recommend that, when simultaneous operations take place, the mandatory separation distance of the FATO from an active runway should be 250m (Ref 1). If, in addition, because of the relative size and weight of operating aircraft, vortex wake generation is an issue in the vicinity, then it is recommended that the separation be increased by as much as is necessary to ensure it no longer affects the FATO. The present investigation was aimed at developing an improved understanding of encounter effects and was limited to the influence of fixed-wing aircraft vortex wakes on helicopters to inform the development of safety cases for FATO location.

In cruising flight through turbulence, the ride bumpiness of a helicopter is more gentle than a fixed-wing aircraft of similar weight and size (Ref 2). There are two principal reasons for this. First and foremost, a key design parameter that governs the vertical response of aircraft to gusts is the wing or blade loading. The higher the wing/blade loading, then the smaller the normal acceleration bump to a sharp edged gust. Helicopters typically have blade loadings 2 or 3 times the wing loading of fixed-wing aircraft. Second, as forward speed increases, the gust response of fixed-wing aircraft tends to increase proportionately with speed. For a helicopter rotor, the loads are distributed as harmonics of rotor speed and the magnitude of low frequency bumps do not increase much above about 100kn (in contrast, the loads at blade passing frequency, felt as vibration, increase linearly with speed). At speeds below about

100kn, however, the gust response of a helicopter is actually greater than a fixed-wing aircraft of similar size and weight flying at the same speed.

To address the level of hazard imposed by simultaneous operations of helicopters and fixed-wing aircraft, this paper examines the response of a helicopter to a vortex wake from a large transport using simulations of helicopter flight behaviour. The question of probability of encounter is not addressed directly, and will depend on a number of factors including the exact position of the FATO relative to the runway, the diurnal/seasonal distribution of prevailing winds and the extent and type of fixed-wing aircraft operations. The nature of the hazard will also depend on the 'age' of the vortex wake and the effect of the ground on the structure and intensity of the vortex. In the present analysis, a worst case situation is assumed whereby the initial strength of the vortex wake is preserved and the encounter is assumed to occur clear of ground effects. In this preliminary study, only axial encounters are modelled – where the helicopter's fore and aft axis is oriented along the vortex core direction. The influence of the helicopter rotor wake on the fixed-wing aircraft wake vortex is also not considered, although this will clearly be more significant for larger helicopters (and smaller fixed-wing aircraft). Section 2 describes how the problem is modelled and Section 3 discusses the results obtained from analytic and numerical investigations. Section 4 proposes criteria for quantifying the severity of a vortex encounter hazard based on handling qualities theory, and Section 5 presents the paper's conclusions and recommendations.

2 Modelling the Helicopter/Vortex Interaction

The vortex wake model used in this investigation was representative of the rolled up tip vortex sketched in Figure 1.

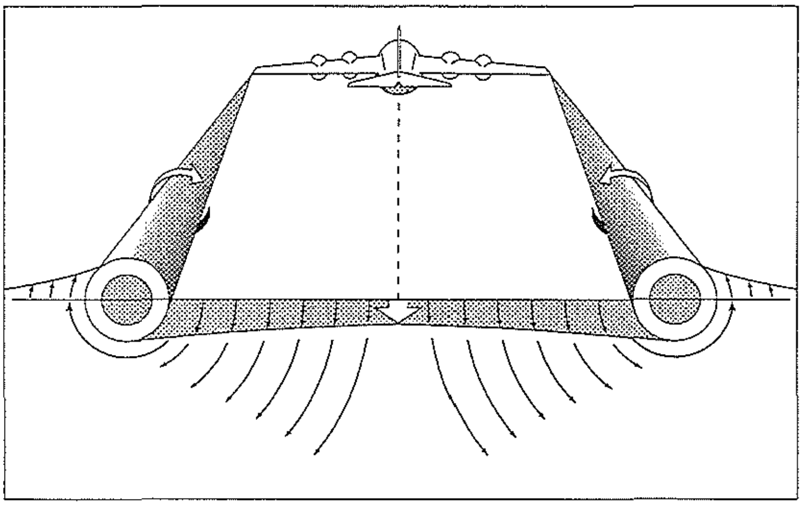

Figure 1: Sketch of Rolled-up Tip Vortex and Axes Systems

The distribution of velocities in the axial direction of the vortex (earth x-axis, into paper) was assumed to be constant whereas the profile in the y-z (right and down in plane of paper) plane were modelled by the following equations taken from Refs 3, 4 and 5. The total tangential velocity, V_T, is approximated as a function of the radial position of the point (r) of interest, normalised by the radius of the vortex core (r_c) and the core velocity, V_c (Ref 3).

$$|r| > r_c \quad V_T = V_c \{ 1 + \ln (r / r_c) \} /(r / r_c) \qquad 1$$

$$|r| < r_c \quad V_T = V_c (r / r_c) \qquad 2$$

For a Boeing 747, the core radius and velocity are given by (Ref 3),

$r_c = 2.51$ m = 8.235 ft
$V_c = 16$ m/s = 52.49 ft/s

These formulae approximate measurements made using a ground-based laser doppler velocimeter installation, tracking the wake of a Boeing 747 (Ref 3). The vertical (w_v) and horizontal (v_v) velocities components in the vortex core are given by :-

$$w_v = -V_T\,(\,y\,/\,r\,) \qquad 3$$

$$v_v = -V_T\,(\,z\,/\,r\,) \qquad 4$$

As given by eqns 1 and 2, and shown in Fig 2, the vortex velocity profiles along the vertical and horizontal axes comprise a linear variation in the vortex core up to the peak positive or negative velocity at the core boundary (given by the dashed line), and a logarithmic decay beyond this point.

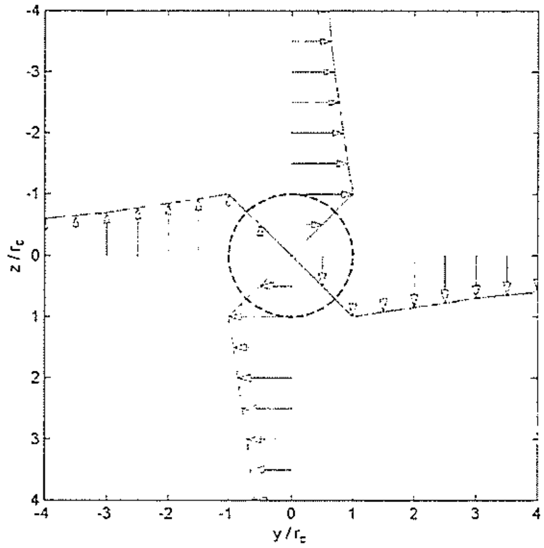

Figure 2; Vortex velocity profiles in y-z plane

The vortex is modelled as a cylindrical feature with the two-dimensional distribution of vertical and lateral velocities in the y-z plane as given in Figures 3 and 4 respectively.

For the purposes of the current investigation, it is assumed that, once the vortex has fully developed, it will initially descend at a velocity dependent on the strength of the vortex. The effect of the ground is such that the vortex pair will descend to an altitude approximately equal to the length of a semi-span - 125 ft (38m) for the Boeing 747 (Ref 3). The vortices then move laterally at a velocity depending on the strength of the vortex and the prevailing wind. Ref 6 suggests an approximate value for the descent and horizontal velocities of about 10 ft/sec (3m/sec).

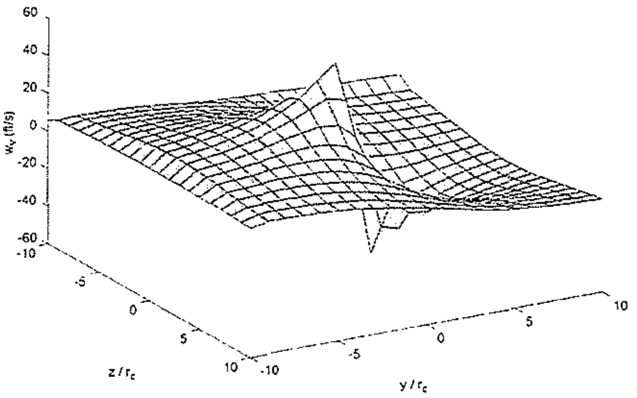

Figure 3; Vertical velocity profile in the tip Vortex of a Boeing 747

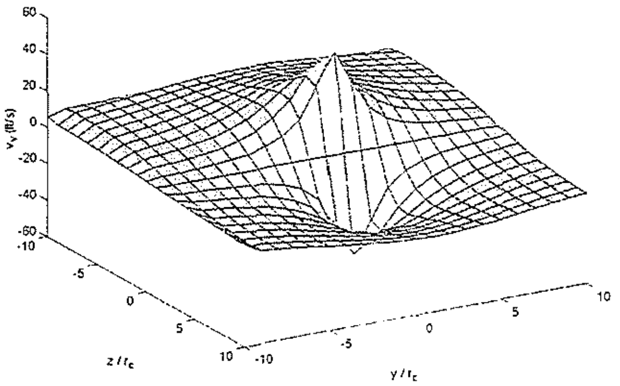

Figure 4; Lateral velocity profile in the tip vortex of a Boeing 747

The rolled-up wing tip vortex described above was assumed to have a constant altitude of 125 ft (38m) and to be moving towards the helicopter from the East at velocities of 5 ft/s (1.5m/s), 10 ft/s (3 m/s) and 20 ft/s (6m/s) (Fig 5).

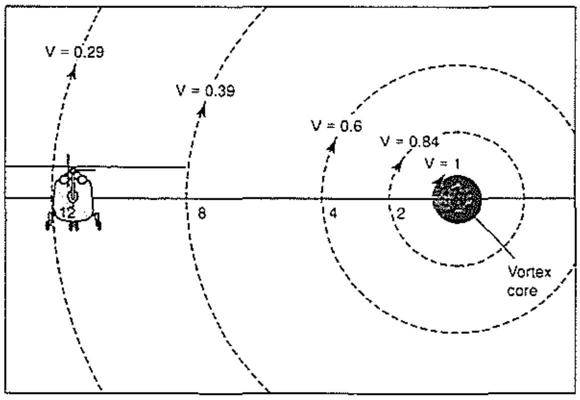

Fig 5; Initial Condition for Helicopter-Vortex Encounter

These speeds correspond to times of approximately 160, 80 and 40 seconds to cover the 250m from the runway. Fig 5 also shows the velocity contours scaled as fractions of the velocity at the outer edge of the vortex core at distances scaled as multiples of the core diameter.

Ref 7 reports the results of tests that indicate vortices still have 'full strength' after 160 seconds but decay rapidly after that as a result of 'vortex breakdown'. As shown in Fig 5, the helicopter was considered facing North at the hover. For ease of implementing the simulation, the position of the vortex remained fixed in space whilst the helicopter was flown through it at an appropriate lateral velocity with all controls fixed at their trimmed values. The results from this approach are approximately the same as those from a moving vortex and a stationary helicopter.

3 Simulation Methodology

The helicopter model used for the simulations was FLIGHTLAB. FLIGHTLAB is, more correctly, a generic helicopter modelling environment where each component of the aircraft/environment system can be modelled to various levels of fidelity, selected by the user. For the present study, FLIGHTLAB was configured as a Lynx Mk3 helicopter with a blade element representation of the main rotor to allow for the penetration effects as the aircraft moves through the vortex. Blade aeroelastics were included, together with aerodynamic lift, drag and pitching moment distributions as nonlinear functions of local incidence and Mach number; dynamic inflow modelled the delay and build up in the reaction of the air in the vicinity of the main rotor to changes in the rotor induced downwash field. In flight at low speed there are numerous effects due to the interaction of the main rotor wake with the empennage and tail rotor which will affect the vehicle's performance and response. A particularly important effect modelled in FLIGHTLAB involves running the model off-line with a prescribed vortex wake, activated to derive a map of tail rotor thrust decrements/increments as a function of wind speed and direction. This map-model is then accessed in the simulation to factor the yaw effectiveness in a quasi-steady manner during manoeuvres.

Before presenting and discussing the results of the FLIGHTLAB simulations in some detail, it is useful to develop a physical understanding of what to expect in the worst case of a hovering helicopter rotor being suddenly immersed in the vortex wake. We can gain some appreciation of this by considering the response to equivalent linear and uniform inflow distributions across the rotor disc.

3.1 Preliminary Analysis

Aircraft Pitch/Roll Response; To estimate the maximum cyclic flapping response and associated hub moments from the velocity distribution shown in Fig 2, we assume an equivalent linear variation of inflow across the disc, peaking at the tip, thus simulating the encounter of the rotor hub with the vortex core (Fig 6). The equivalence in the approximation is derived from the two distributions giving the same overall hub moment as shown in equation 5. Here V_{tip} is the velocity at the blade tip R for the equivalent linear variation and V_c is the velocity at the vortex core boundary, r_c. At the tip of the Lynx rotor (R= 21ft, 6.4m), the equivalent linear velocity function has an approximate peak value of 10m/sec.

$$\int_0^R V_{tip} r dr = \int_0^{r_c} V_c r dr + \int_{r_c}^R V_c \left(1 + \ell n\left(\frac{r}{r_c}\right)\right)\frac{r_c}{r} dr \qquad 5$$

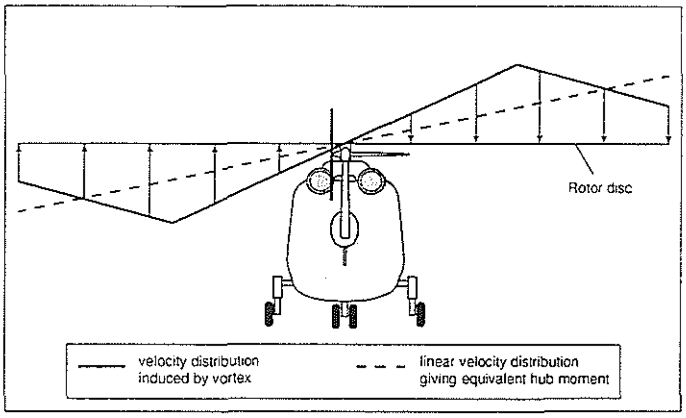

Fig 6 Equivalent Linear Inflow Distribution

If we further assume that the linear variation in inflow across the disc varies with a one per rev cycle around the disc (the cylindrical vortex core structure enforces this approximation), then the incidence changes on the disc are equivalent to cyclic pitch changes. For Lynx, with a tip speed of about 700 ft/sec (213 m/s), the incidence changes give rise to an equivalent cyclic pitch of about 3 degrees (the amount of equivalent cyclic depends only on the rotorspeed – Ref 2), or about 40% of the port or starboard cyclic travel. This, in turn, will result in a flapping response of about 3 degrees, oriented approximately 90 degrees to the cyclic input. Generally, a lateral inflow distribution will give rise to a rotor flapping in the aircraft pitching plane and a longitudinal inflow distribution will give rise to a flapping in the rolling plane. Three degrees of flapping will result in a pitching or rolling motion building up to about 40 deg/sec. To first order, the rate control power depends only on the rotor speed and Lock number. The roll rate will build up quickly, well within a second, while the pitch rate will take about 3 times this long. We could expect to see attitude changes of up to 45deg in roll and 25deg in pitch after about 3 seconds. The Lynx has a hingeless rotor system, which generates powerful hub moments in response to this kind of non-uniform inflow or the equivalent cyclic pitch. For aircraft with articulated or teetering rotor systems, the hub moments will be smaller, but the final roll and pitch rates are likely to be similar to the Lynx, because the damping moments that counteract the build up of rate are reduced in the same proportion as the disturbing moments. The response time for a typical articulated rotor is about double that for the hingeless rotor however, so that the response is generally slower for articulated rotor helicopters and even slower again for teetering rotor helicopters. Nevertheless, we might expect the attitude response within 3 seconds to be between 50 and 75% of the hingeless rotor values, because the rate time constants are still quite small compared with the attitude response times.

Aircraft Heave Response; To estimate the heave (vertical) response of a helicopter to a wake vortex we can examine the simple case of the rotor immersed in a vertical gust of equivalent uniform velocity. The inflow due to the wake vortex peaks at 16m/s at about 40% radius and then reduces to about 75% of this at the tip and continues to reduce logarithmically outboard of the rotor. As the vortex approaches the helicopter there will be an initial period of time when the whole rotor is immersed in an upwash, followed by a non-uniform mix and finally followed by a downwash. If we assume a uniform upwash/downwash doublet of magnitude 10m/s, we can estimate approximately the vertical response of the helicopter flightpath during the approach and departure of the vortex. The helicopter response to this level of normal gust is an initial bump of about 0.3g, followed by a transient growth in rate of climb/descent, with time constant between 3 and 4 seconds. Any helicopter flying into a 10m/s normal gust field would be climbing/descending at over 6m/s within this time constant with a corresponding height change of about 9m. For a Lynx, this is equivalent to the pilot applying about 2 degrees of collective pitch or moving the collective lever over about 15% of its full range.

Limitations of Simple Analysis; The significant difference between the simple instantaneous immersion model described above, and the encounter with a vortex wake, is the penetration effect. If the helicopter flies through the vortex, then the response will intuitively be less than for the instantaneous immersion. Also, the slower the encounter, the greater the exposure and response. On the other hand, if the helicopter moves slowly through the vortex, then an attentive pilot will have sufficient time to apply the corrective control actions, although there is a question as to whether the helicopter has sufficient control power to fully counteract the disturbance, particularly in the collective axis. For example, the application of 2 degrees of collective may result in an over-torque in a highly loaded helicopter.

3.2 FLIGHTLAB Analysis and Results

The results from the FLIGHTLAB analysis are presented in Figs 7 to 11. In all cases time t=0 corresponds to the helicopter trimmed at a location 100 ft (30m) to the port side of the centre of the vortex. It should be noted that even at this distance, the upwash from the vortex is about 4m/s and the hover collective is therefore reduced accordingly. Each figure shows the time response of the aircraft roll, pitch and yaw angles and height.

Fig 7 shows results for the simulated hover with the vortex encountered at velocities of 5 (1.5), 10 (3) and 20 (6) ft/sec (m/sec), or CASE 1. For the 10ft/s case, the aircraft is seen to yaw to port by more than 50deg within about 3 seconds; at the same time the aircraft rolls to starboard by about 5deg and pitches down by about 2deg. The aircraft initially climbs by about 50ft (15m) and then descends rapidly by more than 100ft (30m) in 3 seconds during the second half of the encounter. The relatively small roll and pitch response during the encounter contrasts with the estimates from simple analysis. This can be explained by the fact that the helicopter is lifted up and above the vortex core by the upwash on the port side of the vortex, hence never experiencing the full force of the non-uniform inflow. The climb and descent profile matches the approximate analysis reasonably well; the final descent rate is increased relative to the simple analysis because the initial trim location is already in a significant upwash. This may well be the case in practice, with the pilot adjusting collective to maintain hover. The effect is similar in this respect to wind shear, the pilot needing to react in a timely way to the reversal to avoid the exaggerated effect of the downdraught.

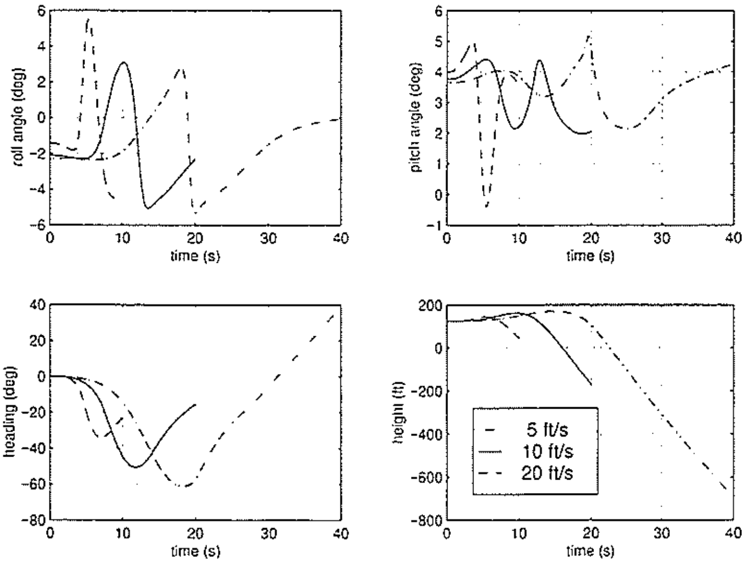

Fig 7 CASE 1; Helicopter Response to a Vortex Encounter - hover with vortex from starboard

To establish the worst case in terms of attitude transients, the case was re-run with the collective continually adjusted to simulate the pilot maintaining height, up to the point where the vortex is encountered, hence forcing the rotor hub to fly through the vortex core. The results are shown in Fig 8, CASE 2. For the 10ft/s (3m/s) approach, on encountering the vortex core, the aircraft is rolled to starboard by more than 30deg in 3 seconds. The aircraft yaws to port by about 70 deg which accounts for the greater roll than pitch motion in this case. The roll and pitch response is initially impeded by the attitude hold function in the Lynx stability augmentation system, but the moment generated by the vortex causes the SAS actuators to quickly saturate, leading to the rapid attitude change shown. Interestingly, the 5 ft/s and 20ft/s cases do not show nearly the same amount of roll response, which suggests that there will be encounter velocities that tune to the vortex and that lead to the most severe response. In the 10ft/s case it appears that the helicopter is virtually 'caught' in the centre of the vortex and powerfully rolled back and forth.

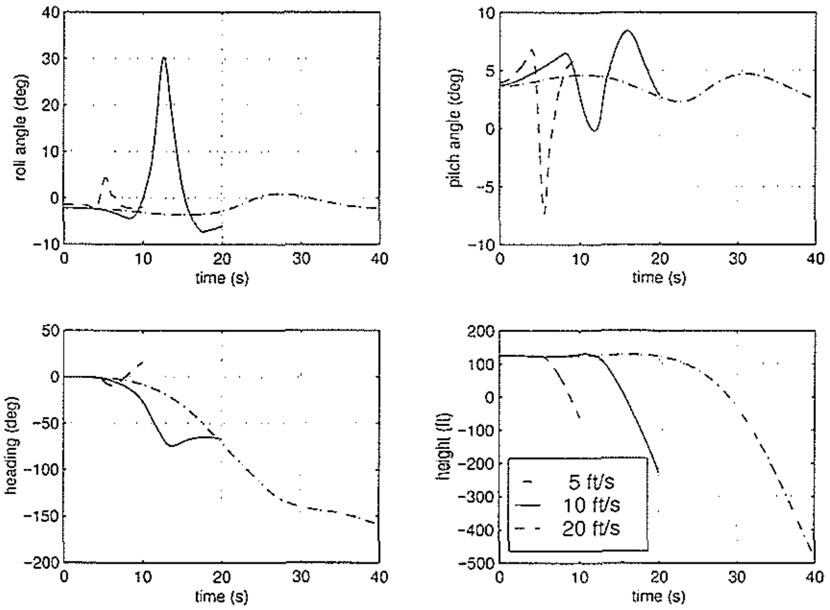

Fig 8 CASE 2; Helicopter Response to a Vortex Encounter – a repeat of CASE 1 with collective pitch adjusted to achieve encounter between vortex core and rotor hub

On further examination, the results of CASE 2 show that for the slower encounter the aircraft is actually pushed back by the vortex tail so that by the time the vortex reaches the initial hover location the aircraft is still to port of the vortex. To explore the effect of vortex velocity on aircraft response when rotor hub/vortex core encounters occur, FLIGHTLAB was configured so that the flight path and heading were fully constrained to ensure equivalent encounters. Fig 9 shows the pitch and roll attitude excursions during these encounters, demonstrating the increased response for the slower vortex passage when the rotor is exposed to the nonuniform inflow for the longest time. For the 5 ft/sec vortex passing velocity, a pitch attitude transient of greater than 40 degs builds up in about 5 seconds.

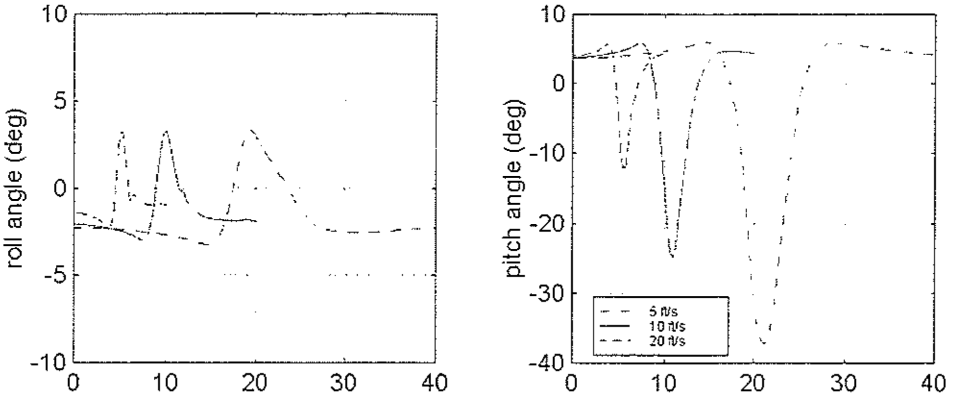

Fig 9; CASE 2 with Flight Path and Heading fully Constrained; Roll and Pitch Attitude Responses

Fig 10 shows CASE 3, where the initial condition has the aircraft some 50 feet below the vortex core, perhaps a more realistic case for a helicopter hovering or on initial climb-out. As the vortex approaches, the aircraft is lifted up, and in this case the rotor hub again passes through the vortex core. The heading changes are now relatively small, within +/- 20deg, ensuring that the maximum response is in the pitch axis. A pitch transient of about 30deg builds up in about 3 secs. This case might be perceived as a near miss, with the vortex passing safely over the helicopter. In actual fact, what happens is that the aircraft is pulled up into the vortex, resulting in a significant transient attitude response.

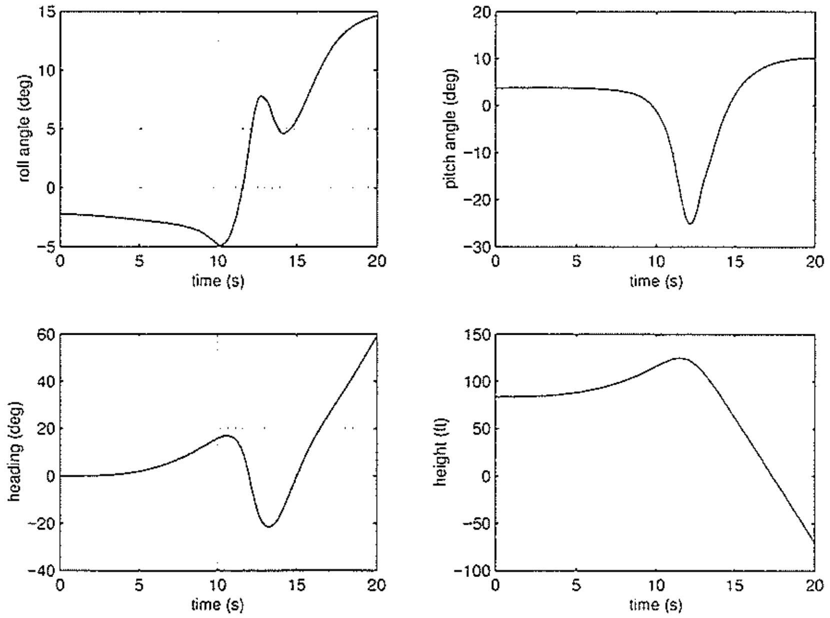

Fig 10 CASE 3; Helicopter Response to a Vortex Encounter – a repeat of CASE 1 with initial height adjusted to achieve encounter between vortex core and rotor hub

The effect of vortex strength will be of considerable interest in developing safety cases for simultaneous operations. Figs 11a and 11b show two cases, CASES 4 and 5. CASE 4 shows the pitch and roll responses for the 10 ft/sec vortex with the CASE 2 constraint on collective to position the helicopter at the vortex core height, when the vortex passes the initial hover location. Three vortex strengths are considered. There is no obvious relationship between response and vortex intensity, particularly in roll. However, if we again apply the full flight path constraint to the simulation, to ensure hub-vortex encounters, then a much stronger relationship applies, albeit nonlinear, as shown in Fig 11b, CASE 5.

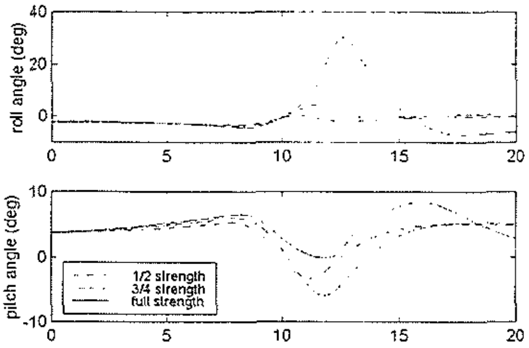

Fig 11a; CASE 4 – Variations in Vortex Strength; free encounters

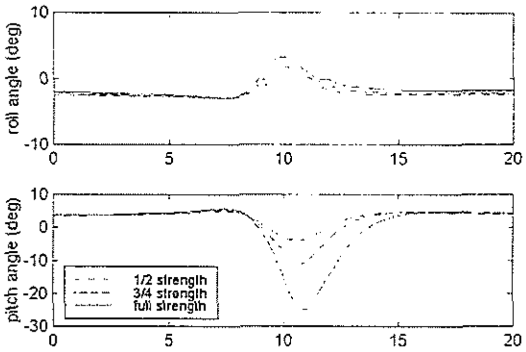

Fig 11b; CASE 5 – Variations in Vortex Strength; constrained encounters

What has happened is that, once again, the helicopter has been pushed away from the vortex in the lower intensity cases for the free encounters (Fig 11a).

Finally, Fig 12 (CASE 6) shows results for a case where the helicopter is flying at 60kn and the vortex again moves in from the starboard side. Such a scenario could be expected during the initial phase of a departure or final phase of an approach to a FATO, although the power margin would be quite different in the two cases. The results are derived from constrained simulation as in previous cases to ensure a close encounter. A pitch attitude excursion of more than 20 degs is experienced, again building in about 3 secs. In practice, this kind of encounter is likely to be even more short-lived than the constrained results show, because the helicopter will be climbing or descending through the vortex. However, the flight path disturbances will still be significant and are likely to be particularly disturbing during the final stages of the approach. Placing the FATO before the fixed-wing aircraft take-off point will minimise the risk of encounter and this kind of reasoning should normally be applied when locating helicopter operating areas at busy airports.

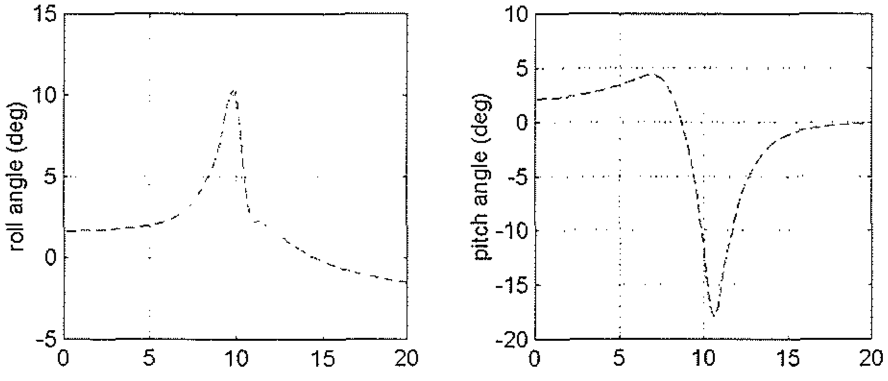

Fig 12 CASE 6; Helicopter Response to Vortex Encounter - 60kn with vortex from starboard

3.3 Discussion

The results show the kind of response levels expected when a helicopter encounters a fixed-wing aircraft vortex. No analysis has been conducted to explore the nature of response variations with aircraft design parameters. The simulated aircraft was a Lynx, but we can expect similar levels of flight path response from helicopters with similar rotorspeeds and blade loadings. For larger helicopters, with higher rotor downwash velocities, we could expect a stronger interaction between the aircraft and helicopter wakes; a vortex travelling above the helicopter could be pulled down into the rotor for example. As far as attitude excursions are concerned, helicopters with 'softer' rotor types will experience smaller pitch and roll responses. However, the control power margin required to overcome the disturbance is likely to be similar. Pilot reaction to the encounter has not been explored in the study, but it has been suggested that a pilot may well constrain the flight path in a similar way to the artificial constraint imposed in the current study to force an encounter. There is also a concern that the pilot reaction to the encounter in power/flight path management terms could exacerbate the problem, in a similar way to flight path management during encounters with shear layers due to sharp weather fronts.

The results show general agreement with the data in Ref 4, where three different helicopters are simulated - UH-1, OH-6 and BO-105. The simulated flight condition is a 1000fpm climb at 60kn, flying directly into the approaching B747 vortex. The results presented indicate roll angle transients of approximately 12, 20 and 24 deg for the three aircraft respectively, within about 2 seconds. In Refs 8 and 9, the authors simulate B747 vortex encounters, again in forward flight conditions. The helicopter type is not given but the mass was approximately 3000kg and rotor radius approximately 5m. Results are presented for various flight encounter angles. Maximum roll (35deg), pitch (35deg) and yaw (20deg) angle transients occur during encounters similar to the type studied in the FLIGHTLAB simulations in this paper. In Ref 10, flight test results are presented for the case of a UH-1 helicopter flown into the wake of a C-54 aircraft and attitude transients were " *confined to small excursions in yaw angle*". The simulated Boeing 747 in the present study is about 14 times the weight the C-54 and it is not clear whether the rotor passed through the vortex core during any of the test encounters reported in Ref 10.

Overall, the results of the FLIGHTLAB analysis confirm the general indications from the simple analysis; that significant attitude transients can build up rapidly when the core is encountered by the rotor and that large rates of climb and descent build up in the upflow and downflow present in the extensive vortex tails. The effect of the ground on the velocity distribution in the vortex tails is clearly important and no attempt has been made to investigate this; further work is required here which was outside the scope of the present study.

We have shown that the control power required to overcome the disturbance caused by a vortex encounter in the worst case is about 40% cyclic and 15% collective. These contrast with the control power requirements for a 'similar' fixed-wing aircraft which can be greater than the capability of the aircraft both in terms of aileron and climb power. Of course, for the helicopter on climb out, there may be insufficient power margin to generate the 15% of additional thrust required to maintain a designated flight path in controlled airspace.

The severity of the transients can be examined in handling qualities terms by drawing an analogy with the failure transients criteria in the handling qualities standard ADS-33 (Ref 11).

4 Alternative Hazard Severity Criteria

In the helicopter handling qualities standard, ADS-33, criteria for similar kinds of transient motions are given in the case of system failures, rather than external disturbances. We can, however, usefully consider applying the same criteria for the transients following vortex wake encounters. Table 1 shows the criteria, quantified in terms of three levels;

- Level 1 corresponds to good handling qualities that enable the pilot to achieve a desired level of performance, well within the margins of error for the mission task, and at a low workload, corresponding to minimal control compensation.

- Level 2 corresponds to handling qualities with tolerable deficiencies that enable the pilot to achieve an adequate performance standard, just within the margins of mission task error, but possibly requiring extensive pilot compensation, hence high workload.
- Level 3 corresponds to handling qualities with major deficiencies that intrude significantly on the pilot's ability to achieve even the adequate performance standard in a mission task, with maximum tolerable compensation.

Beyond Level 3 indicates a risk that control will be lost during some phase of the mission or manoeuvre. In handling qualities parlance, this is sometimes referred to as Level 4 (Ref 12). It is argued that the safety case for the positioning of a FATO should be based on transients that result in handling degradation no worse than Level 3 - i.e. transient attitudes of less than 24deg with no recovery action taken within 3 seconds for low-speed, near-Earth operations. The 3 seconds is based on the pilot flying with some level of divided attention. In the UK Defence Standard, 3 seconds corresponds roughly to the intervention time when the pilot is flying 'passive, hands-on' (Ref 13).

	FLIGHT CONDITION		
LEVEL	**HOVER AND LOW SPEED**	**FORWARD FLIGHT**	
		NEAR EARTH	**UP-AND-AWAY**
1	3 deg roll, pitch, yaw 0.05g n_x, n_y, n_z 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 n_x, n_y, n_z 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 n_x, n_y, n_z 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; Failure Response Transients (ADS-33)

Considering the Level 3 requirements in Table 1, we note that a roll or pitch attitude which peaks at 24 deg in 3 seconds will result in the aircraft being displaced about 30 ft (9m) in the horizontal plane in the same time. A perturbation in normal acceleration peaking at 0.4g (down) in 3 seconds will result in the aircraft losing about 30 ft (9m) in height. Both these estimates are based on an exponential growth in attitude and rate of descent in the 3 seconds. These are significant perturbations and in most cases the pilot will probably intervene well within this time. However, it may be night and there may be poor weather conditions and the pilot may have his attention diverted while waiting for clearance. He may be disoriented by the encounter and take a few seconds to get a grip on what is happening. The results from the FLIGHTLAB analysis show that transients outside the Level 3 limits can be experienced in the worst cases.

Based on the above discussion, an alternative approach to developing a safety requirement could be to define the probability of encountering vortices that result in transients greater than Level 3. Based on calculation, it can then be estimated how well the proposed operation meets these requirements. To pursue this approach further, two new activities need to be undertaken. First, an investigation into the likelihood of encountering shed vortex wakes at any proposed FATO areas needs to be conducted (taking into account, for example, frequency of aircraft types, wind strength and directions etc.). This investigation should include a more detailed study into the ageing of vortex wakes near the ground, to improve the simulation modelling. Second, the proposed approach to hazard severity using the alternative criteria discussed in this Section needs validation. The numbers in Table 1 are derived for the transients due to flight control system failures, where it is assumed that the pilot will not intervene until 3 seconds. The corresponding numbers for the wake vortex interaction response may well be different. Testing is required to validate the approach and to develop an appropriate handling qualities database. Ground-based piloted simulation offers the potential to capture such data in a safe and controlled environment.

5 Conclusions and Recommendations

This report has presented the results of a study into the safety issues associated with locating helicopter landing and take-off areas to facilitate simultaneous operations at busy airports. An analysis has been conducted using both simple engineering models and the high fidelity FLIGHTLAB simulation model configured as a Lynx helicopter. The analysis has considered the helicopter located in the hover above the landing point. Tip vortices from a Boeing 747 are shed and are assumed to move downwards and outwards, and to only have a horizontal velocity by the time the helicopter is reached. To examine the worst case scenario, no vortex ageing/decay is assumed and the helicopter and vortex are assumed to be at the same level at the initiation of the encounter when the vortex is 100ft (30m) to the starboard side of the helicopter. Several encounter velocities have been examined and the results portrayed in terms of transient attitude and flight path excursions. The main conclusions of the analysis are as follows.

(a) Both the simple analysis and FLIGHTLAB simulations indicate that when the helicopter flies through the vortex core, large transient excursions in attitude and flight path occur within a few seconds. The most severe cases appear to be when the helicopter is effectively caught in the core and hence subjected to the strongest non-uniform upwash/downwash. In the worst cases identified, control power margins of 40% cyclic and 15% collective are required to overcome the disturbance. These figures contrast with the control power requirements for a 'similar' fixed-wing aircraft which can be, as is well known, greater than the capability of the aircraft both in terms of aileron and climb power.

(b) When the helicopter does not fly through the core, while flight path excursions are still significant, the attitude response is reduced. For example, in the first case examined with the helicopter at the same height as the vortex, and offset 100ft at the initial condition, the upflow in the vortex actually lifts the helicopter above the core, resulting in a reduced transient attitude response. If the pilot were to reduce collective to hold a hover height or ascending/descending flight path during the encounter, he is likely to experience much greater attitude transients as the core is traversed.

(c) An encounter with a vortex passing about 50ft above the helicopter is likely to result in the upflow lifting the helicopter into the vortex core when large attitude transients will again be experienced. In this sense, near misses may actually be worse cases.

(d) The level of transient response, and hence severity of the hazard, is sensitive to the speed of the vortex encounter. The slower the vortex, the longer the exposure and, intuitively, the larger the response. However, there appears to be an intermediate vortex encounter velocity (between 5 and 20ft/sec) when the transient response is a maximum, because the vortex effectively pushes the aircraft out of its path at the slower traverses. This tuning is likely to be a function of helicopter type and, significantly, the pilot reaction to the encounter.

(e) The aircraft used in the study was the 5000kg Lynx with a hingeless rotor system. No high fidelity simulation work has been conducted with other configurations to establish the effects on larger/smaller aircraft or those with different rotor types. Although more work would be required to quantify the effects, it is felt that the overall results would be similar with different types. Attitude transients may decrease by about 25% for softer rotor systems and heave transients would also reduce for helicopters with slower rotors and higher blade loadings. Aircraft size is likely to be a discriminating parameter in two respects. Firstly, in so far as the helicopter rotor downwash might affect the vortex wake and, secondly, the ratio of rotor radius to wake size will affect the value of the tuned encounter velocity.

(f) No references have been found to previous studies examining the response to vortices in low speed conditions. Nevertheless, comparison with other work where encounters took place in 60kn cruise and climb conditions, indicate general agreement.

(g) The authors have not tried to make judgements on whether pilots would find the transients acceptable or whether there is sufficient control power to overcome the transients in all conditions. However, a new approach to quantifying the extent of the hazard effect has been suggested using the failure-transients criteria from the handling qualities performance standard ADS-33. These criteria suggest that the handling qualities in the worse case scenarios investigated would lie outside the Level 3 area, i.e. risk that control will be lost during mission task.

(h) A recommendation of the Paper is that further work be conducted to develop a more substantial approach to hazard severity and probability using the alternative failure-transients criteria. A handling qualities test database needs to be generated to validate any new approach and ground-based piloted simulation offers the potential to capture such data in a safe and controlled environment. A study into the likelihood of vortex encounters at any proposed FATO area also needs to be conducted, taking into account frequency of aircraft operations, aircraft types and associated vortex ageing and wind strengths and directions.

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