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Encounters with Aircraft Vortex Wakes: The Impact on Helicopter Handling Qualities

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A study concerning the risks associated with locating a helicopter final approach and takeoff area alongside an active runway at a busy international airport is documented. Specifically, by the use of desktop simulation, the problem is addressed of an in-flight helicopter encountering the shed wing tip vortex from a large transport aircraft. Measurements are reviewed of vortices taken using coherent laser radar equipment located under the final approach path to London Heathrow Airport to establish a model of the vortex velocity profile. The simulations have shown the helicopter can experience transient pitch attitude changes of up to 40 deg and accumulated descent rates of 1500 ft/min (457 m/min) during the encounter, assuming that no pilot intervention is made. Established handling qualities metrics have been adapted and suggest that these responses may produce handling difficulties. The simulations were also broadened to consider a range of helicopter designs and the effects of shed vortices from a number of large transport aircraft. It is concluded that under particular circumstances a helicopter can experience significant transient motions on encountering a shed wing tip vortex, although no attempt has been made to estimate the probability of this occurrence.

Introduction

THIS paper documents a study concerning the risks associated with locating a helicopter final approach and takeoff area (FATO) 250 m (820 ft) from an active runway at a busy international airport. The study is an extension of earlier work described in Ref. 1.

The International Civil Aviation Organization (ICAO) recommends that, when simultaneous (fixed- and rotary-wing aircraft) operations take place, the mandatory separation distance of the FATO from an active runway should be 250 m (Ref. 2). 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 implication of the wording in Ref. 2 is that it is the influence of the fixed-wing aircraft vortex wakes on the helicopter that is the main problem and not vice versa.

Helicopters respond to atmosphere disturbances according to the same rules of aerodynamics as fixed-wing aircraft. In cruising flight through turbulence, the ride bumpiness is gentler for a helicopter than for a fixed-wing aircraft of similar weight and size.[3] There are two principal reasons for this. First and most important, a key design parameter that governs the vertical response 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 is. Helicopters have typical blade loadings two or three times the wing loading of fixed-wing aircraft of a similar weight. Second, as forward speed increases, the gust response of fixed-wing aircraft tends to increase proportionately with speed. In 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 100 kn. At speeds up to about 100 kn, however, the gust response of a helicopter is actually greater than the equivalent fixed-wing aircraft 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 aircraft using simulations of helicopter behavior. The question of probability of encounter is not addressed directly. This will depend on a number of factors, including the exact position of the FATO relative to the runway, the temporal distribution of prevailing winds, and the level of fixed-wing aircraft operations. The nature of the hazard will also depend on the life of the vortex wake; hence, before the analysis, a review of some vortex measurements is made to establish that a relevant worst case is when there has been no significant decay. The influence of the helicopter rotor wake on the fixed-wing aircraft wake vortex is also not considered, although this will clearly become more significant for larger helicopters and smaller fixed-wing aircraft. Finally, the paper addresses handling qualities issues only and makes no attempt to estimate transient loads in any of the helicopter components during the encounters.

The paper first describes the analysis of wake vortex measurements and how they have been modeled followed by a presentation and discussion of results obtained from a study of the helicopter response using the FLIGHTLAB modeling environment. The paper finishes with recommendations and conclusions.

Modeling the Helicopter/Vortex Interaction Problem

Comparison of Vortex Models with Measured Data

In this section, a comparison is made between data measured by coherent laser radar on wakes created by real aircraft and a model of the vortex velocity profile attributed to Burnham[4] and Hallock and Burnham.[5] Coherent laser radar (lidar)[6–8] operates by transmitting a laser beam and detecting the radiation backscattered by small particles or droplets (aerosols) that are always present in the atmosphere. The spectrum of Doppler shifts in the frequency of the

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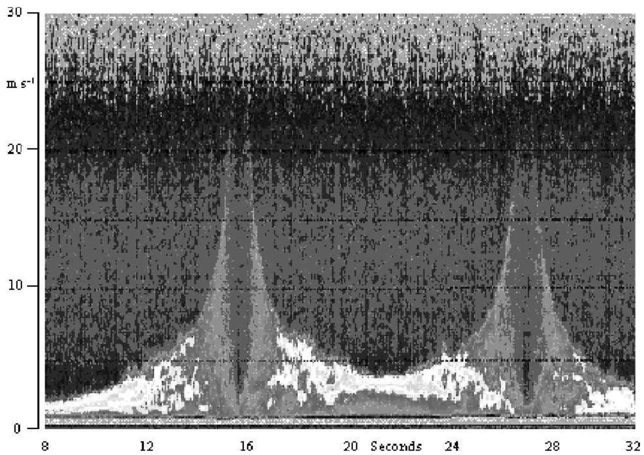

Fig. 1 Lidar measurement of wake vortex pair for Airbus A300.

backscattered radiation is analyzed to give the line-of-sight velocity component of the aerosols and, hence, the motion of the air, along the beam.

In 1994 and 1995, QinetiQ (formerly Defence Evaluation and Research Agency (DERA)) carried out a series of lidar measurements on aircraft wake vortices at London Heathrow Airport (funded by National Air Traffic Services within the U.K. Civil Aviation Authority). Wake vortex data were recorded for approximately 3000 aircraft on approach to Heathrow. The measurements were made in a wide range of atmospheric conditions and from five different sites near the airport. Details of the measurements and analysis of some of the results are presented in Refs. 9–11. Further useful background on the issues involved in such measurements is presented in Refs. 12 and 13.

Figure 1 shows an example data set from Ref. 9 showing the vortex pair from an Airbus A300. The grayscale shading in Fig. 1 represents the strength of signal at each velocity where the lighter regions indicate a strong signal. The lidar cannot distinguish between motion toward or away from the system: Hence, the modulus of the velocity is displayed. More recent work has employed a system with a direction sensing capability, and this allows the reversal of velocity through the vortex core to be clearly observed.[14] In general, a wide range of velocities is picked up at any instant reflecting that the lidar samples the scattering along a considerable path length (here of order ±50 m from the focus of the beam). The precise distribution of these velocities is sensitive to the relative positions of the vortex cores and the laser beam focus and also to any inhomogeneities in scattering level. However, the outline of the plot in Fig. 1 is invariant to these factors, and it is this outline (representing the tangent velocity) that permits a meaningful comparison with vortex models. The outline is calculated via an algorithm that finds the upper and lower limits of velocity (above a preset signal threshold level) at each measurement time throughout the data set. The two peaks visible in Fig. 1 represent the inner cores of a vortex pair comprising a single vortex shed from each wing tip. The measurements are made as the vortices pass over the location of the lidar equipment, the beam of which is pointed vertically up.

Figures 2–5 show examples of the outline tangent velocity for four different aircraft types. The velocity profiles for a single vortex have been calculated by correcting for the effects of the other vortex in each pair, and the correct change of sign across the core has been artificially introduced by reflecting one-half of the profile about zero. The data sets have been chosen as examples of vortices with circulation close to the mean value for each aircraft, so that they can be considered to be representative. In the case of the Boeing 747, three data sets have been averaged to give a more general profile. Note the dramatic differences in vortex structure between the medium two-engine (Boeing 757 and Airbus A310) and large four-engine aircraft (Boeing 747 and Airbus A340), with the latter having higher circulation, but lower peak velocity as given in Table 1 and further described in Ref. 15. Vaughan et al.[15] also highlighted some examples of Boeing 747 data, where evidence was observed

Table 1 Best-fit parameter values to lidar velocity profiles for the Burnham[a] and dispersion models

	Burnham model[a]		Dispersion model		
Aircraft	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

[a]See Refs. 4, 5, and 16.

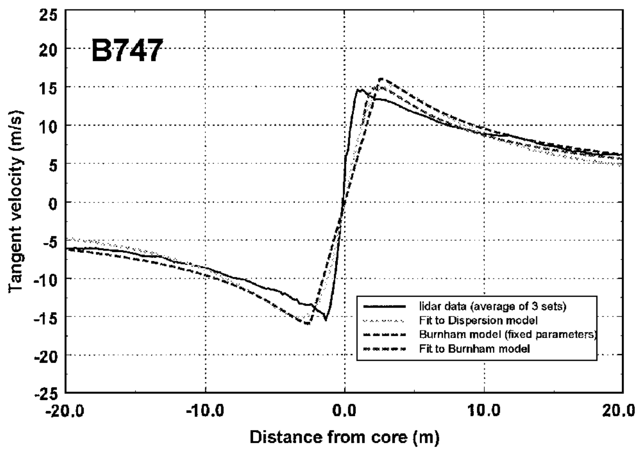

Fig. 2 Vortex velocity profile for Boeing 747.

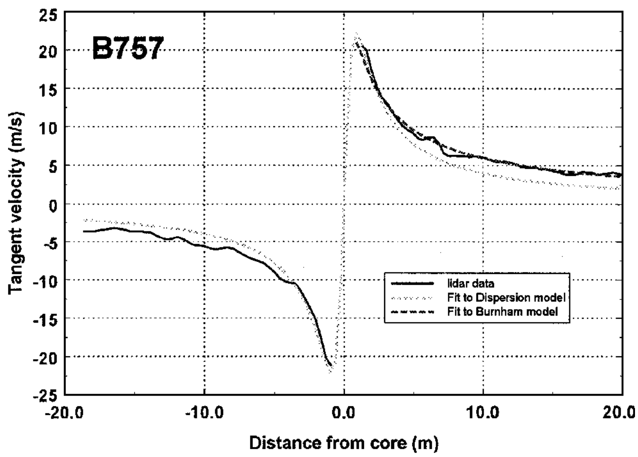

Fig. 3 Vortex velocity profile for Boeing 757.

of substantially higher velocities within a small inner core. In addition, complex structure was also observed in the form of inversions in the velocity profile. The averaging procedure adopted here has tended to wash out these features in the profile of Fig. 2.

A variety of empirical models have been used to describe the vortex tangent velocity profile. Here, we examine the validity of two commonly used examples. The dispersion model[6] takes the form

$$V_T(r) = \frac{\Gamma r}{2\pi\left(r^2 + r_C^2\right)} \tag{1}$$

where $V_T(r)$ is the tangent velocity at a distance r from the vortex core, r_c is the core radius (defined as the distance from the center of the vortex to the peak of the tangent velocity) and Γ is the total circulation around the vortex (in square meters per second).

The other example used is the Burnham model (see Refs. 4, 5, and 16):

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

$$V_T(r) = V_c(r/r_c), \qquad |r| < r_c \tag{2}$$

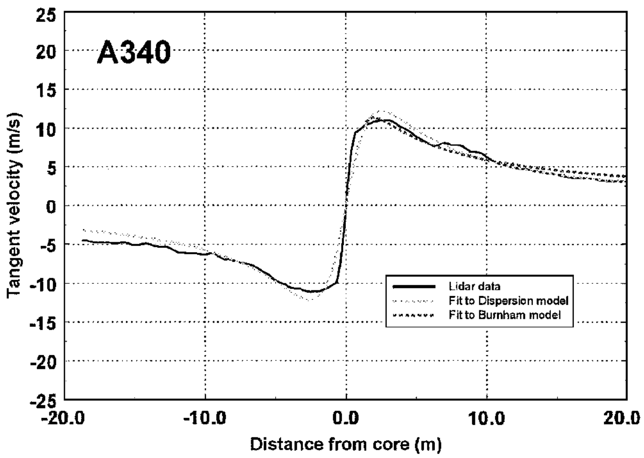

Fig. 4 Vortex velocity profile for Airbus A340.

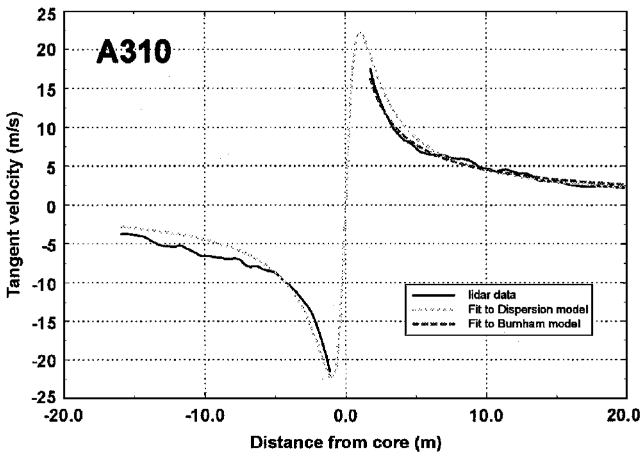

Fig. 5 Vortex velocity profile for Airbus A310.

where $V_T(r)$ and r_c are as defined earlier and V_c is the peak velocity, that is, 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 description of the B747 vortex profile in Refs. 4 and 5.

The models described by Eqs. (1) and (2) have been compared to the lidar data in Figs. 2–5. A best fit was obtained for each of the velocity profiles using both of the models, and the resulting best-fit parameters are given in Table 1.

In each case the fit, although not perfect, is 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 and Airbus A340) should be reliable, but the maximum velocities for the medium aircraft (Boeing 757 and Airbus A310) are estimates, which will be equal to or less than the true value because 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. Note that the values in Table 1 relate only to a single data set for each aircraft (average of three in the case of Boeing 747), but these values, nevertheless, should be broadly representative.

Vortex Trajectory and Decay

Vortex trajectory and decay are the subject of intense current research.[17] Trajectories are influenced both by the vortices themselves (mutual induction and ground effect) and also by meteorological factors such as crosswind and stratification. The onset and rate of vortex decay[17–21] depend on many factors. Some of these factors are intrinsic to the particular vortex structure[20] but, more generally, atmospheric turbulence is known to be a major cause of vortex breakdown. This section presents some specific examples from the QinetiQ Heathrow database to show vortices of near full strength well beyond 1 min after passage of the aircraft. It will also be shown that during this timescale, vortices can drift transversely by distances greater than 490 ft (149 m) without significant loss of strength.

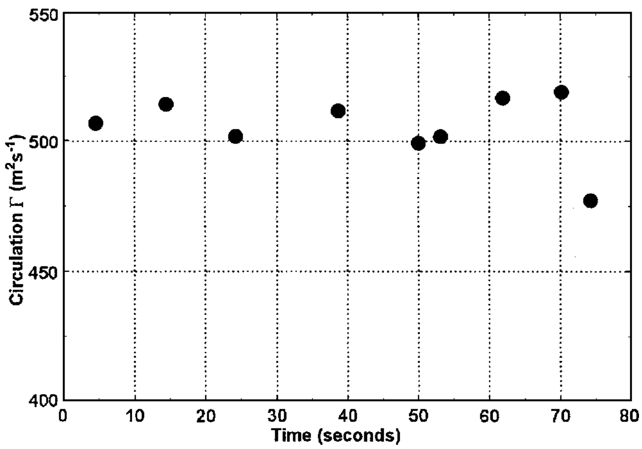

Fig. 6 Example of changes in circulation with time.

Various mechanisms have been proposed to describe vortex decay, perhaps the best known being the Crow instability[18] (also see Crow and Bates[19]). The onset of the Crow instability is normally brought about by atmospheric turbulence. This disturbs the vortex pair from their initially parallel geometry and sets off a ripple in the separation, the amplitude of which increases with time. Eventually the two vortex cores begin to interact, leading to cancellation, catastrophic decay, and the formation of vortex rings.

The QinetiQ measurements at Heathrow contain many examples of long-lived vortices displaying almost undiminished strength beyond 60 s. It is beyond the scope of this study to assess the probability of such events, or to correlate vortex survival with aircraft type and atmospheric conditions. However, it can be concluded that long-lived vortex behavior is not restricted to isolated events, as confirmed by several other studies.[5,12,17,21] Figure 6 shows an example where the circulation as a function of time has been extracted by detailed analysis of the lidar data. The circulation remains remarkably constant for 70 s after passage of the aircraft. At this point, the vortex drifts outside the region of space covered by the lidar scan pattern.

A typical vortex trajectory consists of a vertical sink rate of order 5 ft/s (1.52 m/s), caused by mutual induction of the vortex pair, as described in Ref. 21, and a horizontal drift rate determined by the ambient wind field. An example trajectory from the QinetiQ LIDAR measurements at Heathrow has been reconstructed in Fig. 7. Both vortices are observed to drift considerable distances [for one vortex, in excess of 650 ft (198 m)] before they are lost to the lidar field of view. This behavior is typical in moderate crosswind conditions. The vortices start to experience ground effect at an altitude roughly comparable with their separation [about 164 ft (50 m) for Boeing 747]. This causes the vortex separation to increase and the sink rate to reduce. For long-lived vortices, the pair can separate under ground effect to a degree where they retain little mutual influence. The individual vortices then move horizontally at a velocity determined by the combination of 1) drift induced by ground interaction (~3–5 ft/s or 1–1.5 m/s) and 2) the prevailing crosswind. It is not known what effect ground interaction has on vortex decay.

It is important to establish whether vortex drift tends to lead to more rapid decay. In the example plotted in Fig. 6, the vortex shows long-lived behavior with little reduction in strength over the 70 s for which it lies within the lidar scan. Hence, we conclude that vortices can retain considerable strength after horizontal drifting in excess of 200 m, a distance close to the separation of 250 m (820 ft) specified by ICAO. For stronger winds (exceeding roughly 30 ft/s or 10 m/s) the effect of atmospheric turbulence leads to accelerated vortex decay, where the classical vortex velocity profile can become severely distorted after just a few seconds.

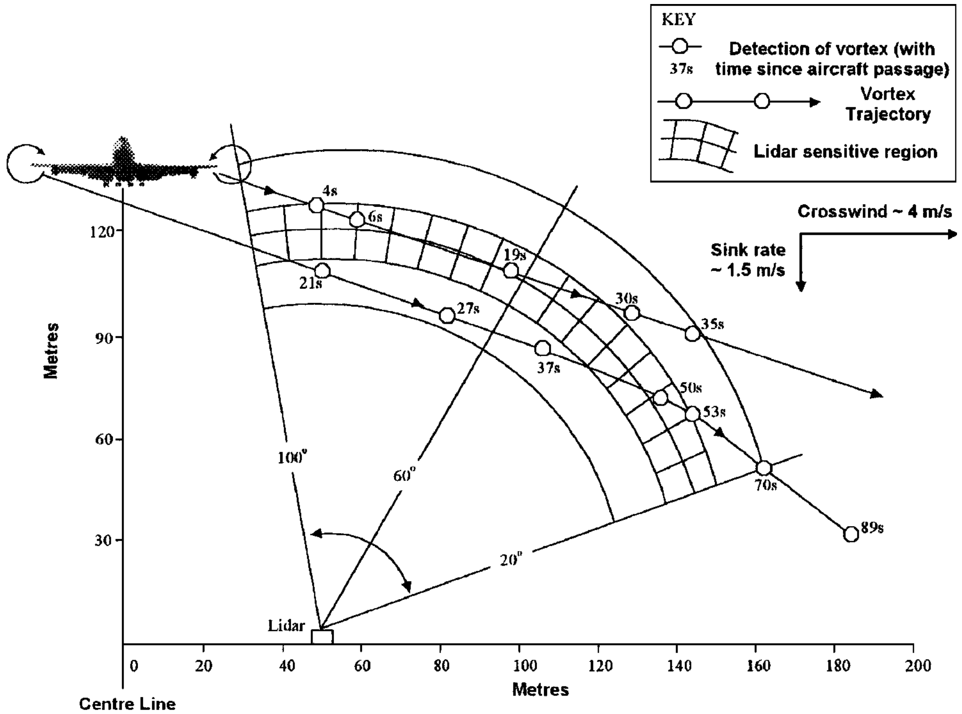

Fig. 7 Example of vortex trajectory.

Much useful information on vortex transport and decay has resulted from a study at Frankfurt Airport, Germany. A Doppler lidar (similar to that used at Heathrow by QinetiQ) was positioned halfway between the two parallel runways [runway separation 1800 ft (549 m)], about 2300–2600 ft (700–790 m) from the landing threshold. Vortices from over 1400 aircraft were measured. Koepp[21] provides statistics on vortex transport and decay, as well as detailed analysis of some specific examples. One such case is illustrated[21] where a Boeing 747 vortex shows little reduction in strength after drifting ~650 ft (200 m). The strength then reduces steadily, but a considerable vortex is still observable over 1300 ft (396 m) from the point of formation. It is also suggested in Ref. 21 that when ground effects are significant, that is, at altitudes below ~160 ft (50 m), the downwind vortex is more hazardous because its self-induced velocity adds to the crosswind, leading to more rapid drift. Koepp[21] concludes that "Under crosswind conditions of that amount (close to 13 ft/s (4 m/s) the vortices actually reach the safety area of the parallel runway with high probability...." The following is also concluded:

> The correlation of the parameters important for the vortex transport with quantities describing the stability of the atmosphere proved to be very difficult.... The experimental results are primarily valid for the Frankfurt/Main Airport. But they may also be applicable to other airports, especially those with similar atmospheric and orographic conditions.

The risk of vortex encounter will depend on the position of the FATO along the runway's length relative to landing and departing aircraft that are generating lift. The transport of a shed vortex to the FATO will usually require longitudinal as well as lateral drift. Conditions of local wind due to turbulence around buildings, etc., are also likely to influence the decay and precise trajectories of vortices.

Simulation of Vortex Encounters

Methodology

An earlier part of this study set out a methodology for examining the response of a helicopter to the vortex shed by a large transport aircraft using simulation and is reported fully in Ref. 1. The helicopter modeled in the study was a Lynx implemented in the FLIGHTLAB environment, and the vortex model used was that attributed to Burnham[4] (also see Refs. 5 and 16) and described in the preceding section.

In this paper, the earlier work has been furthered to examine the effects on helicopters of different overall size, weight, hub design, and blade loading. Also the parameters of the Burnham model (see Refs. 4, 5, and 16) have been modified to simulate vortices shed from Boeing 757 and Airbus A340 aircraft in addition to Boeing 747. Common to all helicopter models was a blade element representation of the main rotor to allow for the penetration effects as the aircraft moves through the vortex. There is also a dynamic inflow model to represent the delay in the reaction of the air in the vicinity of the main rotor to changes in the rotor-induced downwash field.

A possible mitigating factor that has not been considered in this study is the attenuation of the vertical velocities in the vortex profile when the vortex is near the ground. However, insufficient information has been obtained from the QinetiQ lidar measurements, described in the preceding section, to support any modified vortex velocity profile, and more generally, the interaction of vortices with the ground is poorly understood.

In summary, the analysis makes the following assumptions:

1) Velocity profiles in the vortex are modeled using the Burnham model (see Refs. 4, 5, and 16) and will not have decayed in strength at the time the encounter occurs. This has been shown in the preceding section to be appropriate for a worst case.

2) Vortices form in pairs from the wing tips of the source aircraft and initially descend before moving horizontally when near to the ground. The lateral velocity will be mainly a function of the prevailing wind.

3) By the time the encounter occurs, the motion of the vortex is always horizontal.

4) No interactions have been modeled between vortex and the ground.

5) No interactions have been modeled between vortex and the wake generated by the helicopter rotors. However, it is recognized that these effects may become increasing important for helicopters in a heavy weight class.

6) At the initial condition, the helicopter is trimmed 100 ft (30 m) to the port side of the vortex center.

7) The vortex approaches the helicopter from the starboard side at a constant velocity, the encounter velocity.

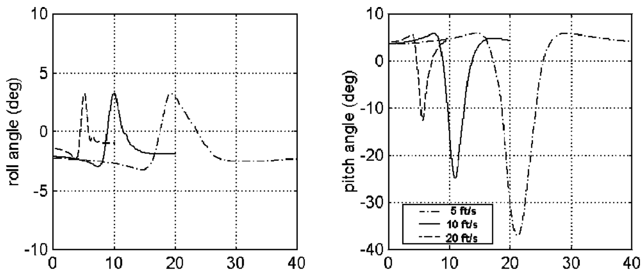

Fig. 8 Vortex encounters using constrained simulation.

8) For all responses, the helicopter's stability augmentation system was engaged, although the magnitude of response meant that the series actuators would have regularly saturated.

9) No pilot recovery actions were made.

Analysis and Results

In Ref. 1, it was found that when a vortex approaches a hovering helicopter from the starboard side then the initial response is for the helicopter to be lifted upward. If the vortex and helicopter were initially at the same height, then the aircraft would be carried over the inner core of the vortex, where significant attitude transients would otherwise be expected. To assess the worst-case attitude response, either the initial vortex/aircraft separation or the collective input needed to be adjusted to cause collision between the inner core and the main rotor of the helicopter. This was shown in Ref. 1 to be neither a convenient nor a foolproof method for guaranteeing the worst case occurred, and so throughout this paper the simulation was mathematically constrained so that the helicopter was only free to respond in the axis of interest. In Fig. 8, the motions in heave and yaw have been prevented to ensure the rotor hub passes directly through the vortex core.

In Fig. 8, there is a clear trend between the magnitude of the pitch response and the vortex encounter velocity. The largest response occurs for the slowest encounter velocity because the exposure to the nonuniform velocities in the vortex core is of longer duration. Because the heading is constrained to remain parallel to the axis of the vortex at all times, the roll responses are due only to the inherent cross coupling of the Lynx.

The constrained simulation technique used to generate these responses ensures that both height and heading are held constant, giving an effect similar to the pilot of the aircraft attempting to maintain flight path and heading. The attitude changes on passing the inner core are the open-loop responses (without pilot intervention) and are indicative of the amount of pilot compensation that would be required to overcome the external disturbance and the time available to react. The control power required to overcome the attitude transients is considered to be typically well within the limits of a conventional helicopter, for example, to overcome the attitude transients during an encounter with a vortex approaching at 10 ft/s (3.05 m/s) would require ~50% of the available control power in pitch. The analysis of height response, presented in a later section, will also use a constrained simulation technique where all attitudes are constrained and only the height is allowed to vary. The predicted responses are again open loop and, therefore, in reality would not be allowed to build to the same extent unless the pilot is for some reason deprived of height cueing information or preoccupied with a secondary task and susceptible to disorientation. However, the method is considered to be appropriate for the assessments conducted for this work. The unconstrained simulations in Ref. 1 also suggested that significant changes in yaw attitude might be experienced at the hover. However, excursions in the yaw axis have not been made the subject of further constrained simulations because it was not felt to produce as dangerous a handling difficulty as changes in pitch, roll, and height.

Attitude Response for Default Configuration

The analyses in the following paragraphs relate to the default configuration comprising the FLIGHTLAB model of a Lynx encountering a shed tip vortex from a Boeing 747 represented using the Burnham model (see Refs. 4, 5, and 16), given by Eq. (2). Unless otherwise stated, the encounter velocity was always set to 10 ft/s (3.05 m/s). In all cases, the Lynx has been simulated with its Automatic Flight Control Systems (AFCS) engaged, although in most cases the level of disturbance means that the series actuators will have saturated, and hence, the AFCS will not be particularly effective during the encounters. As already discussed, and shown in more detail in Ref. 1, the attitude response will only reach its maximum when the main rotor flies directly through the center of the vortex inner core. If there is a vertical separation between aircraft and vortex at the point they cross, then the response will be considerably smaller. To assess the sensitivity of the attitude response to changes in vertical separation, a number of cases were run with vertical separation in the range from 40 ft above to 40 ft (12 m) below. Figure 9 shows the pitch and roll responses for cases where the vortex passes above the rotor with separations of 0, 8, 16, 24, 32, and 40 ft (0, 2.44, 4.88, 7.32, 9.75, and 12.19 m). Similar responses were obtained for corresponding separations below the rotor.

Figure 10 shows the maximum pitch perturbation plotted against the separation of the main rotor hub and the center of the vortex. It is seen that for zero separation the pitch angle reaches a maximum perturbation of nearly 30 deg nose down (within 3 s), and for 40 ft (12.19 m) separation, this angle has reduced to only 4 deg nose down.

To express these results in a more meaningful way a set of hazard severity criteria have been taken directly from the handling qualities criteria Aeronautical Design Standard 33 (ADS33)[22] where they were used to set the limits on transient motions following system failures. The response is assessed over the first 3 s following the failure (or in this case the vortex encounter) and is categorized into

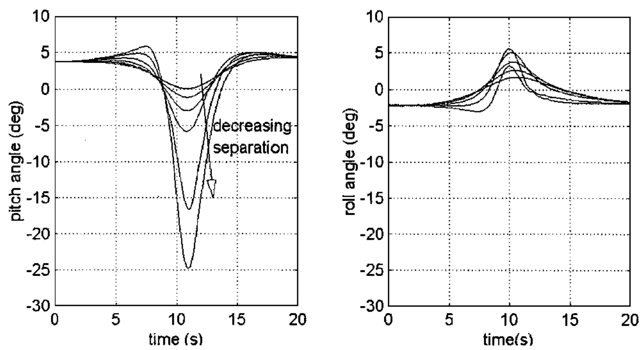

Fig. 9 Pitch and roll responses for vertical separation 0, 8, 16, 24, 32, and 40 ft.

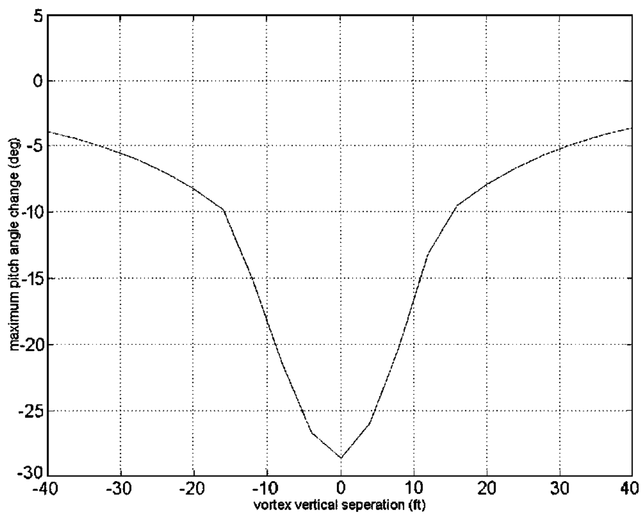

Fig. 10 Maximum pitch angle perturbation against rotor/vortex separation.

three levels. Level 1 represents good flying qualities, level 2 are flying qualities with tolerable deficiencies, and level 3 are flying qualities with unacceptable deficiencies. Responses beyond level 3 would be potentially hazardous because they would bring a risk of loss of control. The outer boundary of level 3 performance is 24 deg of response within 3 s with no recovery action. At this stage, the ADS33 criteria provide a useful guide as to the handling difficulty experienced and is used later to gauge the severity of the predicted helicopter response. Although the criteria have been developed for application following a failure or combination of failures in the control system, the ability of the pilot to recover the aircraft following the initial transient is a similar task to that presented to a pilot encountering a vortex. However, for the current application, the control system is fully functioning at the time of the encounter and during the recovery because this was representative of the likely state of a commercially operated transport helicopter maneuvering at a major airport. Validation of the criteria for this scenario is a desirable item of future work.

If the excursions as predicted in Fig. 10 are within the level 3 criterion, then the center of the vortex inner core needs to pass 15 ft (4.57 m), or less, above or below the main rotor. For a response greater than 24 deg (beyond level 3), this separation reduces to 5 ft (1.52 m). Therefore, it is concluded the magnitude of the attitude response depends quite critically on the separation of vortex center and main rotor and the very narrow separation range required to give significant attitude changes certainly reduces the likelihood of this occurring.

The other variable that has been seen to affect the attitude response is the encounter velocity. Figure 11 shows the maximum perturbation in pitch angle for a range of encounter velocities between 5 and 20 ft/s (1.53 and 6.10 m/s) at zero separation of vortex centre and main rotor. It is seen that for a slower penetration of 5 ft/s the pitch angle changes by over 40 deg, whereas a vortex crossing the rotor at 20 ft/s (6.10 m/s) reduces the pitch change to less than half of this. This suggests an encounter at slower velocity has a greater impact on safety. However, the faster passage also increases the rate of growth of attitude change, a factor that will allow the pilot less time to compensate for the disturbance with a greater risk of overcontrolling. The encounter velocity giving the worst response will, therefore, depend on the balance of these factors and is difficult to determine without the benefit of a piloted assessment. Ground-based simulation would provide the flexibility to explore these handling qualities issues in a safe environment.

The issues surrounding the decay of a vortex in transit from the source aircraft have been discussed in an earlier section. Vortices passing the helicopter at a speed of 5 ft/s (1.52 m/s) will take around 160 s to travel the 820 ft (250 m) between the main runway and FATO. In this time, the probability of the vortex still existing at full strength are reduced, although there is evidence to suggest that this could happen. At 20 ft/s (6.10 m/s), transit will take only 40 s, and so vortex aging is less likely, but vortex breakdown due to atmospheric turbulence may become a greater factor.

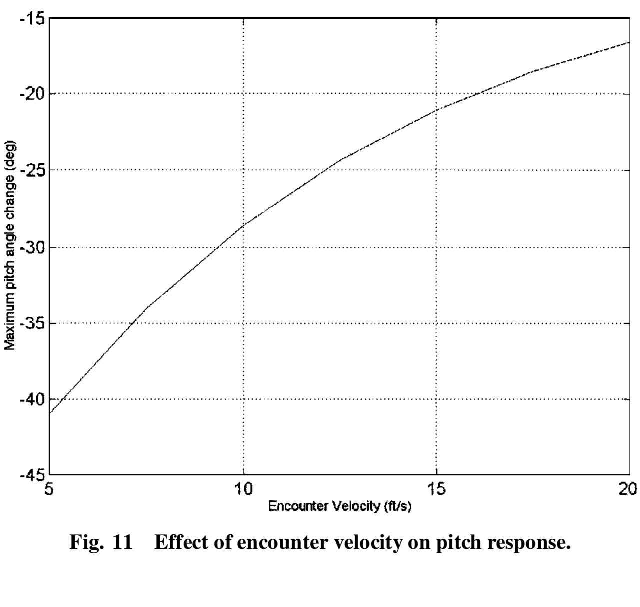

Fig. 11 Effect of encounter velocity on pitch response.

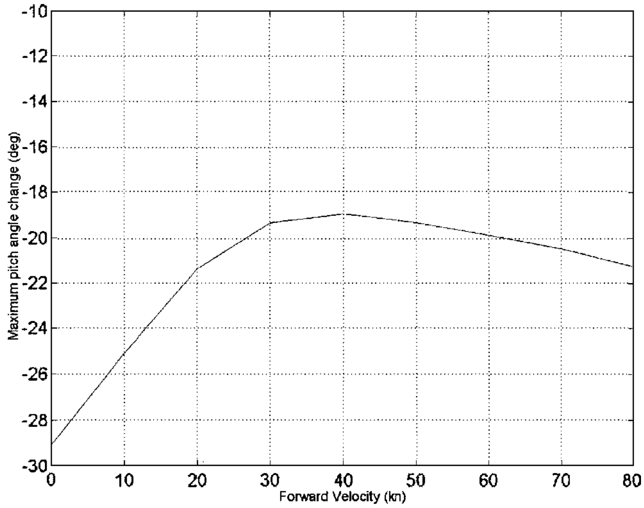

Fig. 12 Effect of forward velocity on pitch response.

Finally, the attitude response will change according to the flight condition. The results so far have focused on the hover condition, whereas it may also be possible for the encounter to occur on approach to, or depart from, the FATO or when the helicopter is hovering in a head wind. To examine the effect of forward velocity on the pitch response the plot in Fig. 12 shows the maximum pitch change for encounters with the vortex approaching at 10 ft/s (3.05 m/s) from the port side and the helicopter flying forward with a speed between 0 and 80 kn. Over this range, the maximum response occurs at hover, although significant attitude changes are predicted at all speeds.

Before leaving the attitude response, note that the largest disturbances that have been seen in the preceding paragraphs could be completely counteracted with a cyclic input in the region of 3–4 deg at the swashplate. Depending on the axis in which the dominant response occurs, for example, vortices approaching perpendicular to the aircraft heading would cause a response in roll, this would typically amount to 50% of the lateral or 25% of the longitudinal cyclic travel. Hence, the encounter does not result in an uncontrollable motion or expose the aircraft to transient loads that lead to excursions beyond the flight envelope, provided the pilot applies the correct compensation in a timely manner to avoid significant departure from the intended flight path.

Height Response of Default Configuration

The height response also varies with the initial vertical separation between rotor and vortex center, and hence, the flight path through the vortex changes. As the initial separation becomes larger, then the flows in the vortex that affect the rotor early in the maneuver have a weaker vertical component and, hence, produce a smaller increase in thrust. At the same time, the horizontal velocities across the disk increase in strength and have the effect of decreasing the thrust by removing some of the translational lift. As the initial vertical separation is increased, the effects of lost translational lift outweigh the gain in thrust due to upwash, and the aircraft no longer climbs as the vortex core approaches. In the steady state, the vertical motion of the aircraft will always match the velocity of the surrounding flow, where the time constant of the response (time to reach 63% of steady-state value) is in the region of 2–4 s. In the results that follow, there are also residual vertical rates due to the influence of lateral velocities in the vortex.

Figure 13 shows the height response for a range of cases where the initial vertical separation varies from 125 ft below to 125 ft (38.10 m) above the vortex center. From the time history plots, it is seen that if the initial separation exceeds a certain value either below or above the vortex center then there is no height increase. Note that at the start of each time history the aircraft is trimmed in the vortex

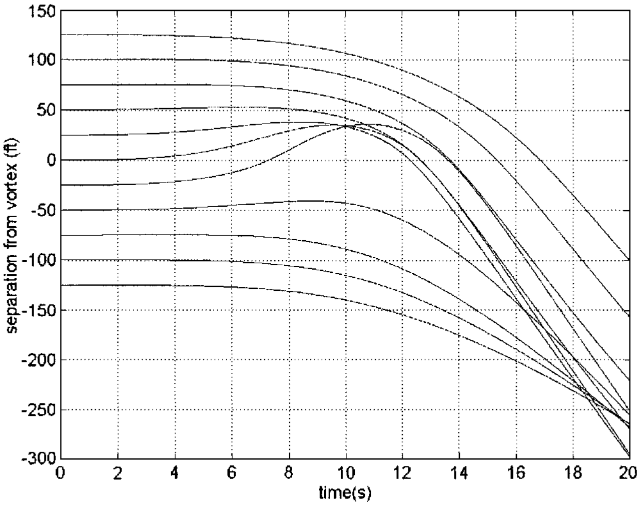

Fig. 13 Height response with varying initial vertical separation.

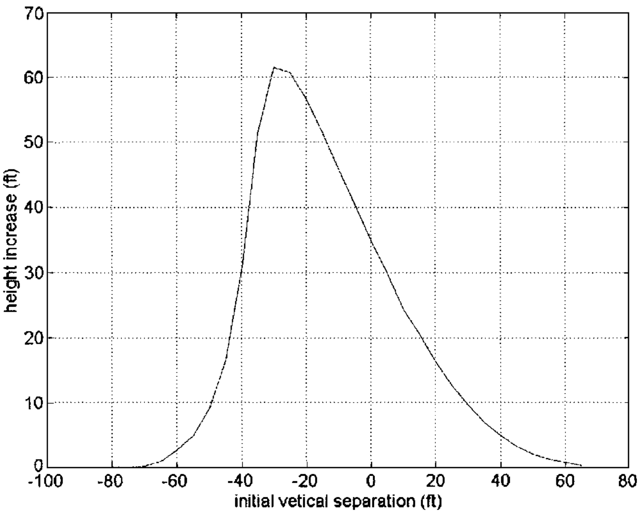

Fig. 14 Effect of initial vertical separation on height increase.

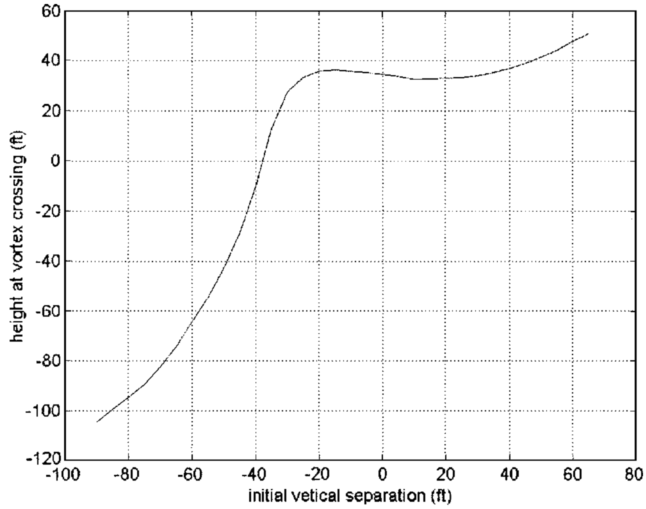

Fig. 15 Vortex/rotor vertical separation as vortex passes.

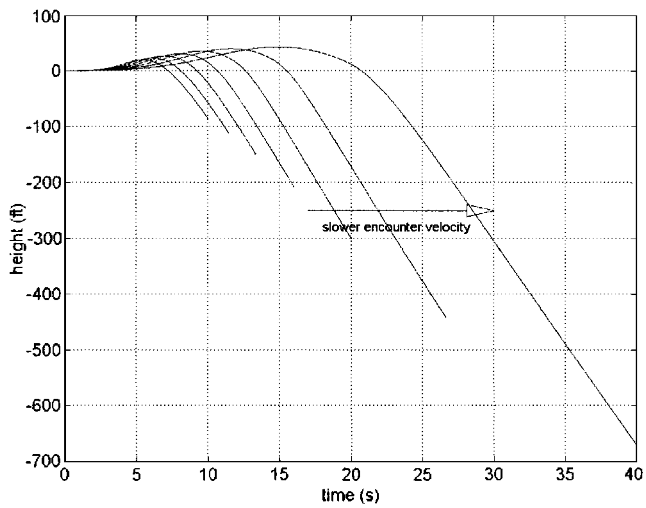

Fig. 16 Height response for encounter velocities 5–20 ft/s.

flows at the starting location, which can give an upwash exceeding 15 ft/s (4.57 m/s) in the cases where the rotor is level with the vortex center. This will have the effect that at the end of the maneuver, when the aircraft is generally positioned in a downwash, a component of the downward velocity will be due to the mismatch between the final flow conditions and the flow at the initial trim condition. For the cases considered, approximately half the steady-state descent rate is due to this mismatch, and the remainder is attributed to the integrated effects of lateral and vertical velocities, that is, the true increment due to the vortex encounter.

Figure 14 shows a plot of the height increase as a function of initial vortex/rotor separation, where it is seen that, practically speaking, for separation of 65 ft (19.81 m) above or 70 ft (21.34 m) below, no height increase is experienced. The preceding section has demonstrated the case of a vortex initially set to pass over the helicopter as a potential worst case due to the helicopter being lifted up into the inner vortex core and a significant attitude transient being experienced. If such an attitude response (level 3 transient, pitch change between 10 and 24 deg) is to be obtained, then it was found earlier that the rotor hub must pass within a vertical distance of 15 ft (4.57 m) from the vortex center.

Figure 15 shows the vertical separation between rotor and vortex center as the vortex passes. From here, it is found that the level 3 transient response will occur when the rotor is initially between 34 and 41 ft (10.36 and 12.50 m) below the vortex center, quite a narrow band.

The effect of varying the encounter velocity is shown in Fig. 16, where the height responses are given for a range of encounter velocities between 5 and 20 ft/s (1.52 and 6.10 m/s). It is seen that as the encounter velocity decreases then the time the aircraft is exposed to the high velocities near the inner core increases, and the maximum height excursion also increases.

Further information about the responses is obtained from looking at the height rates for the same cases, as shown in Fig. 17. The first notable feature is that, in the steady state, the height rates are all approximately the same because this is a function of the flow conditions at the starting trim and end of the maneuver, neither of which change significantly. Second, the height rate builds in a shorter time period for the faster encounter velocities.

It is the magnitude of the height rate that will usually determine the amount of collective input required to maintain a level flight path and, hence, the pilot's ability to overcome the disturbance within the limits of available power. However, when the disturbance occurs over a short period, then the time available for the pilot to react is decreased, and the risk of overcontrolling and, hence, transient torque exceedances, is increased. For the attitude response, this presents the situation where encounters at slow velocity give a large response but with greater time for the pilot to react, whereas encounters at higher velocities give a smaller more rapid response, possibly leading to handling difficulties. The encounter velocity in the worst case would possess the most challenging combination of these effects. Ground-based simulation would offer an effective tool for investigation of these issues.

In summary, it has been seen that if the height response is going to cause the aircraft to collide with the vortex core (producing significant attitude transients), then the initial vertical separation needs

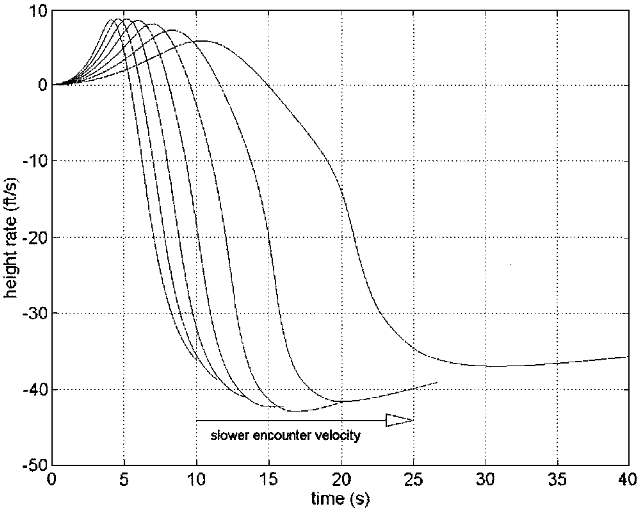

Fig. 17 Height rate response for encounter velocities 5–20 ft/s.

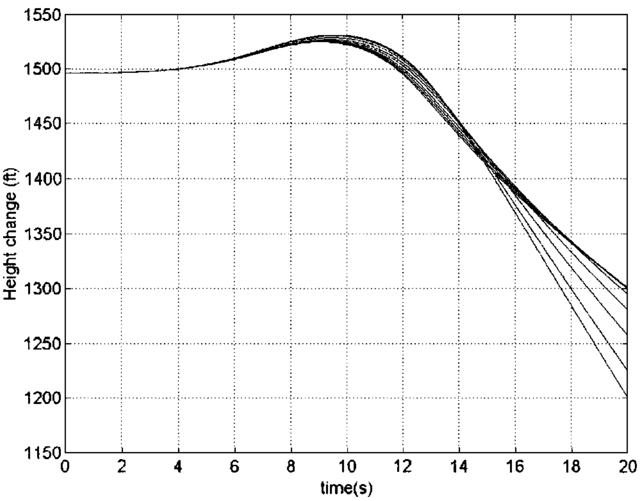

Fig. 18 Height response with varying forward speed.

to lie in a narrow band. In terms of residual descent rates, the results of the analysis have been slightly obscured by the need to trim under the influence of the vortex flows, in particular an upwash of up to 15 ft/s (4.57 m/s) on the portside of the vortex. However, it seems that descent rates of up to 1500 ft/min (457 m/min) are to be expected due to the velocity profiles in the vortex alone, if no recovery action is taken. The important issue arising from this analysis of the height response is whether the aircraft has sufficient thrust and, therefore, power margin to compensate for such disturbances should they be encountered. A further scenario that may be potentially hazardous, but has not been considered in this study, is a helicopter flying into the downwash in the tails of the vortex profile while making its final approach to the FATO. In this case, the aircraft already has a rate of descent when it encounters the downwash and may not have sufficient power to compensate for the disturbance over and above the demands on power in the final stages of approach.

At the time of writing, this additional case and those discussed earlier were being investigated using the Flight Simulation Laboratory at the University of Liverpool. Results from these experiments are expected to be published at a later date.

Figure 18 shows the effects of the aircraft having a forward speed when the vortex is encountered. There is a significant height response in all cases, and the effects of varying the forward speed appear to be small.

Responses of Other Configurations

Thus far, the responses of a Lynx helicopter during encounters with a Boeing 747 vortex have been considered for various flight

Table 2 Sample of typical FATO traffic

Aircraft type	MTOW, lb	Blade loading, lb/ft^2
AS350 (B)	4298	83.0
SK76 (A)	10300	90.7
A109	5730	72.2
B206	4150	103.6
H500	3000	81.2
S-61	21500	91.3
Lynx	10689	99.2

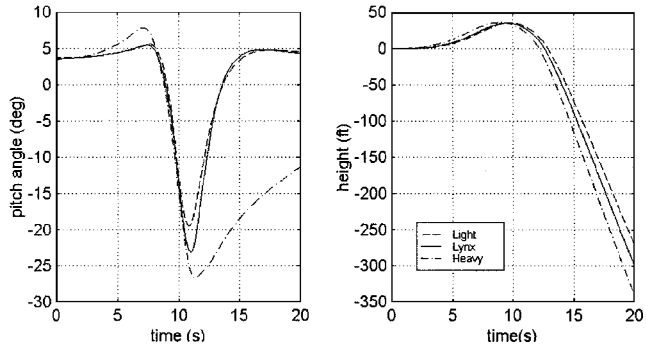

Fig. 19 Attitude and height responses for aircraft of different size and weight.

conditions using the FLIGHTLAB model of the Lynx and a vortex model representative of a heavy Boeing 747. It is important to put these predictions into context by considering other configurations to determine the magnitude of response to vortices from other aircraft and also the effect of aircraft design parameters such as general size and weight, rotor hub design, and blade loading.

Table 2 shows a list of helicopter types that may be expected to operate to a major airport along with the Lynx used for the preceding analyses is also included. They are listed along with their maximum takeoff weights (MTOW) obtained from Refs. 23 and 24 and blade loading calculated from data at the same references.

To assess the general effect of overall weight and size on the response to a vortex, it was not considered necessary to attempt to model specific types but instead to create a light and heavy configuration based on the Lynx with MTOWs of 5500 and 22,000 lb, respectively. (Note the Lynx MTOW is 10,700 lb.) Design parameters such as rotorspeed, rotor radius, pitch inertia, and roll inertia were estimated as a function of MTOW by considering data for a number of other types distributed over a large range of MTOW. Care was taken to keep the blade loading and rotor hub stiffness equivalent to those values for Lynx because the effects of these parameters have been considered separately and are discussed later. Figure 19 shows the constrained attitude and height responses to a vortex from a Boeing 747 encountered at 10 ft/s (3.05 m/s) with zero vertical separation. It is seen that in no case does the overall size and weight significantly affect the peak magnitude of response. The shape of the attitude response for the heavy configuration is modified due to the rotor diameter being much larger than for the other types, and hence, exposure to the non-linear flows in the vortex begins earlier and finishes later. No attempt has been made to tune the AFCS for each particular configuration because this was beyond the scope of work being conducted. The effects on the performance of the control system in each case were not expected to be large, and this appears to be borne out by the results.

An important parameter in determining the magnitude of the pitching and rolling moments generated by the nonuniform flow velocities in the vortex inner core is the stiffness of the retention structure connecting blades to the rotor hub. In order of effective stiffness, common rotor hub designs are teetering, articulated, and hingeless/bearingless. An approximate representation of these different designs can be achieved for flight mechanics calculations by assuming an articulated-type structure with the offset of the flapping hinge being used to simulate the effect of bending stiffness. Typical equivalent hinge offsets would be zero for a teetering hub, 2–4% for

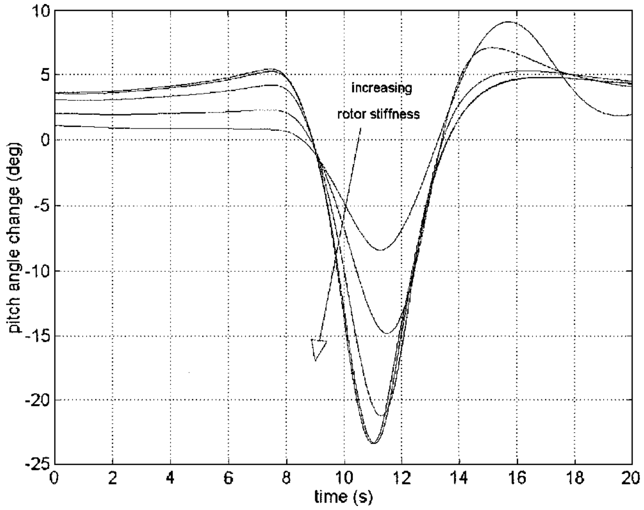

Fig. 20 Effect of rotor hub design on pitch response.

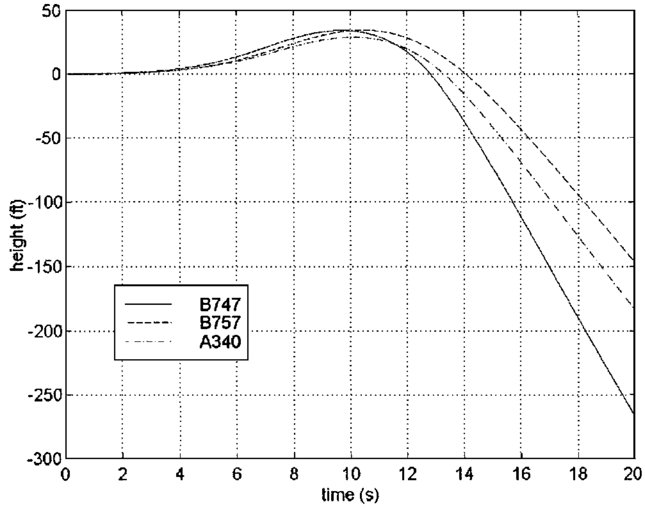

Fig. 22 Height response from vortices of Boeing 747, Boeing 757, and Airbus A340.

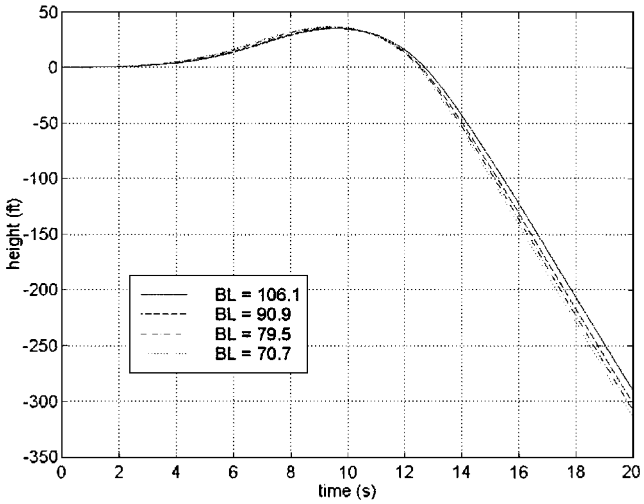

Fig. 21 Height response for varying blade loading.

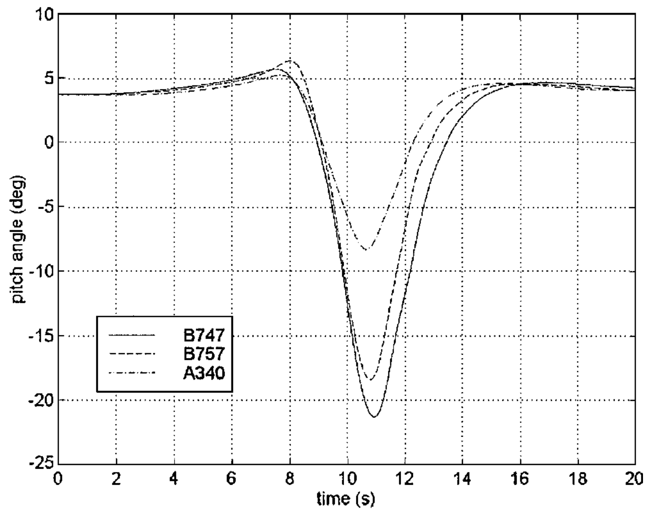

Fig. 23 Pitch response from vortices of Boeing 747, Boeing 757, and Airbus A340.

an articulated hub, and greater than 10% for a hingeless hub. The equivalent value assumed for the Lynx hub was 12.3%.

Figure 20 shows the attitude responses for a vortex encounter with the Lynx model using a value for hinge offset modified to 0, 1, 3.5, 10, and 12.3%. It is seen that as the hinge offset is increased the magnitude of the pitch response also increases. The maximum pitch angle changes (all nose down) are 9.5, 16.9, 21.3, 26.9, and 27.0 deg, respectively, for the hinge offsets considered. Therefore, the articulated hub (3.5% offset) has a pitch angle change 79% of Lynx and the teetering hub (0% offset) only 35%. Therefore, it is clear that stiff rotor hub designs will experience greater attitude transients than articulated or teetering hubs. In contrast, the height responses for the same selection of models were virtually identical, as expected.

The final aircraft parameter considered in this study is the blade loading, defined as the weight of the aircraft divided by the total area of the blades. This parameter is a key factor in determining the sensitivity of the aircraft to gusts in the vertical axis and is listed in Table 2 for a number of types. For lower blade loading, a higher susceptibility to vertical gusts is expected and vice versa for higher values.

The FLIGHTLAB model was again modified, this time to represent a range of blade loadings between 70 and 106 lb/ft^2 by changing the size of the chord on each blade. The heave responses in Fig. 21 show that there is little difference in the predicted height responses, although it can be seen that the lower the blade loadings do indeed give larger responses.

In the model used for this study, it has been assumed that the flow in the helicopter wake would have no significant effect on the velocity profiles in the rolled up tip vortex. In reality, it is expected that for heavier types of helicopter, where the downwash velocities can be very powerful, there will be an interaction with the free vortex. The extent of these effects, however, are not known, and the modeling required to incorporate them in future studies would be a significant undertaking.

Effects of Tip Vortices from Other Aircraft Types

In Ref. 1, it was assumed that the largest effects from vortex encounters would be caused by shed vortices from a Boeing 747. More data have been made available in Table 1 to configure the vortex model as two other types, a Boeing 757 and an Airbus A340. The pitch and height responses predicted for the Lynx model through each of these vortices are shown in Figs. 22 and 23. It is seen that the wake of the Boeing 747 does indeed give the largest pitch and height response, although the pitch response from a Boeing 757 vortex is similar. It would seem that the selection of Boeing 747 vortex to establish a worst-case scenario is justified.

Recommendations

It is recommended that further work be conducted to develop a more substantial approach to hazard severity and probability using the proposed transient response criteria. Test data would be required to validate any new approach and high-fidelity ground-based piloted simulation offers the potential to capture such data in a safe and controlled environment.

The probability of a vortex encounter at a particular FATO and airport will require data to account for the frequency of aircraft operations, aircraft types and associated vortex aging, and wind strengths and directions. The positioning of the FATO relative to approach and departure flight paths for the main runway must also be considered because the longitudinal as well as lateral drifting of the vortex will be important. The analysis of helicopter response has identified the sensitivity of both attitude and height responses to encounter parameters. These should also feature in any probability assessment.

Conclusions

This paper has presented the results of a study into the safety issues associated with locating a helicopter landing and takeoff area 250 m from a runway at a busy international airport used by large transport aircraft. The study follows from some earlier work reported in Refs. 1 and 16. Analysis of data from a series of lidar measurements of tip vortices shed from aircraft at London Heathrow Airport have been analyzed to validate the vortex model used in the study. To examine the worst-case scenario, no vortex aging/decay has been assumed, supported by examples of real data where long-lived vortices have been recorded. The study examined the impact of a vortex encounter at various flight conditions using the FLIGHTLAB model configured as Lynx and a constrained simulation technique to consider attitude and height responses separately. The analysis has considered a helicopter located in the hover and with forward speeds up to 80 kn. Rolled up tip vortices from a Boeing 747 are assumed to move downward and outward but to only have a horizontal velocity by the time they reach the helicopter. A number of encounter velocities have been considered to represent different prevailing wind conditions, and the sensitivity of the aircraft response to the proximity of the vortex center has been investigated. The modeling was also extended to examine the expected responses of helicopters both lighter and heavier than Lynx and with different hub designs and blade loadings. Last, the vortex model has been configured for Airbus A340 and Boeing 757 aircraft to predict the helicopter responses to tip vortices from these types. The conclusions of the analysis are as follows:

1) The Burnham model[4] (see also Refs. 5 and 16) of a vortex has been shown to give an accurate description of the velocities in the shed vortex from a Boeing 747 and was also easily reconfigured to represent vortices from other types.

2) Issues relating to the trajectory and decay of vortices have been discussed and an example provided of a vortex remaining at full strength for more than 1 min while drifting over a distance of 200 m (656 ft). In this case, the record was terminated by the vortex going out of sensor range and not by breakdown of the vortex structure.

3) When a vortex is encountered, the extent of the large attitude transients depends on how closely the main rotor passes the vortex center. A hazard criteria has been proposed, but not validated, using the failure transient requirements set in the handling qualities standard ADS-33. Accordingly, for a transient response worse than level 3 (potentially hazardous) the Lynx main rotor must pass the vortex center with a vertical separation of 5 ft (1.52 m) or less, assuming an encounter velocity of 10 ft/s (3.05 m/s). The main response is in pitch, although smaller excursions are seen in roll due to the inherent cross coupling of the Lynx.

4) A possible mitigating factor in the prediction of helicopter response to vortices is the attenuation of the vertical flows in the vortex by the interaction with the ground. This aspect has not been investigated in this study.

5) When a vortex is encountered with a velocity of 10 ft/s (3.05 m/s), the height response comprises an increase in height on approaching the vortex core followed by a height decrease after crossing the vortex, provided the initial vertical separation between main rotor and vortex center is 70 ft (21.34 m) or less (calculated using Lynx). For greater initial separations, the response comprises a height decrease alone. Depending on the flight path through the vortex, residual descent rates of up to 1500 ft/min (457 m/min) have been predicted to build up in less than 10 s due to the flows encountered in the vortex. If vortex encounters of this type were deemed to be probable, then helicopters using the FATO would need to have sufficient power available to overcome such disturbances. A helicopter entering the downward flows in the vortex tail while making its final approach to the FATO would be a specific case deserving further investigation.

6) If the helicopter is to be lifted up into the vortex inner core and experience potentially hazardous attitude transients (as in item 2), then the initial vertical separation must be in a narrow band between 34 and 41 ft (10.36 and 12.50 m), below the vortex center.

7) As the encounter velocity becomes slower, the helicopter is exposed to the nonuniform velocities in the vortex core for a longer period, and the attitude and height excursions become larger. For Lynx, the collision with a vortex core at an encounter velocity of 10 ft/s (3.05 m/s) causes a pitch excursion of up to 30 deg nose down. Halving the encounter velocity increases the excursion to 40 deg, whereas doubling the velocity gives a pitch change of less than 20 deg. In the extreme, a very rapid response would leave the helicopter practically undisturbed; whereas a very slow encounter would generate large flight-path changes but give the pilot ample time to react. Therefore, it is likely that some intermediate velocity would present the greatest handling challenge to the pilot. Ground-based simulation would provide the flexibility to explore such handling qualities issues in a safe environment.

8) As the forward speed of the helicopter increases from the hover up to 40 kn, then the pitch excursion due to the encounter decreases from 30 to 20 deg. At forward speeds between 40 and 80 kn, the response begins to increase toward the hover value. The height response is not significantly different over this range of speeds.

9) The attitude and height responses are not significantly affected by the overall helicopter size as such but rather by changes to the hub design and blade loading. When compared to the pitch response of the Lynx with its hingeless hub, the response of articulated and teetering hub designs decreases to 80 and 35%, respectively, whereas the height response is virtually unaffected. The blade loading has the effect of increasing the gust sensitivity as its value decreases, although it has been shown that the effect on the response to this vortex is actually small.

10) Finally, the response to a shed vortex from a Boeing 747 has been shown to be larger than that from an A340 or Boeing 757. The selection of the Boeing 747 vortex for the worst-case scenario appears to be justified.

Acknowledgment

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