# EVALUATION OF HELICOPTER ENCOUNTERS WITH WAKE VORTICES

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## Abstract

This paper reports on pilot-in-the-loop flight simulations of helicopter wake vortex encounters conducted by the Japan Aerospace Exploration Agency. To clarify the characteristics of helicopter wake vortex encounters, helicopter responses were compared with those of fixed-wing aircraft in the same conditions. The simulation results indicate that helicopters are less susceptible to wake vortex disturbances than fixed-wing aircraft in the same weight category, with helicopters experiencing half or less the attitude disturbance and height loss than fixed-wing aircraft. The helicopter pilots consequently felt that there was no risk to flight safety even for encounters at distances somewhat less than the current ICAO wake vortex separation minima. This finding supports the feasibility of reducing wake vortex separation for helicopters compared to fixed-wing aircraft.

## 1. INTRODUCTION

Wake vortices are produced by all aircraft as a consequence of lift generation. Fully developed wake vortices form two contra-rotating vortex lines that can adversely affect other aircraft which encounter them in flight [1]. An aircraft encountering such vortices may experience considerable attitude disturbance (especially roll disturbance for a fixed-wing aircraft) due to the swirling air flows around the vortex lines or height loss due to strong downdraft between the two vortices. To avoid potentially hazardous wake vortex encounters, the International Civil Aviation Organization (ICAO) has defined separation minima between aircraft as shown in table 1.

At present, helicopters have had less exposure to wake vortex hazards since their operational environments are different from most fixed-wing aircraft. However, risk exposure will increase as the demand grows for helicopters to operate into congested airports used by large jet transports to increase airport capacity. In addition, reduced separation for helicopters or simultaneous helicopter and fixed-wing operations are highly desirable to avoid impairing the efficiency of existing traffic flows for fixed-wing aircraft [2]. Wake vortex encounters are considered to be a major helicopter safety risk in such mixed operations.

Much research has been conducted to clarify the risks to fixed-wing aircraft of vortex encounters. These activities are summarized in ref. 3. Several encounter severity criteria based on objective flight data such as roll disturbance or height loss have been proposed and are used to assess the encounter risk quantitatively [4-7]. However, only a limited number of papers have reported on the evaluation of helicopter wake encounters, and objective severity criteria have not yet been established [8-12]. In general, helicopters are expected to be robust against atmospheric disturbances including wake vortex due to their high blade loadings, and previous research results have supported this expectation; they reported milder helicopter responses during vortex encounters compared to fixed-wing aircraft [9]. However, these results were based on open-loop simulation, and pilot actions were not considered. Evaluating the risks of helicopter wake vortex encounters including pilot actions might allow a new category for helicopters to be established in the ICAO separation standards which currently use only a weight-based categorisation (table 1), and thus enable reduced separation minima for helicopters following behind fixed-wing aircraft.

This paper describes pilot-in-the-loop flight simulation of wake vortex encounters conducted by

Table 1 ICAO wake vortex separation minima.

| Leading aircraft | Following aircraft | Radar | Non-radar | |
|---|---|---|---|---|
| | | | Departure | Arrival |
| Heavy (≥136ton) | Heavy | 4 nm | 2 min. | 2 min. |
| | Medium | 5 nm | 2 min. | 2 min. |
| | Light | 6 nm | 2 min. | 3 min. |
| Medium (≥7ton) | Heavy | 3 nm | – | – |
| | Medium | 3 nm | – | – |
| | Light | 5 nm | – | 3 min. |
| Light | all categories | 3 nm | – | – |

the Japan Aerospace Exploration Agency (JAXA) to evaluate the severity of helicopter wake vortex encounters including pilot actions. Helicopter responses during encounters were compared with those of fixed-wing aircraft under the same encounter conditions to clarify helicopter encounter characteristics, and the results were used to investigate the feasibility of helicopter-specific reduced separations.

## 2. MODELLING AND SIMULATION

### 2.1. Modelling

### 2.1.1. Wake vortex model

Fully developed aircraft wake vortices are commonly modelled by two contra-rotating vortex lines.

**Vortex circulation**

The initial value of vortex circulation $\Gamma_0$ is given by [1]

$$\Gamma_0 = \frac{L}{\rho U b^*} \tag{1}$$

where $L, U$ denote the lift/airspeed of a wake generating aircraft, $\rho$ is air density, and $b^*$ is the distance between the axes of the vortex lines. If we assume an elliptical lift distribution over the main wing, $b^*$ is given by [1]

$$b^* = \frac{\pi}{4} b \tag{2}$$

where $b$ is the wing span.

**Vortex velocity field**

Many empirical models have been proposed to express the wind field around wake vortices [1]. The 'HALLOCK and BURNHAM' model is used in this study since it provides a velocity distribution from the vortex core centre to infinity in a single expression and fits well with observed data [13]. The tangential velocity $V_i$ induced by a vortex line is expressed in the following form:

$$V_i = \frac{\Gamma r}{2\pi(r^2 + r_c^2)} \tag{3}$$

where $\Gamma$ is the vortex circulation, $r_c$ is the vortex core radius, and $r$ is the distance from the axis of the vortex line.

A vortex line has a 'core' region in which the air rotates as a solid body, and its size is defined by a core radius $r_c$. The initial core radius $r_{c0}$ is given by [13]

$$r_{c0} = 0.035b \tag{4}$$

**Vortex decay**

Vortex decay heavily depends on atmospheric conditions including turbulence, stratification, wind shear and crosswind. For this study, the vortex decay model is based on the lidar measurement data presented in ref. 14. The data used were acquired in stable atmospheric conditions (Richardson number > 1) in which wake vortices are expected to persist for longer than in other conditions. By polynomial fitting the measured circulation decay data (an average of 144 cases), the circulation decay process was modelled as follows (fig. 1):

$$\log(\Gamma/\Gamma_0) = -0.000613t^{*3} + 0.0239t^{*2} - 0.307t^* + 0.296 \tag{5}$$

Here, $t^*$ is dimensionless time given by

$$t^* = \frac{t}{t_0},\ t_0 = \frac{2\pi b^{*2}}{\Gamma_0} \tag{6}$$

Vortex core expansion during the decay process is modelled as follows [9]:

$$r_c = r_{c0}\ (t^* \le 2),\ r_c = r_{c0}\sqrt{t^*/2}\ (t^* > 2) \tag{7}$$

**Examples**

As described above, our wake vortex model is a worst-case model from two perspectives: 1) a wake vortex preserves its velocity field structure throughout the decay process; 2) slow circulation decay in stable atmospheric conditions is assumed. Table 2 shows wake vortex parameters for three aircraft types and figures 2 and 3 exemplify velocity fields and circulation evolutions respectively.

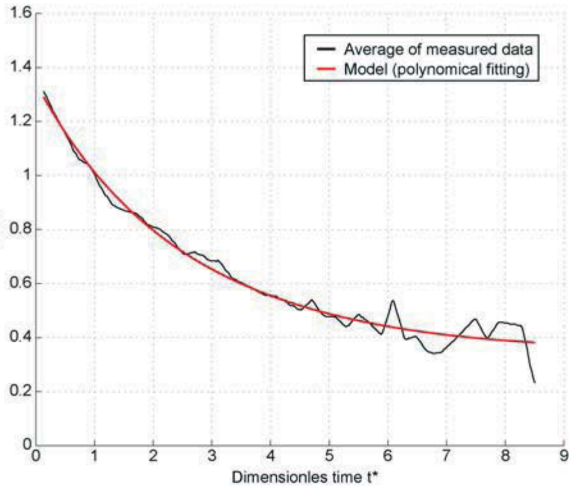


Figure 1 Vortex circulation decay modelling. (Measurement data are quoted from ref.14)

Table 2 Wake vortex parameters.

| | B747-400 | B767-300 | B737-500 |
|---|---|---|---|
| Maximum take-off weight [kg] | $396.0\times10^3$ | $172.4\times10^3$ | $52.4\times10^3$ |
| ICAO wake vortex category | Heavy | Heavy | Medium |
| Airspeed $U$ [m/s] | 90 | 70 | 70 |
| Wing span $b$ [m] | 64.3 | 47.6 | 28.9 |
| Vortex separation $b^*$ [m] | 50.5 | 37.4 | 22.7 |
| Initial circulation $\Gamma_0$ [m$^2$/s] | 697 | 527 | 264 |
| Initial core radius $r_{c0}$ [m] | 2.25 | 1.67 | 1.01 |
| Reference time $t_0$ [s] | 23.0 | 16.7 | 12.3 |

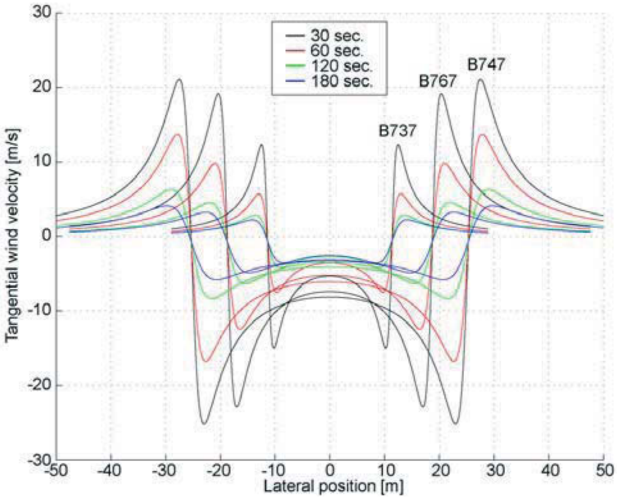


Figure 2 Vortex velocity field.

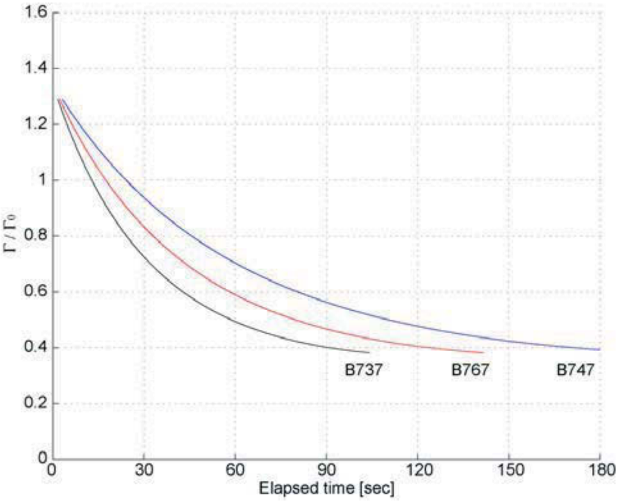


Figure 3 Vortex circulation evolutions versus time.

### 2.1.2. Aircraft model

Two aircraft are modelled for this simulation: a Mitsubishi MH2000 twin turbine helicopter with an articulated main rotor and a ducted fan tail; and a Dornier Do228 twin turboprop fixed-wing aircraft (table 3, fig. 4). Both models are of 'medium' fidelity, with the following features:

- rigid body;
- segmented main wing/rotors (20/16 segments for each wing/rotor blade) with quasi-steady, non-linear lift, drag and pitching moment data for each segment;
- separate fuselage, fin and empennage models;
- three-axis rate-stabilizing stability augmentation system (helicopter only).

To simulate vortex velocity fields over the aircraft, aerodynamic calculation points are distributed at each segment of the main wing/rotors, fuselage, fin and empennage. Wake-induced airflows are calculated at each aerodynamic calculation point and are simply added to inertial velocities and aircraft-induced airflows to calculate aerodynamic

Table 3 Specifications of modelled aircraft.

| | MH2000 | Do228 |
|---|---|---|
| Wing span | 12.2m<br>(rotor diameter) | 17.0m |
| Maximum take-off weight | 4500kg | 5700kg |
| ICAO wake vortex category | Light | Light |

a) Mitsubishi MH2000

b) Dornier Do228

Figure 4 Aircraft modelled for encounter simulations.

forces. Interference between the wake vortex and the aircraft is not considered. This simplification is commonly used in real-time simulation due to computation time constraints. Ref. 15, which uses a more advanced computation model, suggests that this quasi-steady superposition approximation is reasonably valid at airspeeds of 60kts or more.

#### 2.1.3. Flight simulator facility

JAXA's research flight simulator facilities for helicopters and fixed-wing aircraft were used for this study (table 4, fig. 5). While both simulators have six degree-of-freedom motion systems, their dynamic response characteristics are considered inadequate for simulating the rapid manoeuvres expected in wake vortex encounters, and so we conducted the vortex encounter simulations without cockpit motion.

### 2.2. Flight simulation

#### 2.2.1. Simulation scenarios

Simulation scenarios were created with the following characteristics:

- The subject aircraft encounters wake vortex during an instrument landing system (ILS) approach to a 3,000m-long runway. The ILS glide path angle was set to three degrees. The localizer (LLZ) and glide slope (GS) sensitivities were set to 0.924 deg/dot and 0.36 deg/dot respectively.
- To give worst-case results, the Boeing 747-400 was chosen as the wake vortex generator. This is one of the heaviest aircraft in the ICAO separation minima 'heavy' category (table 2 and figs. 2, 3).
- The wake vortex was modelled by two straight vortex lines parallel to the runway extended centreline and fixed in space at a height of either 300ft in visual meteorological conditions (VMC) or 500ft in instrument meteorological conditions (IMC).
- The vortex circulation strength was determined from the prescribed separation between the leading aircraft (wake vortex generator) and the subject aircraft following it. It remained constant during each run.
- Atmospheric conditions were calm (no prevailing wind with no turbulence apart from the wake turbulence).
- The subject aircraft were an MH2000 and a Do228 (table 3, fig. 4). Both are categorised as 'light' aircraft in the ICAO separation standards.
- For the following aircraft, maximum landing weight was chosen as power margin is minimised in this condition.

#### 2.2.2. Encounter parameters

The following parameters were used to characterise encounters: 1) separation between leading and following aircraft, 2) encounter geometry and 3) visibility conditions. The values of these parameters are shown in table 5.

**1) Separation between leading and following aircraft**

In addition to the minimum three-minute separation which complies with ICAO separation criteria for the arrival of a 'heavy (leader)–light (follower)' combination (table 1) in a non-radar environment, one- and two-minute separations were also investigated to examine the feasibility of reducing separation. A no wake vortex case was also evaluated as a reference.

Table 4 Specifications of JAXA's flight simulator facility.

| | Helicopter | Fixed-wing aircraft |
|---|---|---|
| Control loadings | electric (cyclic, pedal, collective) | electric (column, wheel, pedal) |
| Visual system | 6 ch, half dome<br>FOV:H180×V80deg | 6 ch, WAC<br>FOV: H124×V35deg |
| Motion system | 6 DoF, electric | 6 DoF, hydraulic |


a) Helicopter cockpit


b) Fixed-wing aircraft cockpit

Figure 5 JAXA's flight simulator facility.

**2) Encounter geometries**

By changing the lateral positions of the vortex lines, two encounter geometries were investigated: 1) the glide path intersects with a single vortex line; 2) the glide path passes between two vortex lines. In both cases, the glide path is parallel to the vortex axes (parallel encounter).

**3) Visibility conditions**

Although visibility is not considered in the ICAO separation minima, outside visual cues are quite important for pilots to detect attitude disturbances or flight path deviations during vortex encounters. To evaluate encounters in IMC where such cues are not available, IMC visibility was modelled as equivalent to CAT-I minima in addition to VMC; the pilots had no visibility (corresponding to flight in cloud) down to 250ft height, and had an 800m runway visual range below 250ft height.

### 2.2.3. Pilot tasks

Each simulation run began with the aircraft trimmed in a proper approach condition. The target approach speed and start altitude were set as shown in table 5.

The pilots were required to carry out the following tasks in the encounter simulations:

- During approach, maintain the target airspeed and the flight path using instruments. The use of visual cues is also permitted in VMC.
- If a vortex is encountered, take corrective action and attempt to continue the approach.
- If the upset is judged to be severe enough to require a go-around, announce 'going-around' and initiate the missed approach procedure.

The simulation run ended when the aircraft reached the decision height of 200ft or was 'steady' on the climb-out during a missed approach.

The pilots were asked to make a go-around decision assuming a 'passenger transport' mission since this type of mission would require the most conservative (safe) decision-making. No quantitative criterion for a go-around was provided.

### 2.2.4. Pilot's subjective severity rating

After each simulation run, pilots were asked to evaluate the severity of the encounter using the Overall Hazard Rating (OHR), an ordinal scale between 0 and 5 where higher numbers mean greater hazard. This rating is based on the questionnaires described in ref. 5.

Overall Hazard Ratings:

0: No perception of wake vortex. No pilot action required.
1: Slight disturbance. Moderate pilot action required.
2: Moderate disturbance. Considerable pilot action required.
3: Go-around manoeuvre required. No hazard to continued flight.

Table 5 Parameters of encounter simulations.

| Parameters | Options |
|---|---|
| Separation | 1 / 2 / 3 minutes and no wake vortex case (reference) |
| Encounter geometry | 1) glide path intersects with a single vortex line; 2) glide path passes between two vortex lines |
| Visibility condition | VMC /<br>IMC (equivalent to CAT-I minima) |
| Vortex height | 300ft (VMC) / 500ft (IMC) |
| Glide path angle | 3 deg |
| Approach speed | 100kt |
| Start height | 600ft (VMC) / 800ft (IMC) |

Table 6 Vortex encounter simulation runs.

a) Helicopter (total runs / runs where OHRs ≥ 3)

| Visibility condition | | VMC | IMC |
|---|---|---|---|
| Sepa-ration | no wake | 12/0 | 9/0 |
| | 3 min. | 18/0 | 14/2 |
| | 2 min. | 16/1 | 11/2 |
| | 1 min. | 16/3 | 1/0 |
| Total (all runs) | | 62/4 | 35/4 |
| Total (wake runs only) | | 50/4 | 26/4 |

b) Fixed-wing aircraft (total runs / runs where OHRs ≥ 3)

| Visibility condition | | VMC | IMC |
|---|---|---|---|
| Sepa-ration | no wake | 9/0 | 5/0 |
| | 3 min. | 14/4 | 8/6 |
| | 2 min. | 15/6 | 5/2 |
| | 1 min. | 14/8 | 0/0 |
| Total (all runs) | | 52/18 | 18/8 |
| Total (wake runs only) | | 43/18 | 13/8 |

4: Go-around manoeuvre required. Flight safety might be compromised.

5: Temporary or total loss of control. Unable to continue flight.

## 3. RESULTS AND ANALYSIS

### 3.1. Overview of simulation trials

In total, 16 pilots (8 pilots each for the MH2000 and Do228) flew 191 encounters. These participants are considered to be representative of Japanese small aircraft operating communities, coming from commercial operators, aircraft manufacturers and the fire department. Those pilots who had actual experience of vortex encounters considered the simulation to be very realistic.

Table 6 shows the conducted simulation runs. The IMC cases were evaluated only by pilots who had instrument flight qualification.

### 3.2. VMC case results

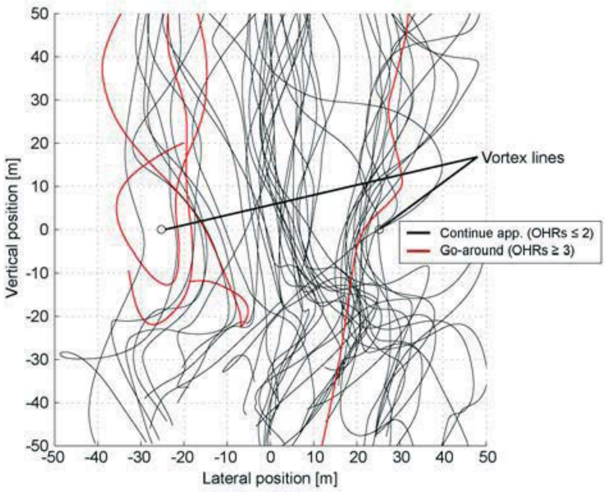
#### 3.2.1. Aircraft response during encounters

Figure 6 shows flight paths during wake vortex encounters. The black lines show flight paths where the OHR was rated less than 3; i.e. no go-around was required and the pilots were able to complete the approach. The red lines show flight paths where the OHR was rated 3 or more; i.e. the approaches were abandoned.

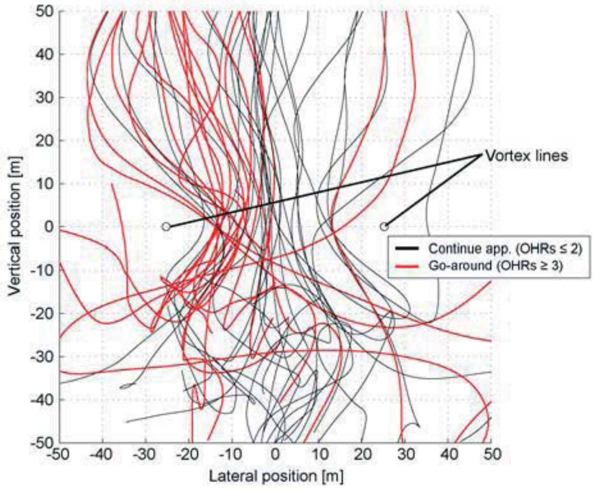
Two main patterns emerged from the encounters:

1) The following aircraft passed between two vortex lines which had been conveyed by wake-induced crosswinds prevailing at the upper regions of the vortex lines. The aircraft experienced a strong downdraft and lost height.
2) The following aircraft flew close to one of the vortex lines. Such cases occurred when pilots were able to maintain the approach path well despite the wake-induced crosswinds. These aircraft experienced considerable attitude disturbance resulting in a missed approach in the majority of cases.

The aircraft responses during wake turbulence encounters are therefore considered to be characterised by height loss and attitude disturbance.



a) Helicopter



b) Fixed-wing aircraft

Figure 6 Flight paths during encounters in VMC.

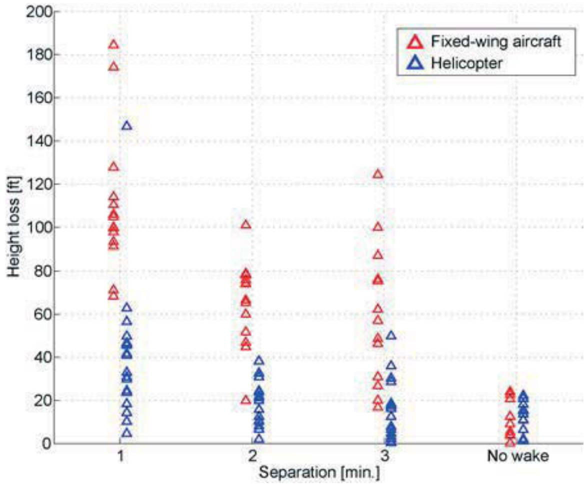


Figure 7 Height losses during encounters in VMC.

#### 1) Height loss

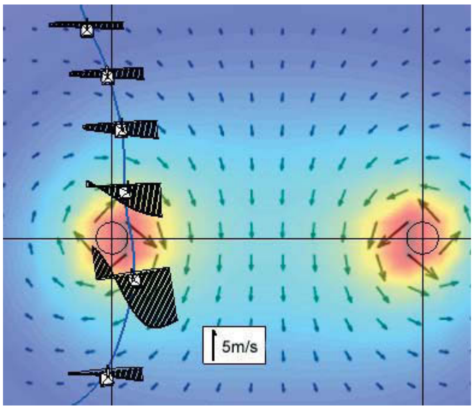
Figure 7 shows height loss during encounters, with the maximum deviation during each run. For the helicopter, height losses were less than 60ft (except for one case where a pilot conducted excessive recovery actions), whereas those of the fixed-wing aircraft reached 190ft. Height losses for helicopters at two-minute separation were much less than those for the fixed-wing aircraft at the three-minute separation specified by ICAO. The helicopter's ability to control lift directly by changing collective pitch enabled quick recovery action and contributed to the comparatively smaller height losses.

### 2) Attitude disturbance

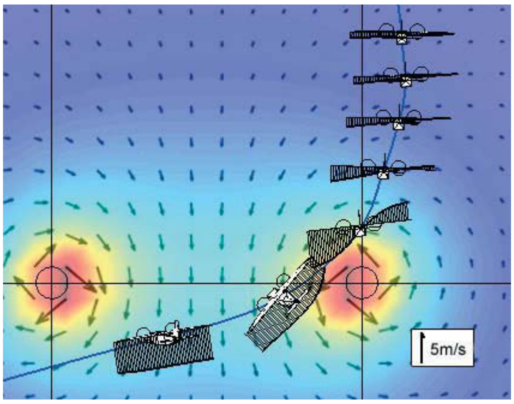
Figure 8 exemplifies encounters in which the aircraft flew near a vortex line at one-minute separation. The flight paths, aircraft attitudes, and vertical wind distributions over the wing/rotors are illustrated. Both the helicopter and the fixed-wing aircraft experienced vertical winds that changed drastically over the aircraft near the vortex line; for example, the right wing of the fixed-wing aircraft experienced an updraft while the left wing experienced a downdraft. These wind changes over the aircraft induced large attitude disturbances, especially roll disturbance to the fixed-wing aircraft.

Figure 9 shows three-axis attitude disturbances (roll/pitch/heading) during wake vortex encounters. Roll disturbance was dominant for the fixed-wing aircraft, whereas for the helicopter the disturbances in each axis were almost of the same order due to the strong 'cross-coupling' characteristics of helicopter flight dynamics. The fixed-wing aircraft experienced much greater attitude disturbances than the helicopters, roll disturbance reaching nearly 60 degrees at one-minute separation and over 30 degrees even at three-minute separation, while disturbances for the helicopters remained within 15 degrees in all three axes at two- and three-minute separations. The possible reasons for these milder helicopter responses are as follows:

- high blade loading: The helicopter's (MH2000) blade loading is 2.5 times higher than the fixed-wing aircraft's (Do228) wing loading. This higher blade loading contributes to the smaller acceleration disturbances against turbulences

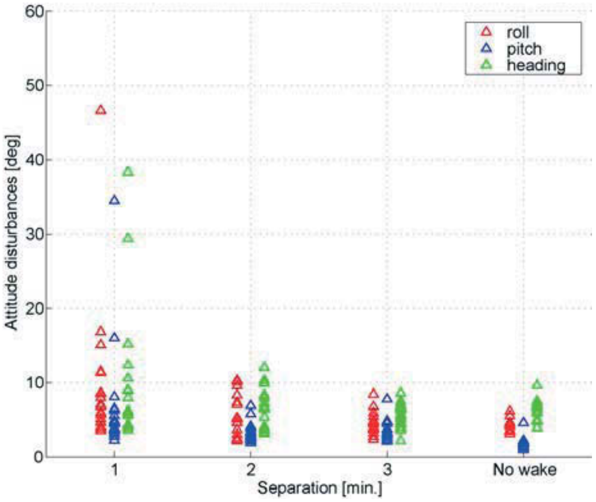


a) Helicopter

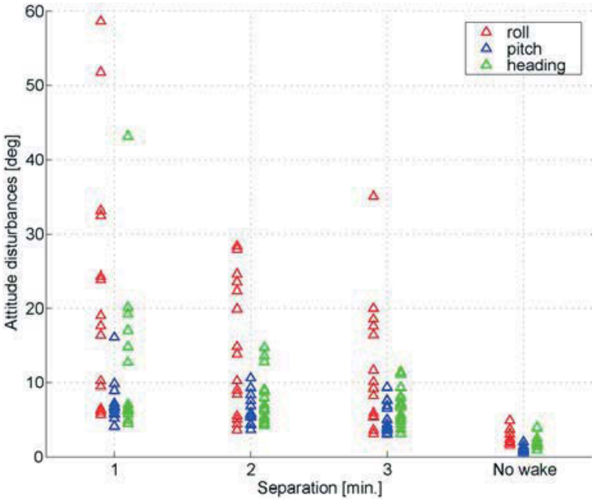


b) Fixed-wing aircraft

Figure 8 Typical encounters at 1 minute separation in VMC.



a) Helicopter



b) Fixed-wing aircraft

Figure 9 Attitude disturbances during encounters in VMC.

compared to the fixed-wing aircraft.

- articulated main rotor dynamics: The helicopter (MH2000) has an articulated main rotor with a relatively small flapping hinge offset of 4% radius. This results in smaller moment inputs from the rotor to the fuselage compared to fixed-wing aircraft in which the wing is attached rigidly to the fuselage.

### 3.2.2. Overall Hazard Rating

Figure 10 shows the pilots' OHR scores for the encounters. The horizontal axis shows the separation between the leading and following aircraft, and the vertical axis shows the mean values and standard deviations of the OHR scores. The results clearly indicate the helicopter is less vulnerable to wake vortex disturbance than the fixed-wing aircraft. Since the experiment was designed to give worst-case scenarios in which aircraft experienced the strongest wake vortex effects, the pilots of the fixed-wing aircraft scored OHRs of 4 ('flight safety might be compromised') even at the three-minute separation specified by current ICAO standards. They also scored OHRs of 5 ('temporary or total loss of control') at one- and two-minute separations. On the other hand, no helicopter pilot scored OHRs of 4 or 5; all scores were 3 and less. The helicopter experienced four missed approaches in 50 approaches and the fixed-wing aircraft experienced 18 missed approaches in 43 approaches (table 6). The estimates and 95% confidence intervals of 'missed approach' probability were 8% (2–19%) for the helicopter versus 42% (27–58%) for the fixed-wing aircraft.

However, detailed examination of the flight data revealed that the helicopter's main rotor blade flapping/lead-lag angle limitations were violated in a single case at one-minute separation. The OHR score of this case was 3. Figure 11 shows the pilot control inputs (cyclic and collective), main rotor blade flapping/lead-lag angles and aircraft attitudes (roll/pitch) for this case. Although the fluctuations of flapping/lead-lag angles exceeded limits, they were well within the limits at the time of the wake vortex encounter (i.e. at minimum distance from the vortex line) indicated by blue dashed line in fig. 11. It is therefore considered that these exceedances were caused by the pilot's excessive recovery action. If such exceedances were to occur during actual flight, rotor blades might suffer structural damage. In addition, the effects of blade elastic deformation cannot be neglected when the fluctuations of blade angles reach such large values. Since the rotor blades are modelled as rigid in our simulation, we double-checked the data for excessive blade angle fluctuations to assure the validity of the simulation result. For this simulation trial, only the case shown in fig. 11 was found to have large blade angle fluctuations.

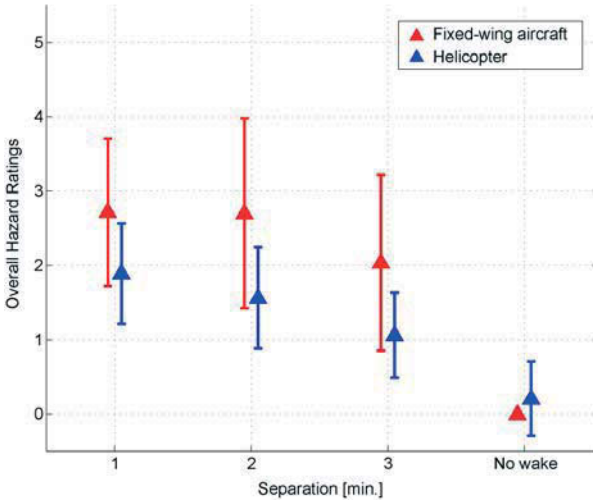


Figure 10 Overall hazard ratings in VMC.

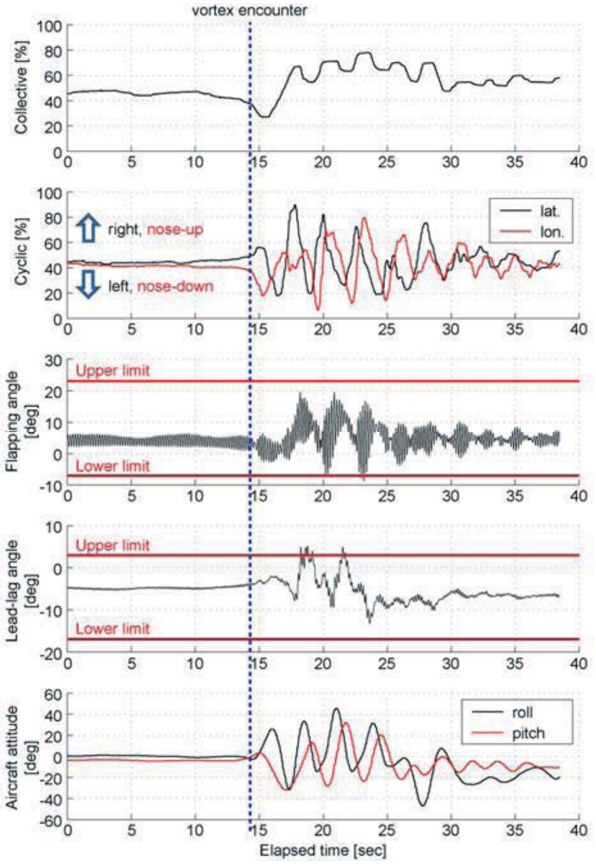


Figure 11 Example of excessive pilot control during helicopter encounter. (1 minute separation, VMC)

### 3.3. IMC case results

Figure 12 shows flight paths during wake vortex encounters in IMC. Compared to the flight paths in VMC (fig. 6), the flight paths in IMC were scattered over a wider region since the pilots had no external visual cues to indicate course deviation. Consequently, there were fewer cases in which the aircraft flew near the wake vortex lines than in VMC.

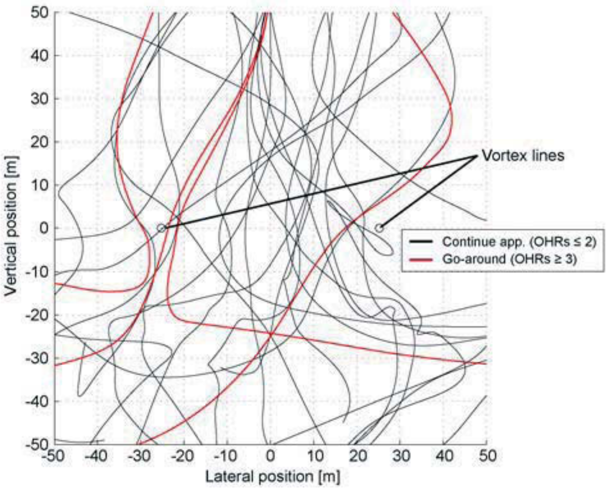
Figure 13 plots LLZ deviation with mean and standard deviation in the vertical axis, and the pilot OHR scores along the horizontal axis. The LLZ deviations in cases where the OHR was 3 or more (approach abandoned/control lost) are clearly larger than those in cases where the OHR was less than 3 (approach successfully completed). This suggests that LLZ deviation strongly affected the pilots' go-around decision-making. The pilots commented as follows:

- Correcting course deviation is more difficult in IMC since corrective control inputs are usually smaller than those in VMC.
- The aircraft motion was sometimes opposite to control inputs (due to wake-induced crosswinds). This caused confusion in corrective control.

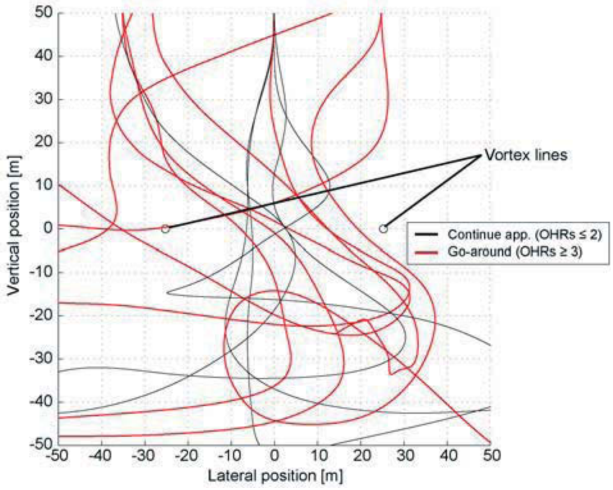
The helicopter experienced four missed approaches in 25 approaches and the fixed-wing aircraft experienced eight missed approaches in 13 approaches at two- and three-minutes separations in IMC (table 6). The estimates and 95% confidence intervals of 'missed approach' probability were therefore 16% (5–36%) for the helicopter and 62% (32–86%) for the fixed-wing aircraft; compared to 3% (0.07-15%) for the helicopter and 34% (18-54%) for the fixed-wing aircraft at the same separations in VMC. Although the number of IMC runs was quite limited, the possibility of a 'missed approach' in IMC seems to be comparable or even greater than in VMC. Wake-induced crosswinds were considered to be a major factor causing these missed approaches in IMC.

### 3.4. Motion cue effects

In the wake encounter simulations, the pilots were unable to perceive any acceleration disturbance since the cockpit was fixed and there was no 'g-meter' provided. We attempted to confirm how the helicopter pilots' OHRs correlated with acceleration disturbance by comparing the subjective OHR severity ratings with objective severity metrics derived from flight data including acceleration



a) Helicopter



b) Fixed-wing aircraft

Figure 12 Flight paths during encounters in IMC.

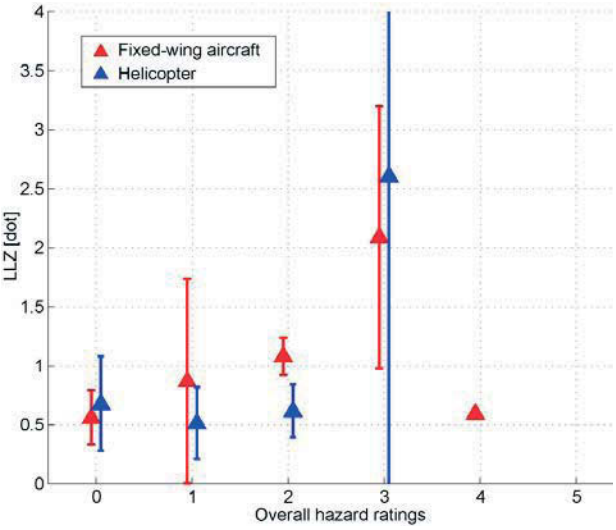


Figure 13 LLZ deviations versus OHRs in IMC.

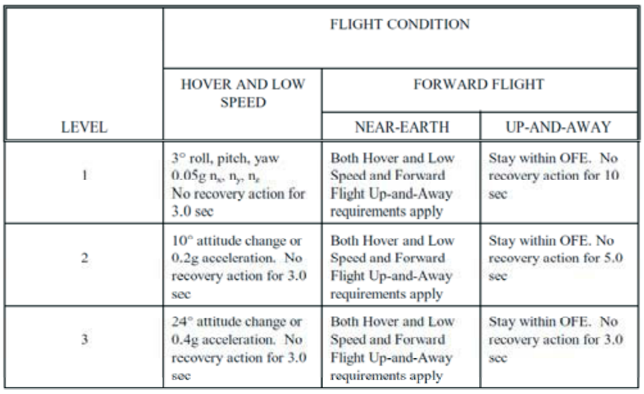
disturbance.

Based on the discussions presented in refs. 10 and 11, we used the ADS-33E-PRF handling qualities criteria for system failures [16] as the objective severity metrics for wake vortex encounters. The premise is that pilots make recovery actions against disturbances in a same manner regardless of the cause of the disturbance; whether it is wake vortex or a system failure. Based on this premise, we evaluated the wake-induced disturbances using the ADS-33's criteria defining acceptable transient upsets following system failures (table 7). Figure 14 shows the relationship between the OHR ratings and ADS-33 metrics (level 1/2/3).

Figure 15 plots helicopter attitude and acceleration disturbances (mean values and standard deviations) during wake vortex encounters versus the pilots' OHRs. The ADS-33 level 1/2/3 criteria are also shown by coloured zones. The ADS-33 criteria for attitude disturbance are well-correlated with the OHR scores since the pilots were able to detect attitude disturbances using visual cues and instrument indications. Although the ADS-33 criteria for acceleration disturbances also have positive correlations with the OHR scores, large acceleration disturbances well beyond the ADS-33 level 3 limit were scored as OHRs of 3. It is considered that such large acceleration disturbances should be scored as OHRs of 4 or more according to the relationship between OHR and the ADS-33 metrics (fig. 14), and the pilots might be underestimating acceleration disturbances due to the absence of motion cues.

In the parallel encounters evaluated in this paper, wake vortex effects mostly manifested as attitude disturbances or height loss, both of which could be

Table 7 ADS-33 criteria for transients following failures. (quoted from ref.16)



| LEVEL | FLIGHT CONDITION | | |
|---|---|---|---|
| | HOVER AND LOW SPEED | FORWARD FLIGHT | |
| | | NEAR-EARTH | UP-AND-AWAY |
| 1 | 3° roll, pitch, yaw<br>$0.05g\ n_x, n_y, n_z$<br>No recovery action for 3.0 sec | Both Hover and Low Speed and Forward Flight Up-and-Away requirements apply | Stay within OFE. No recovery action for 10 sec |
| 2 | 10° attitude change or 0.2g acceleration. No recovery action for 3.0 sec | Both Hover and Low Speed and Forward Flight Up-and-Away requirements apply | Stay within OFE. No recovery action for 5.0 sec |
| 3 | 24° attitude change or 0.4g acceleration. No recovery action for 3.0 sec | Both Hover and Low Speed and Forward Flight Up-and-Away requirements apply | Stay within OFE. No recovery action for 3.0 sec |

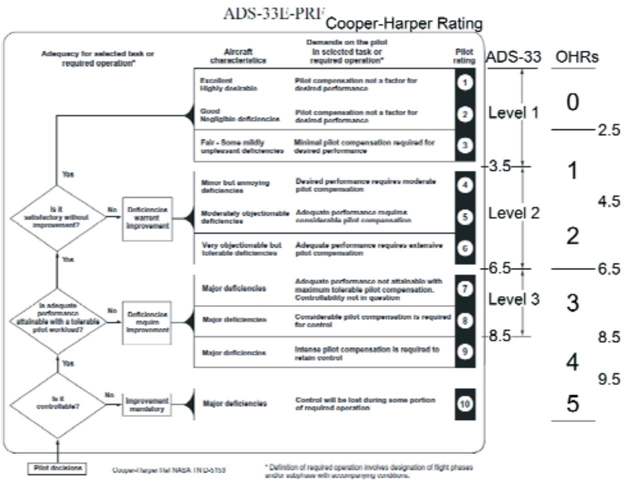
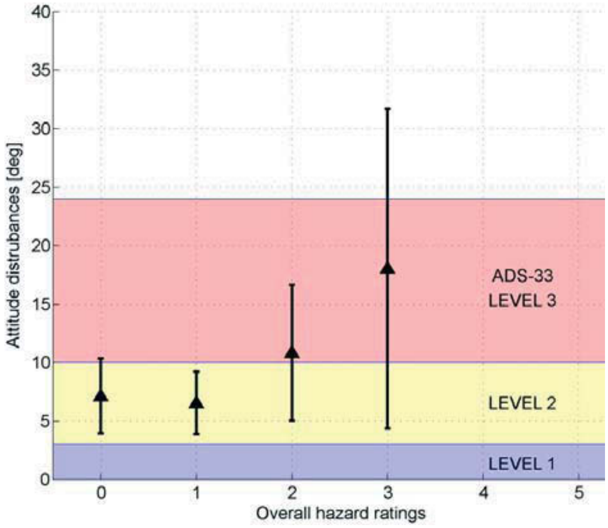
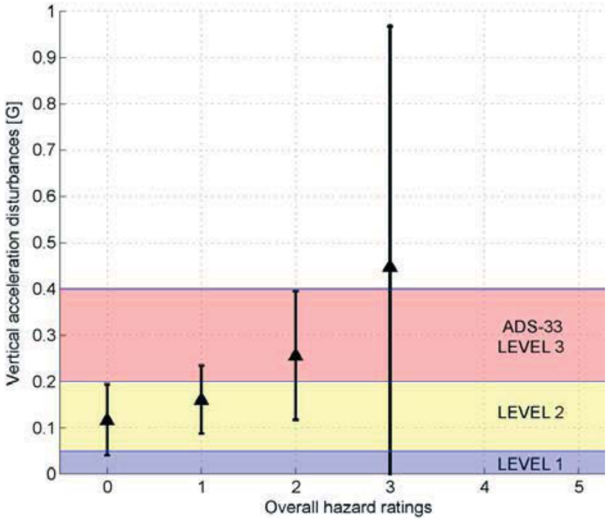


Figure 14 Relationship between OHRs and ADS-33 handling quality criteria. (flowchart is quoted from ref.16)



a) Attitude disturbances



b) Vertical acceleration disturbances

Figure 15 Helicopter attitude/acceleration disturbances versus OHRs.

well detected by visual cues and instrument indications. The absence of motion cues was therefore thought to have only a relatively small effect on the OHR scores. However, if different encounter geometries, such as a transverse encounter, were evaluated, acceleration disturbance might be a major factor in determining the OHRs. In such cases, motion cues would be indispensable for wake encounter evaluation.

## 4. CONCLUSIONS

This paper reported on pilot-in-the-loop flight simulation of wake vortex encounters conducted by JAXA. A helicopter (Mitsubishi MH2000) and a fixed-wing aircraft (Dornier Do228) were flown in parallel encounters with a Boeing 747-400's wake vortices at different in-trail separations. The major findings are summarised as follows:

- Helicopters are less susceptible to the effects of wake vortex compared to a fixed-wing aircraft of the same weight category. Helicopter pilots felt no hazard to flight safety during wake vortex encounters even at one-minute separation, which is substantially less than the current ICAO separation minimum of three minutes. On the other hand, fixed-wing pilots reported conditions hazardous to flight safety even at three minutes separation.
- During wake vortex encounters, the attitude disturbances and height losses experienced by the helicopter were half or less of those of the fixed-wing aircraft. The helicopter attitude disturbance is characterised by being multi-axis, whereas the fixed-wing aircraft experiences predominantly roll disturbance.
- In IMC, course deviations due to wake-induced crosswinds become a major cause of missed approaches in addition to attitude disturbance and height loss. The probability of a missed approach in IMC therefore tends to increase compared to VMC.

Although the number of scenarios and the number of runs were limited, these results strongly support the feasibility of reducing wake vortex separation for helicopters compared to fixed-wing aircraft. If helicopter-specific reduced separation is realised, it will allow the increased use of helicopters at congested airports, boosting airport capacity. It would be especially beneficial in Japan where helicopters comprise almost 40% of civil aircraft. Currently, re-categorisation of wake vortex separation minima (RECAT) is being conducted by the FAA and EUROCONTROL [17]. It would be a possible option to assess a helicopter-specific reduced separation in this framework. To fully assess the risk of helicopter vortex encounters, many factors still remain to be assessed including the risk of structural damage, especially to main rotor blades which experience significant wind changes along their spans, and encounters of helicopters with a hingeless main rotor since these may experience larger attitude disturbance than helicopters with an articulated main rotor.

### Future plans

In addition to creating a helicopter-specific wake separation category, another possible way to realise reduced separations is dynamic separation based on a wake vortex prediction and monitoring system using numerical weather forecasting and remote wind sensing devices. This type of wake advisory system has been developed for fixed-wing aircraft by the German Aerospace Centre (DLR) [18][19]. To apply such an advisory system to helicopters, objective severity criteria for helicopter wake vortex encounters based on helicopter characteristics and vortex parameters are necessary. The authors plan to develop such objective severity criteria based on the relationship between pilots' subjective OHR scores and the objective flight data obtained from these simulation results.

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## REFRENCES

[1] Gerz, T., Holzäpfel, F. and Darracq, D., "Aircraft Wake Vortices: A Position Paper," Wakenet, 2001.

[2] Rollet, P., Haisch, S., Korn, B. and Haverdings, H., "Rotorcraft Specific IFR Approaches," OPTIMAL Final User Forum, Paris, France, 2008.

[3] Rossow, V. J., "Lift-generated vortex wakes of subsonic transport aircraft," Progress in Aerospace Sciences 35 (1999), Pergamon, Germany, 1999.

[4] Vicroy, D. D. and Nguyen, T., "A simulation study to develop an acceptable wake encounter boundary for a B737-100 Airplane," AIAA Paper

96-3372, San Diego, CA, July 1996.

[5] Luckner, R., Höhne, G. and Fuhrmann, M., “Hazard Criteria for Wake Vortex Encounters during Approach,” German Air and Space Travel Congress 2003, München, Germany, 2003.

[6] Hahn, K.-U., Schwarz, C., Friehmelt, H., “A Simplified Hazard Area Prediction (SHAPe) Model for Wake Vortex Encounter Avoidance,” 24th ICAS Congress, Yokohama, Japan, 2004.

[7] Holzäpfel, F., Kladetzke, J., Amelsberg, S., Lenz, H., Schwarz, C. and Visscher, I. D., “Aircraft Wake Vortex Scenarios Simulator for Take-off and Departure,” 26th ICAS congress, Anchorage, U.S.A., 2008.

[8] Dunham, R. Jr., Holbrook, G. and Mantay, W., “Flight Test Experience of a Helicopter Encountering an Airplane Trailing Vortex,” the 32nd American Helicopter Society Annual Forum, 1976.

[9] Saito, S., Azuma, A., Okuno, Y. and Hasegawa, T., “Numerical Simulation of Dynamic Response of Fixed and Rotary Wing Aircraft to a Large Aircraft Wake,” 13th European Rotorcraft Forum, Arles, France, 1987.

[10] Padfield, G. D., Manimala, B., and Turner, G. P., "A Severity Analysis for Rotorcraft Encounters with Vortex Wakes," Journal of the American Helicopter Society, Vol. 49, No. 4, 2004.

[11] Lawrence, B. and Padfield, G. D., "Wake vortex Encounter Severity for Rotorcraft in Approach and Landing," 31st European Rotorcraft Forum, Florence, Italy, 2005.

[12] Lawrence, B., Padfield, G. D., and Taghizad, A., "Rotorcraft Wake Vortex Encounters: A Flight Mechanics Perspective," 32nd European Rotorcraft Forum, Maastricht, Netherlands, 2006.

[13] Hahn, K.-U., “Coping with Wake Vortex,” 23rd ICAS congress, Toronto, Canada, 2002.

[14] Holzäpfel, F., “Probabilistic Two-Phase Wake Vortex Decay and Transport Model,” Journal of Aircraft, Vol. 40, No. 2, 2003.

[15] Whitehouse, G. R. and Brown, R. E., “Modeling the Mutual Distortions of Interacting Helicopter and Aircraft Wakes,” Journal of Aircraft, Vol. 40, No. 3, 2003.

[16] United States Army Aviation and Missile Command, Aviation Engineering Directorate, “Aeronautical Design Standard: Performance Specification; Handling Qualities Requirements for Military Rotorcraft,” Vol. ADS-33E-PRF, 2000.

[17] Lang, S. and Lepadatu, C., “Re-categorization of the Wake Turbulence Separation Minima – RECAT,” Wakenet Europe workshop 2007, Brussels, Belgium, 2007.

[18] Holzäpfel, F., Gerz, T., Frech, M., Tafferner, A., Kopp, F., Smalikho, I., Rahm, S., Hahn, K.-U., and Schwarz, C., “The Wake Vortex Prediction and Monitoring System WSVBS – Part I: Design,” 1st CEAS European Air and Space Conference, Berlin, Germany, 2007.

[19] Gerz, T., Holzäpfel, F., Gerling, W., Scharnweber, A., Frech, M., Wiegele, A., Kober, K., Dengler, K. and Rahm, S., “The Wake Vortex Prediction and Monitoring System WSVBS – Part II: Performance and ATC Integration at Frankfurt Airport,” 1st CEAS European Air and Space Conference, Berlin, Germany, 2007.