

Hazards due to Helicopter Wakes



R.A. Kist and K.P. Garry

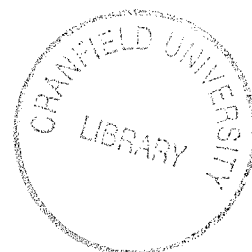
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The local velocities induced in the wake of a helicopter can be a serious hazard to light aircraft operating nearby. A theoretical model is developed which makes it possible to estimate the rolling moment induced on a light aircraft entering the wake of a helicopter. The model shows good agreement with the limited amount of flight test data available. An annotated bibliography of the literature available on helicopter wakes is presented in order to identify specific areas in which further research is required.

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Summary

The hazard to light aircraft of the wake from a helicopter in flight out of ground effect is known to be greater than that generated by a fixed-wing aircraft of the same weight. A fatal accident, involving a medium weight helicopter in hover and a light aircraft, which was overturned during approach for a touch-and-go by the wake induced by the hovering helicopter, occurred at Kidlington, Oxfordshire in July 1992. This prompted the AAIB to recommend an investigation of the hazard caused by hovering helicopters to light aircraft that fly in the vicinity of the wake.

There are three main types of wake possible, depending on both (i) Airspeed and (ii) height above ground, relative to the size of the rotor. (Note that the airspeed is the resultant of the aircraft speed and the ambient wind speed)

The first occurs at an airspeed of less than 5 knots, and consists of a near-vertical downwash that is spread out radially along the ground. This can be dangerous to other aircraft in the immediate vicinity (up to a few rotor diameters, and certainly less than 90 metres), but can be neglected for the typical flight separations required for the other two types of wake.

The second is a wake in which a horse-shoe shaped ground vortex is induced. This occurs when the airspeed is approximately 5 to 20 knots resulting in the rotor downwash and airstream interacting inducing a vortex. This can be a hazard to aircraft at quite large distances, especially as the vortex may float up higher than the rotor.

The third wake type occurs at relatively high airspeeds of more than 20 knots and is the most dangerous. It is a rotor disk-edge vortex which is comparable to fixed-wing aircraft induced tip vortices, but much stronger than for aircraft of identical weight. Since the disk-edge vortex reaches its maximum strength during helicopter approach and transition to hover, this is likely to be the criterion for safe separation minima.

In an extensive literature survey it is found that the hover wake hazard, especially in an ambient wind, has not been investigated thoroughly, and although theoretical methods for most aspects of the hazard calculation are available, they are not yet validated by measured data.

A theoretical model, based on available methods, to determine the upset bank angle of a light aircraft entering the wake after a given time is presented. Induced roll angle at various separation distances can be calculated for any combination of helicopter and fixed-wing aircraft.

This model is considered acceptable for the disk-edge vortex wake case, both in and out of ground effect, it is therefore a useful tool for the determination of separation minima. The ground vortex case is shown to be weaker than the disk-edge vortex, but there is a lack of data for validation and further research is needed. The case of hover in nil or very light wind is shown to be relatively insignificant compared to the ground and disk-edge vortex cases.

When this model is applied to the Kidlington accident it is possible to predict the upset bank angle of the fixed wing aircraft to good agreement with the observations of witnesses.

Since a conservative approach to all calculations has been adopted, validation through experimental measurements is strongly recommended to check the validity of the method and avoid making an overcautious estimate of the helicopter wake hazard.

Foreword

This report has been produced by the College of Aeronautics, Cranfield University (CoA) under contract to the Chief Scientist's Division (NATS).

It forms part of the response of the CAA to recommendation 93-14 of the report on the accident to Piper PA-28-161 Cadet, G-BPJT at Oxford Airport, Kidlington on 12 July 1992. This stated that:

"The CAA, together with interested parties, should develop and implement a research programme into wake vortex and downwash effects."

Copies of this report have been provided to SRG and the NATS staff responsible for developing ATC procedures. It has also been made available to the Department of Transport and the Air Accident Investigation Branch for their consideration.

In the report CoA present a review of helicopter wakes which covers theoretical modelling, wind tunnel experiments and flight tests. They recommend methods for predicting the behaviour of helicopter wakes, and further research into some aspects of the behaviour which are not well understood.

CoA conclude that:

- The wake of helicopters can be hazardous, especially in medium ambient wind velocities. By far the most dangerous is the wake induced just before transition to hover, and also important is the ground vortex, which is the strongest in a 20kt wind. More research is needed to understand the decay of the vortices, as well as their generation.
- When the model presented here is applied to the accident at Kidlington, it is possible to reconstruct the upset to the Piper aircraft to good agreement with the observations of witnesses.

John Greenwood
Safety Studies Section
Chief Scientists Division NATS

December 1993

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Contents

Summary.....	ii
Foreword.....	iii
Acknowledgements.....	iv
List of Figures.....	vi
Notation.....	ix
1. Introduction.....	1
2. Summary of Possible Wake Types for Helicopters in Ground Effect.....	3
3. The Characteristics of the Different Investigation Techniques.....	6
3.1 Theoretical Modelling of a Rotor in Ground Effect.....	6
3.2 Wind Tunnel Testing.....	7
3.3 Full Scale Testing in the Field.....	8
4. Theoretical Modelling of the Wake Hazard based on Current Knowledge.....	10
5. Using the Calculation Method on the Kidlington Accident.....	14
6. Conclusions.....	18
7. Recommendations for Further Research.....	21
References.....	23
Bibliography.....	27
Appendix A: Abstracts of the Literature on Helicopter Wakes.....	31
A.1 Literature Relating to Theoretical Modelling.....	31
A.2 Literature Relating to Wind Tunnel Testing.....	39
A.3 Literature Relating to Full Scale Testing in the Field.....	44
Appendix B: Separation Requirements Calculation Method.....	48
B.1 Shape of Wake Determination.....	48
B.2 Determination of the Strength of the Ground Vortex.....	49
B.3 Determination of the Strength of the Disk-edge Vortex.....	50
B.4 Calculation of the induced Horizontal Velocities.....	51
B.5 Calculation of the Decay of the Vortex.....	52
B.6 Prediction of the Path of the Vortex.....	54
B.7 Calculation of the Roll Angle of the aircraft.....	56
B.8 Evaluation of the method with measured upset angles.....	60

Figures

List of Figures

1. Summary of wake type occurrence with relative rotor height and normalised advance ratio. (Sun, ref. 18)
2. Downwash in nil wind conditions (Ferguson, ref. 32)
3. Rotor wake structure: vortex representation (Kusmarwanto, ref. 22)
4. Skewing of the rotor wake at increasing forward speed (advance ratio (μ) indicated), (Miller, bibl. 20)
5. Wake development in light wind conditions (Sheridan, ref. 11)
6. Wake recirculation formation (Sheridan, ref. 11)
7. Schematic of the ground vortex formation mechanism (Ferguson, ref. 32)
8. Geometry of the ground vortex at advance ratio $\mu = 0.04$ (Sheridan, ref. 11)
9. Geometry of the ground vortex at advance ratio $\mu = 0.05$ (Sheridan, ref. 11)
10. Flow visualisation of ground vortex at advance ratio $\mu = 0.05$ (Sheridan, ref. 11)
11. Schematic 3-dimensional representation of the ground vortex with the helicopter in rearward flight. (Heyson, ref. 16)
12. Secondary vortex induced when primary vortex reaches the ground (Sun, ref. 18)
13. Schematic representation of the formation of disk-edge vortices at advance ratio $\mu = 0.08$ (Sheridan, ref. 11)
14. Schematic arrangement of the 3-dimensional disk-edge vortex wake (Tymczynszyn, ref. 34)
15. Measurement in the wake of a CH-54 with a weight of 38,000 lbs at 30kts, 28 seconds after the aircraft has passed the measurement point (Ferguson, ref. 33)
16. Representation of ground effect using a mirror image rotor (Kusmarwanto, ref. 22)
17. Schematic of the shear layer formed as the wall jet streams along the ground. (Sun, ref. 18)
18. Example of flow velocity vector visualisation for a rotor in ground effect at low advance ratio. (Heyson, ref. 8)

19. Example of measured rotorwash flight test data from Indianapolis Heliport (Weiss, ref. 25)
20. Schematic of the principle of the model used by Sun to calculate the ground vortex (Sun, ref. 18)
21. Ratio of ground vortex to tip vortex strength. (Sun, ref. 18)
22. Principle adopted for the calculation of the ground vortex by He. (He, ref. 24)
23. Ratio of ground vortex to tip vortex strength. (He, ref. 24)
24. Measurements of the wall jet velocity decay for a CH-53 in hover - case 1. (Ferguson, ref. 33)
25. Measurements of the wall jet velocity decay for a CH-53 in hover - case 2. (Ferguson, ref. 33)
26. The wall jet velocity presented on a logarithmic scale (Levinsky, ref. 7)
27. Comparison of the results from different calculation methods of vortex core radius
28. Measurements of vortex persistence for aircraft wakes as a function of the ambient wind. (Kurylowich, ref. 14)
29. Comparison of the theoretically predicted wake vertical velocity with measured data, at $t = 28$ seconds behind a CH-54 at a speed of 15 m/s.
30. Measured and calculated (a) vortex trajectories, (b) lateral vortex position histories, (c) vortex elevation histories, at various Reynolds numbers in ground effect (Zheng, ref. 36)
31. Theoretical prediction of the 'up float' of the wake vortex for various rotor heights above the ground plane (Levinsky, ref. 7)
32. Wind tunnel measurements of ground vortex location indicating the lateral spread (Sun, ref. 18)
33. Theoretical prediction of the effect of the relative position of a light aircraft to the vortex centre and of the core radius on induced rolling moment.
34. Variation of upset bank angle with separation distance between a T-34C and a UH-60 helicopter (Tymczyszyn, ref. 34)
35. Variation of upset bank angle with separation distance between a T-34C and a CH-53E helicopter. (Tymczyszyn, ref. 34)

36. Comparison of the results of the developed method with measured data (ref. 34) for a T-34C penetrating the wake of a typical 20,000 lbs helicopter (such as the S-61 and the UH-60), as a function of separation time
37. Comparison of the results of the developed method with measured data (ref. 34) for a T-34C penetrating the wake of a typical 70,000 lbs helicopter (such as the CH-53E), as a function of separation time
38. Comparison of the results of the developed method with measured data (ref. 34) for a T-34C penetrating the wake of a typical 20,000 lbs helicopter (such as the S-61 and the UH-60), as a function of separation distance
39. Comparison of the results of the developed method with measured data (ref. 34) for a T-34C penetrating the wake of a 70,000 lbs helicopter (such as the CH-53E), as a function of separation distance
40. Geometry, performance and appearance of the PA-28-161 Cadet
41. Map of the situation at the time of the accident at Kidlington airport (AAIB, ref. 37)
42. Smoke visualisation of the wake of a S-76 during the transition to hover in a similar fashion as at Kidlington (FAA Technical Centre, Mr J. Sackett)

Notation

b	Number of rotor blades
b	Span of aircraft (m)
C_{l_α}	Lift coefficient slope on 3-dimensional wing (/ rad)
C_T	Thrust coefficient, $T / \rho V_{tip}^2 \pi R^2$
c	Chord of a wing (m)
D	Rotor diameter (m)
h	Rotor height above the ground (m)
I_{xx}	Moment of inertia around the longitudinal aircraft axis (kg m^2)
L	Lift (N)
M_{roll}	Roll moment working on aircraft (Nm)
R	Rotor radius (m)
R_{core}	Core radius (m)
T	Rotor thrust (N)
t	Time expired after the vortex encounter (sec)
V_{tip}	Tip speed of a rotor (m/s)
V_{vortex}	Velocity induced by a vortex (m/s)
V_F	True airspeed of helicopter (m/s)
V_∞	True airspeed of aircraft (m/s)
W	Weight of helicopter or aircraft (N)
ϕ	Roll angle of aircraft (rad)
Γ	Strength of a vortex (m^2/s)
μ	Advance ratio, V_F / V_{tip}
μ^*	Normalised advance ratio, $\mu / \sqrt{C_T / 2}$
ρ	Density of the air (kg/m^3)

Chapter 1. Introduction

The wake hazard of fixed wing aircraft is well known and has been extensively investigated. The information for helicopter wakes is far from complete. The velocities induced by a helicopter can be much stronger, especially at low advance ratios and in hover, than might be expected from a fixed wing aircraft of comparable weight. When a rotor is in hover in nil wind conditions the near vertical downwash will be spread out radially along the ground, as is shown in figure 2. These horizontal velocities could create extra lift on light aircraft, which can be dangerous especially if it occurs asymmetrically.

When the rotor operates in an ambient wind the extent of the region influenced by the wake is greater as a vortex is formed near the ground. This wake could be a hazard to light aircraft that encounter it because a rolling moment is induced when an aircraft penetrates a vortex. At higher wind speeds or forward velocities the rotor has a wake very much like the wake of an aircraft with high wing loading, inducing similar strong vortices.

A fatal accident at Kidlington, Oxfordshire in 1992, involving a Piper Cadet during a touch and go manoeuvre, and an S.61 helicopter in hover taxi near the runway, resulted in the Cadet crashing following a sudden roll, as reported in reference 37. This accident has prompted the Aircraft Accident Investigation Branch (AAIB) to recommend the investigation of the helicopter wake hazard with the aim of establishing 'safe' separation minima between hovering helicopters and other aircraft in differing atmospheric conditions.

There are broadly three types of approach to the investigation of aircraft wakes, the determination of induced velocities, the path of the vortices and the possible effect of aircraft in the vicinity. These are:

1. Theoretical modelling of the rotor wake in ground effect
2. Wind tunnel testing
3. Full scale testing in the field

each has distinct advantages and disadvantages. This report takes each of the above as a basis for the initial investigation. A summary of the characteristics of the different types of wakes based on the available literature is given in Chapter 2. In Chapter 3 a description of the existing investigation techniques is presented and the advantages and disadvantages of each are discussed. Chapter 4 describes the different segments of the hazard investigation that have to be addressed, and discusses the availability of theoretical models in the current literature necessary to develop a theoretical model. It is shown where there are gaps in current knowledge. In chapter 5 the developed method is applied in an attempt to evaluate the Kidlington accident involving the Cadet aircraft. In chapter 6 conclusions are drawn on the accuracy of the model as developed from the available literature and on the gaps that exist in the current knowledge. In chapter 7 recommendations are made on the best techniques and test

program for further research, the aim of which would be to validate or improve the developed theoretical model for the determination of new guidelines to avoid aircraft and rotorcraft wake interaction, and also to improve current knowledge.

In Appendix A detailed abstracts of the references and the bibliography are given where appropriate, with comments on the applicability of each to this investigation. In Appendix B the mathematical equations of the theoretical model that is developed are presented and results of several different methods are compared with measured data.

Chapter 2. Summary of Possible Wake Types for Helicopters in Ground Effect

The magnitude of the rotor wake is dependent on disc-loading, rotor diameter and rotor characteristics, but the wake type is mainly dependent on the advance ratio μ (the true airspeed to rotor tip speed ratio) and rotor height. It transpires that there are four possible wake types. In Figure 1 the transition lines between the different types are plotted as a function of the normalised advance ratio (this is advance ratio corrected for different thrust levels) and rotor height (expressed in rotor diameters). For each combination of rotor height and normalised advance ratio Figure 1 shows the wake type that will occur through the four areas on the graph, which are:

Hover in nil wind conditions - generation of the so-called 'uniform wall jet'

During hover the rotor downwash strikes the ground and spreads out radially, as shown in figure 2. The single blade tip vortices are carried down on the outside edge of the downwash 'column', as can be seen in figure 3, and then are spread out in a stream parallel to the ground, which is often referred to as the wall jet. This diminishes their effect very quickly, as the elongation weakens the strength of the vortex, diffusing its total energy. The vortices are each relatively small and will probably not roll up into one single vortex unless the wall jet velocities are very low, in which case the individual tip vortex strengths are very small.

Low advance ratios - recirculation

The downwash column is skewed by the relative oncoming wind, as can be seen in figure 4, and the vorticity concentration in the upwind wall jet increases as it is retarded by the wind. At some distance upstream of the rotor the local velocity is zero at a point where the velocity of the oncoming wind equals that of the wall jet (see figure 5). This point gets closer to the helicopter as the advance ratio increases, and the resultant interaction of the wall jet and ambient wind becomes stronger. Air is forced upwards and is recirculated into the rotor, as is shown in figure 6. The roll-up is still negligible. It is basically similar to the ground vortex, described in the following section, which makes a clear transition point between the two types difficult to establish from flow visualisation studies.

Intermediate advance ratios - ground vortex

At intermediate advance ratios a horse-shoe ground vortex develops. The flow mechanism which results in the formation of this vortex is complex. It is shown in figure 7. When the column of air beneath the rotor strikes the ground a proportion is deflected forwards in the same direction as the helicopter flight path, or into the prevailing wind. This forward flow is retarded by the oncoming airflow which is pushed upwards, eventually being deflected over the top of the rotor wash and carried downwind (in a more pronounced fashion than in the recirculation phase). It can be seen in figures 8 and 9, with a visualisation in figure 10. The blade tip vortices are concentrated on the outer

edge of both the downwash column and the subsequent wall jet. Ahead of the rotor this vorticity is concentrated near the stagnation point and since this point is relatively close to the rotor, the tip vortices are still very strong and start to roll up. In this way a strong vortex is formed near the ground which curves around the rotor wake following streamlines that are approximately parabolic (see figure 11).

A ground vortex also appears when a vertical jet impinges on a flat plate in a uniform free stream, so the mass flow of the rotor clearly contributes to the vortex strength. The ground vortex that develops in the case of a rotor has a greater strength because the blade tip vortices, with the same sense of rotation, are absorbed into the ground vortex. In the case of an ambient wind, the profile of the atmospheric boundary layer serves to strengthen the ground vortex still further. This can be explained by representing the atmospheric boundary layer as a series of vortices, that have the same sense of rotation as the ground vortex, and are similarly absorbed.

The ground vortex does not stay near the ground but may rise since, through viscous effects, a secondary vortex is created alongside the ground vortex (see fig 12), which pushes it upwards and increases its lateral displacement. It is very important in the investigation of rotor hazards to take this rise into consideration.

Greater advance ratios: disk-edge vortex

At greater advance ratios the whole wake is blown back clear of the ground and starts to resemble that of a fixed wing aircraft with strong disk-edge vortices. This can be seen in figures 13, 14 and 15. This is a result of the large skew angle of the downwash column which induces the blade tip vortices to roll up on the lateral extremes of the column, see figure 4 at the higher advance ratios. As the disk-edge vortices are stronger at lower advance ratios the greatest hazard to a following aircraft will occur at the transition from the disk-edge vortex to the ground vortex wake type. Since this situation always occurs during transition from approach to hover this poses the greatest hazard to the following aircraft.

The benefits to the helicopter of ground effect (a lower power requirement) disappear at higher advance ratios (see Heyson, ref. 1, 1959) and therefore it can be concluded that the wake geometry and vorticity close to the rotor will not be significantly affected by the proximity of the ground, so the strength of the disk-edge vortex in ground effect will be almost identical to that out of ground effect. As in the ground vortex case the disk-edge vortices will tend to rise if the rotor is close to the ground. This is an important consideration in the current investigation.

Influence of Helicopter Wake on Light Aircraft

A light aircraft intersecting the helicopter wake is threatened mainly by the ground and disk-edge vortices because they are so concentrated and induce very strong rolling moments, especially if the aircraft penetrates the vortex and flies along its length. The other parts of the wake can produce some vertical acceleration, but this will probably not be very hazardous unless the aircraft is really close to the ground. The strongest

rolling moment will probably be induced if the aircraft gets into the centre of the vortex. From the flight tests in the report of Connor (ref. 2, 1962) it is shown that even a relatively light helicopter can induce strong rolling moments out of ground effect, so a heavy helicopter will clearly be potentially hazardous to a low flying aircraft that penetrates the wake, because there is little room to manoeuvre close to the ground.

The crucial questions are (i) what is the rotor wake like, (ii) how strong are the vortices, (iii) what is the largest safely acceptable vortex strength and wall jet velocity for a light aircraft, (iv) how long does the vortex retain its strength and (v) how quickly is it dispersed when carried by the wind ?

When considering new regulations it is imperative that these aspects are well understood. A summary of the modelling requirements for their simulation is given in chapter 4.

Chapter 3. The Characteristics of the Different Investigation Techniques

3.1 Theoretical Modelling of a Rotor in Ground Effect

Possible Theoretical Models

There are several methods of modelling a rotor wake, as seen in refs 32, 24 and 14. Vortex theory is accurate with a lifting line to represent each rotor blade and trailing vortices at the root and the tip (see figure 3). Until recently the curved trailing vortices were approximated by short straight segments, but now there are also methods to take into account the curvature of the vortices. This is not so relevant for a wake at a distance, so it is not considered necessary for a wake hazard model. Ground effect is represented by a mirror vortex system (comparable to figure 16). The wake can be 'prescribed' - which means certain characteristics of the wake geometry are assumed in advance to save calculation time, or it can be 'free' - which means no assumptions are made about the wake geometry and the program is left to calculate the geometry. The latter is more realistic but takes more calculation time.

The influence of the wake on a light aircraft can be modelled by integrating the extra lift induced on a segment of the wing due to the horizontal and vertical velocities, induced by the rotor. The most hazardous location for the aircraft is in the centre of the tip or ground vortex if the core radius is relatively large compared to the half-span, as is shown in appendix B. However, with a theoretical model it is relatively simple to estimate the moment in other locations as well.

In the literature there are theoretical methods available relating to various aspects of the wake hazard, an investigation of the possibility of developing an approximate model of the helicopter wake hazard is described in chapter 4. Virtually all aspects of this research are covered by a theoretical method of some sort. However, it is difficult to assess the accuracy of some of them, necessitating further research.

Advantages of Theoretical Modelling

Using lifting-line theory it is possible to make a simplified model of a rotor in ground effect with a wind velocity incorporated. Such a model could be suitable to run on a desk top PC. The main advantage is the flexibility to change the rotor parameters, wind velocities and the position of the aircraft in the vicinity, in a reasonably short time and at low cost. Any combination of helicopter, aircraft, separation, wind velocity, hovering height and other parameters may be simulated.

Disadvantages of Theoretical Modelling

Unfortunately existing computer models like ROTWASH and HELIWAKE and other theoretical methods such as that developed by He (ref. 24, 1988) do not predict the

worst case regarding the strongest possible ground vortex. The velocity profile of the atmospheric boundary layer is likely to have an effect on the strength of the ground vortex because the velocity in the layer can be described as a circulation with the same direction as the ground vortex. This probably increases the ground vortex strength, although the extent may be small, but this is not included in any existing vortex calculation program. There is no lack of theoretical methods, but there is a lack of data to compare them with. Very few experimental data to check the accuracy of the results are available. Full scale data is particularly scarce. Safe separation minima can best be determined using a theoretical method, but future research in this area will have to start with measurements in wind tunnels or full scale tests in order to validate the theoretical method.

3.2 Wind Tunnel Testing

Establishing Test Conditions

For tests in a wind tunnel the model should ideally be geometrically and aeroelastically identical to the full scale rotor. In addition the Reynolds number, tip Mach number, thrust coefficient and cyclic pitch setting should also be identical. For an investigation of the effects of an ambient wind on rotors the atmospheric boundary layer should be to the same scale as the rotor. However in practice all of this is very difficult to achieve.

A review of the significance of each factor follows.

Geometric scaling:

This is important towards the tip, but near the root less so because there is little induced velocity in that part of the rotor, so the wake is affected very little by a different root and hub form. The profile of the rotor blades is of course very important as well as the number of blades, but the effect on the wake of these parameters at a considerable distance downstream may be limited.

Aeroelastic scaling:

This is important primarily for testing the vibration levels of rotor blades and other parts of the helicopter since the flap and lag or sway characteristics of the rotor blades are dependant on aeroelastic effects. Once again the effects of these characteristics on the wake at large distances downstream are likely to be small.

Reynolds number:

Matching of the full scale and model scale Reynolds number would be ideal but is impossible. The atmospheric wind is modelled at a very small scale, typically 1/100th, which would require at model scale the rotor tip velocity to be a hundred times the full scale tip speed, which is clearly impossible. However, as reported in bibliography 2, tip speed does not appear to be significant as long as the advance ratio is correct. Another possible solution, as used in reference 28, is the use of an alternative fluid to air for the wind tunnel tests such as

refrigerant medium R-12, with which considerably higher Reynolds numbers can be reached.

Advantages of Wind Tunnel Testing

Wind tunnel testing has the advantage over theoretical calculations that there are no assumptions that have to be made to determine the behaviour of the flowfield. Primarily for the type of investigation considered here, this means that viscous effects are represented. Providing that the model scale Reynolds number and other scaling parameters, such as Mach number, are identical to the full scale case, a wind tunnel simulation is an accurate representation. Even if such scaling parameters are not matched exactly, which is most often the case in practice, it is normally possible to extrapolate to full scale conditions using a knowledge of the flowfield characteristics and empirical data.

Disadvantages of Wind Tunnel Testing

Unfortunately, it is quite difficult to achieve a match for all relevant scaling parameters. The atmospheric boundary layer can be modelled only at a relatively small scale (typically 1/100th), this is achieved by introducing ground roughness to the wind tunnel floor upstream of the working section. The ground boundary layer is therefore thickened so that, at the model location, the flow has the same shear profile and turbulence distribution that would be measured full scale. In order to obtain the correct interaction of rotor and wind shear the rotor should be the same scale, but the full scale Reynolds number would be very difficult to achieve in that case. The wind tunnel must also be large to enclose the spread of the ground vortex.

3.3 Full Scale Testing in the Field

Setting up the Test

A typical test scenario would include a helicopter in the hover, at a wheel height determined by the minimum that might occur in operational circumstances, since it should be as close to the ground as possible for the strongest ground vortex and trailing vortex up float. The location of the vortex would have to be determined and the velocities measured using the techniques detailed by Sullivan et. al. (ref. 15. 1979, see Appendix A). The horizontal velocities may also be measured using similar techniques.

A full scale test near the ground including a second aircraft intersecting the wake is considered to be too dangerous for obvious reasons.

Advantages of Full Scale Testing

The major advantage of full scale testing is that it is a true representation that does not rely on assumptions or simulation. As few measurements of vortices in helicopter

wakes exist, especially at full scale, it would be very worthwhile to do these tests as evaluation of theoretical methods would then be possible.

Disadvantages of Full Scale Testing

As with all full scale aerodynamic tests there are numerous potential practical problems. Obviously the ambient wind conditions are beyond the control of the researcher and consequently allowances would have to be made for the likely timescales involved. Ideally a range of ambient wind speeds of 0 - 30 knots should be considered to give insight of the possible range of wake geometries and this speed should be steady throughout the measurement period. It is not necessary to include speeds higher than 30 kts. as the strength and lifespan of the disk-edge vortex will diminish rapidly above this speed.

In order to evaluate the influence of the atmospheric boundary layer, measurements of both mean and fluctuating wind velocity components should be made at a number of heights above the ground, upstream of the aircraft under test. Mean velocity measurements are possible with conventional pressure based probes or cup anemometers, but fluctuating components require more sophisticated aerovane, hot film or sonic anemometers supplemented by high speed multi-channel data sampling and storage instrumentation, see for example Hourigan (ref. 35, 1991).

Measurement of velocity components in a fluctuating wake is difficult and this is particularly true outside of a controlled laboratory environment. If large flow angularity and/or reversing flows are likely then the only reliable technique is the three axis laser Doppler anemometer. The complexity of this type of instrumentation often necessitates a compromise and the use of more conventional aerovane anemometer systems with reduced frequency response and angular sensitivity.

Valuable geometrical information on the wake can be gained from flow visualisation studies. The flow can be seeded with smoke or a fluorescent dye, released either from the helicopter itself or upstream, and filmed. Another technique uses arrays of monofilament streamers, the lengths of which should be chosen to complement the local flowfield. Careful thought would have to be given to planning the recording of the flow geometry.

Chapter 4. Theoretical Modelling of the Wake Hazard based on Current Knowledge

It is possible and convenient to split the investigation in several segments to clarify what is known and what still needs to be investigated for calculation of helicopter wakes in ground effect and their effect on following aircraft. This division should also simplify research as each segment is a relatively well-defined problem. No reference is known that covers the complete picture, but on each segment there are usually several reports and papers in which theoretical methods (analytical or numerical) or results of full scale or wind tunnel measurements are presented.

The segments roughly follow the development of the rotor wake:

Determination of the Type of Wake

The first segment is determination of the form of the wake; ie. the wall jet situation, the recirculation situation, the horse-shoe shaped ground vortex wake or the disk-edge vortex wake that is like a fixed wing aircraft wake. The parameters that may determine this are (i) wind velocity, (ii) the nature of the atmospheric boundary layer, (iii) the ratio of rotor height and rotor diameter and (iv) the mean vertical velocity induced by the rotor. Item (iv) is not always considered to be a determining parameter, and the advance ratio is often used as the determining factor.

As the ground vortex exists even when a jet impinges on the ground ie. with no tip velocity or rotation, it seems logical that the amount of air flowing through the rotor disc or jet nozzle is one of the most important sources of the ground vortex. Therefore the normalised advance ratio, which is the advance ratio corrected for thrust, is used for more realistic comparison. References that give specific forward speeds for the transition of the wake geometry are, Curtiss (ref. 17, 1982), Sheridan (ref. 11, 1977), Hanker (ref. 20, 1983) and Dhar (ref. 27, 1989).

Unfortunately, as can be seen in figure 1, the measured values of the transition velocity are not consistent. A reason for this may be that both induced velocity and advance ratio are factors, as the latter will also influence the tip vortices through the tip speed, which in turn may also determine the occurrence and strength of the ground vortex. Another reason might be the fact that the transition from one wake type to another is difficult to define since recirculation and the beginning of the ground vortex have a similar mechanism, and the ground vortex has not completely dissipated when the disk-edge vortices appear. Considering the scaling problems encountered by Dhar (ref. 27, 1989), measured values might not be identical due to these scaling problems.

Although new research is needed to find the correct transition points, taking into account the atmospheric boundary layer, it might still be possible to propose safe separation minima based on current information. The ground vortex, if it exists at very low wind speeds, would be very small. For higher advance ratios it would be possible to calculate the strengths of both the ground vortex and the disk-edge vortex for a

range of wind velocities at which there are conflicting results and take the most powerful to give the separation required for safety.

Determination of the Strength of the Ground Vortex or Disk-edge Vortex

This strength depends partly on the strength of the bound vortex, which is the vortex along each rotor blade that is creating lift (identical to the bound vortex representation of lift on a fixed wing aircraft). This is a function of rotor tip speed, helicopter weight (in the hover condition), rotor diameter, advance ratio and the number of blades. The induced velocity through the disc, the relative rotor height and the atmospheric boundary layer also contribute. In the literature there are relatively few reports that go deeply into calculating these vortex strengths, but Levinsky (ref. 7, 1970) has developed a theoretical method, as have Ferguson (ref. 32, 1991) and He (ref. 24, 1988, for ground vortex only). There are few measured data especially for the ground vortex, to check against the theoretical estimates. The measurements are mostly from wind tunnel tests, so they are not a complete simulation. In the disk-edge vortex case ground proximity will have little effect on the disk-edge vortex strength. Full scale test results of disk-edge vortex strength and core radius measurements in free air might therefore be used to predict vortex strength in ground effect (although close to the ground the wake will have a different path and possibly a different decay rate). The vortex core radius has also to be determined, as given by Levinsky (ref. 7, 1970). A comparison of these theoretical methods is given in Appendix B.

Determination of the Horizontal Velocities induced by the Rotor

This is important mainly at lower advance ratios because the induced velocities decrease as the mass flow through the disc increases. At very low advance ratios it will not have a strong effect outside the immediate vicinity of the helicopter (of the order of several rotor diameters) as the velocity decreases inversely proportionately with distance. At higher advance ratios (from an advance ratio of about 0.05, when the forward speed is higher than the vertical induced velocity) the relative increase in velocity of the air is very small. The induced velocities get smaller compared with the hovering induced velocity, because of the increase in mass flow through the disk. The condition that could be important is at low to medium advance ratios, when the induced velocity is still significant, but is directed rearwards by the wind and may remain strong for a much greater distance. Unfortunately, very few measurements have been made in this area. It is difficult to predict if this could affect an aircraft significantly at distances where the vortex hazard has ceased to exist.

Determination of Vortex Decay

This depends on the age of the vortex which follows directly from the separation distance and true airspeed of the helicopter, together with the vortex core size, vortex strength and atmospheric conditions (calm or turbulent, wind velocity). Zheng (ref. 36, 1992) and Levinsky (ref. 7, 1970) have developed calculation methods, which include ground effect.

There are indications that the vortex decay might be more rapid for helicopter wakes than for fixed wing aircraft, since the vortices are the result of the roll-up of segments of the tip vortices that trail each blade of the rotor. Therefore the viscous core is larger than that for aircraft (especially if the helicopter is at a low advance ratios), diminishing the vortex energy and also the hazard to light aircraft. This effect may result in a relatively less hazardous wake for helicopters with more blades, but more research is needed on the core sizes in helicopter wakes and the effect of blade number to confirm this.

Determination of Vortex Paths

It is important to predict the location of the wake to determine hazardous areas for aircraft. The vortex paths depend on wind velocity and direction and relative rotor height. Attention has to be paid to the up float process which is not easily predicted. This process is described and calculated by Zheng (ref. 36, 1992) and by Levinsky (ref. 7, 1970). To compile new safety regulations it might be sufficient to give a maximum height above the rotor that the wake vortices might reach assuming the strongest up float possible. If an aircraft has to go below that level a horizontal separation would ensure safe operation. The maximum height of the vortex as a result of the up float can be estimated using the method described by Zheng (ref. 36, 1992), see appendix B. Zheng does not include the effect of the exhaust heat on the wake, which might be another cause for up float according to Tymczyszyn (ref. 34, 1991).

The spread of the disk-edge vortices is addressed by Levinsky (ref. 7, 1970) and Zheng (ref. 36, 1992) who give predictions of their path, but not that of the ground vortex. Attention has to be paid to the effect of cross winds, as these can either clear the flight path of the aircraft of the rotorwake altogether or might keep one of the vortices near the axis of it. Allowance would have to be made for fluctuation of the wind direction.

Determining the Maximum Roll Moment a Following Aircraft Might Encounter

Assuming a following aircraft does fly into the wake, several parameters determine how great the effect will be. The most important parameters that determine the rolling moment induced by the wake vortices are (i) vortex strength and vortex core radius at the aircraft location, (ii) aircraft span, (iii) the root and tip chords (taper ratio) and (iv) the lift curve slope of the aircraft.

Depending on the core radius to span ratio the maximum rolling moment might occur when the vortex centre is located off the centreline of the aircraft. As the core radius of a helicopter wake is relatively large compared to the span of small aircraft, it is a safe assumption that the aircraft in the centre of the vortex is the worst case, (see Appendix B). Kurylowich (ref. 14, 1979) gives simple formulae for the rolling moment on an aircraft in the centre of a vortex.

These simple formula are conservative as they do not take into account 3-dimensional effects, which result in smaller effective angles of attack. Realistic evaluation of the roll

rate and angle requires a more sophisticated approach which incorporates the fact that the roll moment diminishes because of rolling (as it depends on the local angle of attack).

It might also be necessary to estimate the rolling moment induced by the horizontal velocities. Although this is done by Ferguson (ref. 33, 1991) for parked aircraft, his theoretical method is very simple (assuming a centre of the additional lift off the centre line at a seemingly random position). There could be a significant rolling moment from the wall jet effect if the induced horizontal velocities were different on the left and right side of the aircraft, creating a lift differential and hence an induced rolling moment. Attention might also have to be paid to the induced vertical acceleration due to the horizontal velocities to check that pitch control problems are not a severe hazard.

The Predictions of the Model

In this chapter it has been shown that the elements required for a mathematical model of the encounter of a fixed wing aircraft with a helicopter vortex are available. In Appendix B the equations are set out, and where possible compared with measured data or other methods, equations (1) to (9) define the model.

Figures 36 to 39 show some predictions derived from the equations, and also test measurements made when a light aircraft was flown in the wake of a helicopter (Ref. 34, Tymczyszyn, 1991). They show the predicted and measured bank angles induced in a following aircraft after one second of the vortex encounter, as a function of the separation time (Figures 36 and 37) or separation distance (Figures 38 and 39)

The predictions match the measurements well for induced bank angles above 30 degrees but less accurately with increasing time or distance.

It can be seen from figures 36 and 37 that the helicopter vortices are very strong compared to those induced by the B747. The data for a speeds of 10 and 15 m/s are the maximum possible disk-edge vortex strength, but the predictions are not conclusive, as no data are available to make comparisons. Indeed the decay may well be far stronger than predicted

In figures 38 and 39 it can be seen that the actual separation required for a given bank angle is much larger for a B747 than for both helicopters. This can be explained by the slow forward speed of the helicopter, as the separation distance is the distance the leading aircraft has travelled from the current position of the following aircraft, so the equation for separation distance as a function of separation time is:

$$\text{Distance} = V_F \cdot t$$

This means that when a helicopter is flying at 15m/sec. its trailing vortex is four times as old when a following aircraft encounters it as that of a B747 during an approach for the same separation distance.

The results of figure 39 are interesting in that the data agrees with that taken from ref. 34, at small separation distances since strong vortices occur at slow speeds. It also shows the phenomena Tymczyszyn (ref. 34, 1991) observed, that the wakes at lower

speeds were stronger at small separation distances, but decreased faster with increasing distance (as can be seen for the 10 m/s data in figure 39).

When the decay factor, derived in Appendix B.8 (see equations 7 - 9), is applied to the ground vortex, it can be seen in Figure 36 that its decay would theoretically be very slow compared to the disk-edge vortex, because the forward speed (V_F) is very low. Research is necessary to check the validity of the decay factor in the ground vortex case. In figure 38 it can be seen that because of the low forward speed the distance over which the ground vortex is a hazard is relatively small.

It has to be kept in mind that for figures 38 and 39 the data are for vortex ages of up to four minutes, while in many circumstances the vortex may be diffused far earlier. This is especially true for the case of the ground vortex, formed in ambient winds of up to 20 knots, where it seems improbable that the vortex exists for much longer than one or two minutes. This can be seen in Figure 28 for fixed wing aircraft wing tip vortices and both the presence of the ground and the nature of the ground vortex will probably decrease the lifespan even further. Further research is needed to confirm this.

Chapter 5. The Model Applied to the Accident at Kidlington

Using equations (1) to (9) of appendix B several aspects of the accident at Kidlington can now be evaluated. It has to be understood that the lack of precise data requires some estimation in order to reconstruct the accident.

First it is necessary to try to estimate the origin of the wake that induced the fatal rolling moment on the Cadet aircraft. It may not simply be the hover taxi phase, as the vortices (whether they are of the ground vortex or disk-edge vortex type) take a finite time to reach the threshold of the runway. The vortex propagation velocity is assumed to be identical to the wind velocity; very near the rotor the wall jet velocity might increase this for a short distance, but not for more than 20 to 30 m. (this is shown in appendix B: the velocity decreases sharply to negligible values within a few rotor diameters). The wind velocity at Kidlington was 8 knots or 4 m/s shortly after the crash, but in the information to the pilots by the AFISO it was stated that it was 13 knots or 6.5 m/s. This difference should be kept in mind, as it will later be shown to be very significant to the hover wake type it could have induced.

At these drift rates it means the wake, which had to travel the distance between the position of the hovering S-61 helicopter and the Piper Cadet (which was approximately 275 m), would take between 42 and 68 seconds to reach the aircraft, (see figure 41). This is not only a considerable time in terms of vortex decay (not impossible in calm weather), but also it would mean that the helicopter would have had to be hovering stationary for that period of time, as the helicopter had just left the runway when the accident happened. The commander of the helicopter stated that it took 30 seconds to manoeuvre to his location at the time of the crash. Assuming this time is taken from the point hover was established, it suggests that a hover induced wake could not have reached the PA-28 at the time of the accident, especially at a measured wind velocity of 4 m/s.

It may be possible that the vortex which interacted with the Cadet originated at an earlier phase in the flight, for instance during the flaring manoeuvre or even during the approach of the S-61, see fig. 41. For example if the wake originated a small distance before the hovering location it would have taken 35 to 45 seconds to reach the Cadet, while the S-61 could well have taken the same time to move to the hover and clear the runway. With the limited information available it is not possible to establish this with any certainty, but the non-hover wake vortex origin appears plausible. An assumption that the origin of the wake was pre-hover would make the prediction of the strength of the wake when it interacted with the Cadet, using the method developed here, much more plausible.

Since the horizontal wall jet velocities have been shown to be relatively small at distances of 200 to 300 m, it is improbable that anything other than a helicopter induced vortex could have caused the roll of the Cadet. Therefore, the values of the advance ratio (μ) or the normalised advance ratio (μ^*) would be expected to be such that, according to Figure 1, either a ground vortex or disk-edge vortex type would have had to have been induced. Otherwise the roll observed for the Cadet could not have been generated by the helicopter.

In hover with wind velocities of 4 to 6.5 m/s the μ and μ^* values in this case would have been:

$$\mu \approx \frac{4 \text{ to } 6.5}{190} = 0.02 \text{ to } 0.03$$

$$\mu^* \approx \frac{4 \text{ to } 6.5}{12} = 0.33 \text{ to } 0.54$$

When these values are overlaid on the graph of possible wake types (figure 1) with a relative rotor height (h/D) of (15ft total helicopter height +10ft wheel height during hover)/60ft rotor diameter, or 0.42, the wake would clearly have just been in the recirculation phase, according to Curtiss (ref. 17, 1982), or there may have been a small ground vortex according to Sheridan (ref. 11, 1977). If the vortex was induced earlier, the forward speed of the S-61 would have been added to the wind velocity, which would make a disk-edge vortex most likely, especially since the height above the ground would have been greater (100 feet above the threshold or 1.66 diameters, and approximately half that at the midway point indicated before). Although it would mean that there would have been little ground effect, at this relatively low forward speed the disk-edge vortices would have been very strong (as was shown in figure 36). If the fatal vortex was induced during the final flare-off phase of the flight, the maximum vortex strength would be reached.

If the wind fluctuation was such that, for a short time period, it reached a high enough velocity to generate a vortex in hover, the vortex may have drifted to the location of the aircraft in a shorter time span. Considering the calm atmosphere it seems unlikely that this was the case.

With the assumption that either a disk-edge or ground vortex was induced by the S-61 a theoretical estimate can be made of strength and decay for both cases.

Disk-edge Vortex Strength

The disk-edge vortex strength can be calculated using the data generated in appendix B (fig. 36), which is the bank angle after 1 second at different separation times for an encounter of the S-61 wake by a T-34C. (The results for a T-34C are similar to those for a PA-28, see figure 40, since the only difference is the smaller moment of inertia of the PA-28, and that has only a limited effect in the first tenths of a second, after which the roll rate is constant).

As stated in the previous section, if the wake that reached the aircraft was induced in the final phase of the helicopter flight, shortly before the hover was reached, the true airspeed for the helicopter would be between 10 and 20 m/s depending on location and wind velocity. At these speeds there would be very strong vortices induced in the wake and although their core radii would be relatively large, their life span would be sufficient to reach the aircraft. It can be seen from figure 36 that the upset bank angle in one second, without pilot intervention, for a separation of 40 seconds and a speed of

10~15 m/s would be approximately 180 degrees, inverting the aircraft. Witnesses stated that in a very short time the aircraft banked 90 degrees (according to the model that would have taken half a second). Considering that the model represents a worst case and that the aircraft was in contact with the ground soon after banking, the results from the theoretical model appear to be reasonable and, at the same time, support the idea of an encounter with a disk-edge vortex generated before the hover phase.

Ground Vortex Strength

The ground vortex could only have occurred if the wind velocity was greater than 4 m/s. Assuming this would have been the case, the maximum strength could have been 6 times the tip vortex strength at a true airspeed of 10 m/s, which, for an S-61, is given by equation 1, see Appendix B, with weight assumed to be 9000N, the rotor radius 9.5metres, the tip speed 200m/s and the number of blades 5:

$$\Gamma_{tip} = \frac{2 \cdot W}{\rho \cdot R \cdot V_{tip} \cdot b} = \frac{2 \cdot 90000}{1.225 \cdot 9.5 \cdot 200 \cdot 5} = 15 \text{ m}^2\text{s}^{-1}$$

The strength of the ground vortex is not larger than 6 times the tip vortex strength (see Figures 21 ,23 and Appendix B), so its greatest possible strength is given by:

$$\Gamma_{gv} = 6\Gamma_{tip} = 90 \text{ m}^2\text{s}^{-1}$$

In figure 36 it can be seen that the resulting roll angle with a separation time of 40 seconds, which was the minimum, is 70 degrees after 1 second. This is much lower than for the disk-edge vortex case and is below that indicated by eye witness reports.

Vortex Paths for Both Cases

If vortex initiation was before the hover, the height of the helicopter would have been marginally above the hover height, approximately 10 to 15 metres. Since the aircraft was at a height of 10 metres the wake could have intersected it.

If the helicopter was in hover taxi it would have been below the lowest altitude of the aircraft, but allowing for vortex up float once again intersection may have been possible.

It is difficult to calculate the lateral position of the vortices, but since the direction of the wind was directly from helicopter to the location of the aircraft at the time of the roll, the virtual lack of lateral movement of the disk-edge vortex (unless it is near the ground for a long time) makes intersection by the PA-28 very likely. The ground vortex spread was shown to be much greater, so unless there was a wind direction fluctuation it is not very likely that an encounter could have occurred in this case.

Conclusions on the Kidlington Accident

The accident could be accounted for using this theoretical method if it is assumed that the wake which was responsible for the sudden roll of the Cadet was induced before hover was reached. If, in contrast, the wake is assumed to have been induced during hover, intersection of the vortices with the PA-28 is shown to be possible but the severity of the roll could not be explained.

Chapter 6. Conclusions

The wake of helicopters flying out of ground effect is a potentially serious hazard to light aircraft, and helicopters hovering in ground effect can produce wakes that are equally dangerous. In an ambient wind the wake of a rotor in ground effect is skewed back. If the wind is light the wake will penetrate it and create a strong vortex that rolls up on the ground well outside the rotor diameter and for some distance behind the helicopter. If the wind is strong the wake is swept back clear of the ground and rolls up into disk edge vortices like the tip vortices behind a fixed wing aircraft. The last case is particularly dangerous since the strength of the vortices of heavier helicopters such as CH-53, CH-47 and S-61 can be close to those induced by wide body aircraft in landing as is indicated by both theoretical methods and also by measurements of a CH-54 wake. Since the strongest trailing vortices are induced during the transition to hover, this flight phase is the greatest hazard to light aircraft. In contrast to the wake induced vortices of fixed wing aircraft the vortices induced by helicopters, although strong, are generated at relatively low forward speeds and the hazard is therefore confined to a smaller area.

Wake avoidance is obviously the safest option, but it may not always be a practical one. Heavier helicopters should always be kept clear of active runways, making sure that the wake can not drift on to the runway by operating the helicopters downwind of active areas. If this is not practical, the aircraft should maintain the minimum separation distance specified for helicopters in flight, even if the helicopter is hover taxiing. Since this may result in an aircraft, as it is approaching the runway, getting closer to the helicopter than the minimum, a good estimate has to be made of the initial separation. This is the separation with the helicopter in forward flight, on approach to transition for hover on the runway. It is important to anticipate by how much the aircraft and helicopter will close during this manoeuvre, since clearly their relative flight speeds will be constantly changing. An additional separation should be allowed to cater for the time during which the helicopter is stationary in hover.

Aircraft that operate above a hovering helicopter are normally clear of any wake hazard, with two possible exceptions. The first is the possibility that the helicopter is following a descending flightpath and is trailing a wake at a higher altitude, this can be particularly persistent in calm weather. Helicopter vortices have been observed to persist for four minutes. As with heavy fixed-wing aircraft, this is perhaps the greatest threat to light aircraft particularly when operating close to the ground. The second exception is the possibility of vortex up float, ie. vortices that are induced by a hovering helicopter may not follow the expected path to the ground, but will rebound because of viscous effects. Up float will be worst when the helicopter is close to the ground. Although it is not extensively researched, there are indications that the upfloat results in the vortex levelling off at one and a half times the hover height at most, the danger is therefore not nearly as high as in the descending flight path case. It does however deserve attention, as there are indications that there may also be a buoyancy effect due to the hot engine exhaust in the wake.

It is considered that the best way of investigating the wake hazard is to analyse it in various segments. These are (i) determination of the wake form, (ii) calculation of the

vortex strength and core radius, (iii) the magnitude of the wall jet velocity, (iv) the vortex decay rate, (v) the possible paths of the vortex and (vi) the roll rate of an aircraft induced by the vortex and wall jet.

Determination of the wake shape is qualitatively quite well understood, but there is very little consistency in the experimental measurements of transition velocity between different wake types. The reason for this may be that all the data are from wind tunnel tests at different scales and in one case with a simulated atmospheric boundary layer. However, it is possible to give estimates for the wind speeds for a typical hover taxi height that cause the different wake types. At wind speeds above 5 to 10 knots the ground vortex is gradually formed and reaches its peak strength at approximately 20 knots. At a wind speed between 22 and 30 knots the disk-edge vortex is formed, which is very strong at those low speeds, but probably decays very rapidly, especially as the turbulence in such a strong ambient wind will shorten the lifetime of the vortex significantly.

There are few measured data relating to the strength of ground vortices, but in three reports a calculation method and computer program are presented. However, no atmospheric boundary layer is included, and this should ideally be incorporated.

There is ample information relating to the wall jet in hover, but little on the horizontal velocities in the wake at medium advance ratio. It does appear from the available data that, at the separation distances this investigation is concerned with, the wall jet velocities are negligible.

The decay of a vortex as well as its path in ground effect are quite well described in the literature. This includes the increase in altitude of the vortices after reaching the ground. Although primarily focused on fixed wing aircraft, some of the data are applicable to helicopter vortices. It is probable that the cores of helicopter vortices are larger than those of fixed-wing tip vortices, but only one source gives this information together with an empirical formula for estimating the strength. When compared with actual measurements, it is shown that the true decay rate is greater than predicted by the methods currently available, so more research has to be done to find the correct decay equations for helicopters.

The induced rolling moment on an aircraft is well documented in the literature and a conservative estimate of the upset bank angle following wake penetration can be made by analytical means. The theoretical approach presented here assumes that the pilot does not react, so it is valid for a short interval only. It is primarily intended as a tool for comparison of the helicopter hazard with the more well-known fixed-wing aircraft hazard.

A calculation method, based on the existing literature, is presented in Appendix B. This gives reasonable estimates of the roll angle for an aircraft penetrating the wake, in principle making it possible to estimate separation minima. More testing is needed for validation and possibly improvement of some of the less well researched areas of this method, such as the wake-type occurrence and the decay rate. A recommended test programme is described in chapter 3.

Results from the roll angle prediction model are shown to be reasonable for small separations when compared to the flight tests as performed by Tymczyszyn (ref. 34, 1991), which were out of ground effect. It is not directly useful for the determination of separation minima in its current form since an overestimate of the vortex strength results in the predicted roll angles reducing with time too slowly. A circulation decay factor, suggested by Kurylowich (ref. 22, 1979), may solve this problem, as is shown with an altered factor for helicopters, but more research is needed to determine a more suitable value for helicopter wakes. A comparison with situations in ground effect is not possible, as no data are available.

When the model is used for a reconstruction of the accident at Kidlington, it appears initially that there is a difference between the predicted and observed aircraft roll rates. The wind does not appear to be strong enough to induce either a ground vortex or a disk-edge vortex for a helicopter in hover. Even if it is assumed that the actual wind was marginally stronger than measured directly after the accident, it can be shown that the ground vortex might have induced a roll rate on the Cadet aircraft, but still not as rapid as that observed by witnesses.

It is shown to be possible, considering wind speed and the time required for the helicopter wake to reach the aircraft, for the Cadet to have penetrated the wake that was induced a short while before the helicopter initiated hover. This would explain the strength of the wake, as the helicopter would have enough forward speed to induce the very strong disk-edge vortices. In addition to this, the shorter decay time would cause a less decayed vortex which poses an even greater hazard.

If the theoretical model is applied to the above condition, the roll angle after one second is of the same order as described by witnesses. This would support the possibility that the wake of the helicopter that caused the sudden roll was induced in the latter stages of the approach, rather than in hover.

Chapter 7. Recommendations for Further Research

The theoretical techniques adopted for the calculation of vortex strength and vortex core radii are not yet validated with measurements from full scale or wind tunnel tests. It is important that such a validation be made before any attempt to refine the theoretical model is considered. In this chapter the techniques best suited to fill this gap in current knowledge are reviewed.

Research relating to the Occurrence of Various Wake Types and Vortex Measurements

Although some measurements are available that relate the transition from one type of wake to another with the advance ratio, they are inconclusive. The results are highly scattered and in order to be conservative the type of wake with the strongest vortex has to be used when evaluating separation minima. This may lead to requirements that are too conservative. It would therefore be beneficial to both the theoretical knowledge and practical operations to carry out further research in the area.

Wake formation and vortex development are sensitive to viscous effects, so it is preferable to carry out tests at full scale. The location of the wake vortices can be found using smoke flow visualisation and as the helicopter height would be between 0.4 and 2 rotor diameters, measurements of the vortex strength and core radius at varying distances from the rotor (for vortex decay determination) could be made with the measurement techniques described in reference 15. A possible limitation would be in obtaining and accurately monitoring the required test conditions. Perhaps the greatest disadvantage is the cost, especially as the timescales involved in waiting for the required range of meteorological conditions may be excessive.

Wind tunnel tests have the advantage of offering controllable test conditions, they are relatively inexpensive compared with full scale tests and can be well suited to ground effect research (as opposed to research of out of ground effect). The disadvantage of scale model wind tunnel tests is the difficulty in matching all the scaling parameters, particularly those involving the atmospheric boundary layer. This means that it is hard to assess if the values of the data extrapolate to full scale situations. Measurements relating to vortex core size and decay are susceptible to scaling problems since they are clearly determined by viscous effects and often they are invalidated by wind tunnel wall interference since few experimental facilities are large enough and have long enough test sections to allow even the model scale wake to develop without constraint. The wind tunnel section must be wide enough to allow the full lateral development of the ground vortex. Providing careful consideration is given to the above factors valuable data can be gained from wind tunnel test programmes.

Research on Vortex Paths

The paths followed by the vortices have been reasonably well researched in model tests but as far as the determination of separation minima is concerned, there is a practical limit to the use of this data since the exact paths are subject to external influences such as wind fluctuations. As viscous and wind tunnel wall interference effects are relatively important to the prediction of vortex paths, further wind tunnel research would have to be planned very carefully. If however full scale tests with flow visualisation were possible it would be relatively straightforward to include an assessment of the vortex paths in the test programme and further enhance current understanding.

Research of Induced Horizontal Velocities

In order to check the assumption that the induced horizontal flow can be neglected at the estimated safe separation minima, measurements of the velocity behind the rotor in the wind direction should be made; this should be equal to the freestream wind speed at some distance behind the rotor. The helicopter would have to hover at the lowest possible height, at a range of ambient wind speeds, in order to investigate the greatest velocities induced in the wake.

Summary of Recommended Further Research

It is recommended therefore that more research should be carried out in relation to both the transition of the different wake forms and the strengths and core sizes of the vortices. The investigation should ideally include the effects of the atmospheric boundary layer and correct viscosity values. It would therefore be most accurate at full-scale.

Horizontal induced velocities in the wake, with an ambient wind, should also be investigated, with an emphasis on the lateral differences as these would have a significant effect on predictions of induced rolling moment. A recording of the path of the vortices would also be valuable. Wind tunnel research is an alternative, less expensive, testing method and for the purpose of this investigation it might still be acceptable.

References

1. **H.H. HEYSON**
Ground Effect for Lifting Rotors in Forward Flight
NASA TN D-234, 1959
2. **A.B. CONNOR and T.C. O'BRYAN**
A brief evaluation of helicopter wake as a potential operational hazard to aircraft
NASA TN D-1227, 1962
3. **H.H. HEYSON**
Linearised Theory of Wind Tunnel Jet-Boundary Corrections and Ground Effect for V/STOL Aircraft
NASA TR R-124, 1962
4. **F.A. DUWALDT**
Wakes of lifting propellers (rotors) in ground effect
CAL BB-1665-S-3, 1966
5. **W.H. RAE**
Limits on Minimum-Speed V/STOL Wind Tunnel Tests
Journal of Aircraft, May-June 1967
6. **J.T. WAREING**
Consideration of V/STOL downwash and the ground environment
SAE PAPER 680282, 1968
7. **E.S. LEVINSKY and T. STRAND**
A method for calculating helicopter vortex paths and wake velocities (final report)
F33615-69-c-1101, July 1970
8. **H.H. HEYSON**
Theoretical Study of Conditions Limiting V/STOL Testing in Wind Tunnel with Solid Floors
NASA TN D-5819, 1970
9. **G.W. LEESE and J.T. KNIGHT**
Helicopter downwash data
AEWES-MISC-PAPER-S-74-17, 1974
10. **A.J. LANDGREBE and B.V. JOHNSON**
Measurement of Model Helicopter Rotor Flow Velocities with a Laser Doppler Velocimeter
Journal of the AHS, July 1974

11. **P.F. SHERIDAN and W.WIESNER**
Aerodynamics of Helicopter Flight Near the Ground
Pre-print No. 77.3-04, AHS Forum 1977
12. **N.J. COOK**
Determination of the Model Scale Factor in Wind Tunnel Simulations of the Adiabatic Atmospheric Boundary Layer
Journal of Industrial Aerodynamics, 2 (1978) 311-321
13. **N.J. COOK**
Wind Tunnel Simulation of the Adiabatic Atmospheric Boundary Layer by Roughness, Barrier and Mixing Device Methods
Journal of Industrial Aerodynamics, 3 (1978) 157-176
14. **G. KURYLOWICH**
A method for assessing the impact of wake vortices of USAF operations / Final report
AFFDL-TR-79-3060, 1979
15. **T. SULLIVAN, J.N. HALLOCK, B. WINSTON, I. MCWILLIAMS and D. BURNHAM**
Aircraft wake vortex takeoff tests at Toronto International Airport
FAA-RD-78-143, 1979
16. **H.H. HEYSON**
Operational Implications of some NACA/NASA Rotary Wing Induced Velocity Studies
NASA TM-80232, 1980
17. **H.C. CURTISS, W.F. PUTMAN and E.J. HANKER**
Rotor Aerodynamics in Ground Effect at Low Advance Ratio
Princeton University Report No.1571-MAE, 1982
18. **M. SUN**
A Study of Helicopter Rotor Aerodynamics in Ground Effect at Low Speeds
Princeton University, 1983
19. **T.A. EGOLF and A.J. LANDGREBE**
Helicopter Rotor Wake Geometry and its Influence in Forward Flight
NASA CR-3726, 1983
20. **E.J. HANKER and R.P. SMITH**
Parameters Affecting Helicopter Interactional Aerodynamics in Ground Effect
Proceedings of the 39th Annual Forum of the AHS, May 1983

21. **E.A. BOYD and I. KUSMARWANTO**
Ground Effect on a Rotor Wake
C of A Report 8323, 1983

22. **I. KUSMARWANTO**
Ground Effect on a Rotor Wake
C of A Thesis, 1985

23. **J.N. HALLOCK**
Rotorcraft wakes - an annotated bibliography
FA-427-PM-84, 1986

24. **C. HE and Z. GAO**
A study of the rotor wake in nap-of-the-earth
Chinese Journal of Aeronautics, vol. 1, July 1988

25. **R.M. WEISS, J.G. MORROW, D. GALLAGHER, M. DIMEO AND S. ERLISHMAN**
Analysis of Heliport Environmental Data: Indianapolis Heliport, Wall Street Heliport
DOT/FAA/CT-TN87/54, 1989

Vol. 1 Summary (NTIS: ADA 206 708)
Vol. 2 Wall Street Heliport Data Plots(NTIS: ADA 212 312)
Vol. 3 Indianapolis Downtown Heliport Data Plots (Not available from NTIS)

26. **P. DHAR**
A comparative study of a rotor wake in ground effect under simulated wind tunnel conditions and during field trials
C of A Thesis, 1989

27. **V.R. STEWART**
Characteristics of the ground vortex formed by a jet moving over a fixed ground plane
AIAA-89/0650, 1989

28. **J.D. SINGLETON, W.T. YEAGER and M.L. WILBUR**
Performance data from a wind tunnel test of two main-rotor blade designs for a utility-class helicopter
NASA TM 4183, 1990

29. **R.M. WEISS**
Analysis of Heliport Environmental Data: Intracoastal City
DOT/FAA/CT-TN89/43, 1990

30. **S.W. FERGUSON**
Evaluation of rotorwash characteristics for tiltrotor and tiltwing aircraft
in hovering flight; final report
DOT/FAA/RD-90/16, 1990
31. **J.B. CRITCHLEY and P.B. FOOT**
United kingdom civil aviation authority wake vortex database: analysis of
incidents reported between 1982 and 1990
CAA PAPER 91015, 1991
32. **S.W. FERGUSON and J.D. KOCUREK**
Rotorwash computer model (user's guide)
DOT/FAA/RD-90/25, 1991
33. **S.W. FERGUSON**
Analysis of rotorwash effects in helicopter mishaps (Final report)
DOT/FAA/RD-90/17, 1991
34. **J.J. TYMCZYSZYN, K.J. BIEHL and S.A. TEAGER**
Flight test investigation of the wake vortices generated by rotorcraft
Paper 13 of the Proceedings of the aircraft wake vortices conference
DOT/FAA/SD-92/1.1, 1991
35. **D.T. HOURGIAN, C.W.SUTTON, F.J.BIRD**
Instrumentation for airwake measurements on an FFG-7
Flight Tech. Memo 450 ARL Melbourne, 1991
36. **Z. ZHENG and R.L. ASH**
Viscous effects on a vortex wake in ground effect; Final report
NASA-CR-190400, 1992
37. **AIR ACCIDENTS INVESTIGATION BRANCH**
Report on the accident to Piper PA-28-161 Cadet, G-BPJT at Oxford
Airport, Kidlington on 12 July 1992
Aircraft Accident Investigation Branch Report 1/93 (EW/C92/7/2), 1993
38. **ESDU Data Sheet No 82026**

Bibliography

1. **H.B. SQUIRE**
The growth of a vortex in turbulent flow
ARC-16666, 1954
2. **I.C. CHEESEMAM and W.E. BENNET**
The effect of the ground on a helicopter rotor in forward flight
ARC R & M 3021, 1957
3. **J.L. MCLOUD**
Wind Tunnel Tests of a Full Scale Helicopter Rotor with Symmetrical and with Cambered Blade Sections at Advance Ratios from 0.3 to 0.4
NACA TN 4367, 1958
4. **H.H. HEYSON**
A Note on the Mean Value of Induced Velocity for a Helicopter Rotor
NASA TN D-240, 1960
5. **H.H. HEYSON**
Equations for the Induced Velocities near a Lifting Rotor with Nonuniform Azimuthwise Vorticity Distribution
NASA TN D-394, 1960
6. **R.B. GRAY**
Experimental Smoke and Electromagnetic Analog Study of Induced Flow Field about a Model Rotor in Steady Flight within Ground Effect
NASA TN D-458, 1960
7. **H.H. HEYSON**
Tables of interference factors for use in wind-tunnel and ground-effect calculations for VTOL-STOL aircraft: part 1- wind tunnels having width-height ratio of 2.0
NASA TN D-933, 1962
8. **H.H. HEYSON**
Tables of interference factors for use in wind-tunnel and ground-effect calculations for VTOL-STOL aircraft: part 2- wind tunnels having width-height ratio of 1.5
NASA TN D-934, 1962
9. **H.H. HEYSON**
Tables of interference factors for use in wind-tunnel and ground-effect calculations for VTOL-STOL aircraft: part 3- wind tunnels having width-height ratio of 1.0
NASA TN D-935, 1962

- 10. H.H. HEYSON**
Tables of interference factors for use in wind-tunnel and ground-effect calculations for VTOL-STOL aircraft: part 4- wind tunnels having width-height ratio of 0.5
NASA TN D-936, 1962
- 11. I.A. SIMONS**
Blade vortex interactions on helicopter rotors in forward flight
Southampton University Memorandum ISAV 126, 1965
- 12. D.S. DOUGLAS, M. GEORGE and E. KISIELOWSKI**
Investigation of the downwash environment generated by V/STOL aircraft operating in ground effect
USAAVLABS-TR-68-52, 1968
- 13. L.F. EAST**
The Measurement of Ground Effect using a Fixed Ground Board in a Wind Tunnel
A.R.C. Report R & M No.3689, 1970
- 14. J.L. TANGLER, R.M. WOHFIELD and S.J. MILEY**
An Experimental Investigation of Vortex Stability, Tip Shapes, Compressibility and Noise for Hovering Model Rotors
NASA CR-2305, 1973
- 15. P.F. SHERIDAN and R.P. SMITH**
Interactional Aerodynamics- A New Challenge to Helicopter Technology
35th Annual Forum, AHS, Washington D.C., May 1973
- 16. F.H. SCHMITZ and C.R. VAUSE**
Near Optimal Take Off Policy for Heavily Loaded Helicopters Exiting from Confined Areas
Journal of Aircraft, May 1976
- 17. H.H. HEYSON**
Theoretical Study of the Effect of Ground Proximity on the Induced Efficiency of Helicopter Rotors
NASA TM-X-71951, 1977
- 18. K.P. REDDY**
Calculations of the Aerodynamic Flow Field in the Vicinity of a Sea King Helicopter
ARL-AERO-REPORT-158, 1983
- 19. R.J. ADAMS, E.D. MCCONKEY, L.D. DZAMBA and R.D. SMITH**
Analysis of helicopter accident risk exposure near heliports, airports, and unimproved sites
DOT/FAA/RD-90/9, 1992

20. W.O. MILLER and D.B. BLISS

Direct periodic solutions of rotor free wake calculations

Journal of the American Helicopter Society, volume 38 nr 2, April 1993

Table 1: Literature of particular use for the theoretical modelling of the several segments

Useful literature	Shape of wake	Strength of ground vortex	Strength of disk-edge vortex	Wall jet velocity	Decay of vortex	Path of vortex	Moment on aircraft
Curtiss (ref. 17, 1982)							
Sheridan (ref. 11, 1977)							
Hanker (ref. 20, 1983)							
Dhar (ref. 26, 1989)							
Sun (ref. 18, 1983)							
Ferguson (ref. 32, 1991)							
Levinsky (ref. 7, 1970)							
He (ref. 24, 1988)							
Zheng (ref. 36, 1992)							
Ferguson (ref. 33, 1991)							
Kurylowich (ref. 14, 1979)							

 = Theoretical model

 = Graph or measured values for direct use in the theoretical model

Appendix A: Abstracts of the Literature on Helicopter Wakes

A breakdown of the most relevant theoretical modelling literature is given in table 1. for convenience.

A.1 Literature Relating to Theoretical Modelling

There is a considerable volume of literature available that deals with the modelling of rotor wakes using lifting line theory which is based on the representation of lifting wings, or rotors, by vortices creating lift as well as trailing vorticity, making it possible to calculate the induced velocities in the wake. Some of these methods include the wake in ground effect by mirroring the vortex system, a technique that is explained in chapter 4. The following reference list is confined to the category including ground effect. Initially a list of references is given, which are considered directly useful to the investigation. The bibliography that follows is primarily valuable for gaining background knowledge on the general subject.

References

S.W. FERGUSON (ref. 32, 1991)

This report details a computer program called **ROTWASH** that calculates the rotor wash as well as the hazard it presents to people standing in it. The mathematical model used is of relatively simple nature to get reasonably accurate results in a short time. This approach was chosen because the problem with more complex and accurate computer models is that it takes a long time using large computers to get the results that are required. The relative cost means that often it is not possible to look at many different configurations in a limited time span.

The output from ROTWASH can be in the form of either tabulated or graphical data. There are several modes of program operation available. The first is a wall jet option, giving the mean and highest rotor wake velocities in hover in ground effect at a chosen radial station at various heights. An ambient wind velocity can also be included if desired. With these data the overturning force and moment on a man in a given station can be found as an option. Another option is the ground vortex calculation, giving the strength of the ground vortex, as well as the position of its core. Finally there is a disk-edge vortex option, which estimates the circulation and downwash settling angle at a given location.

The ROTWASH program does not take into account the velocity profile of the atmospheric boundary layer which can be represented theoretically by a number of vortices with the same direction as the ground vortex. It is to be expected that the atmospheric boundary layer increases the strength of the ground vortex when compared to values of ground vortices that originated in a uniform parallel flow. As

Ferguson states, there has been very little research into the ground vortex and the results of the calculations have to be used with care. The program does not take into account the exact rotor parameters (chord, blade section, tip form, twist), although this might be justifiable as the effects of these are probably not very significant at a distance. The interaction of other aircraft with the wake is not specifically considered.

S.W. FERGUSON (REF. 30, 1990)

In this report the **ROTWASH** program is used to evaluate the rotorwash of tiltrotor and tiltwing aircraft (because they produce an even stronger wake than helicopters as the disc loading is quite high). Since it is an application of the ROTWASH program on a type of aircraft that is not operational yet the results are of limited use for this investigation.

S.W. FERGUSON (ref. 33, 1991)

In this report the **ROTWASH** program is used to analyse helicopter mishaps. These include accidents involving oil drums, ground vehicles, personnel, other parked rotorcraft and parked aircraft. The most relevant are the calculations concerning overturning light aircraft on the ground and in the air (but at low flight levels). Very basic equations are used for determining the induced rolling moment as a result of the horizontal velocities creating an asymmetrical lift, overturning parked aircraft. It is a very basic method, only usable for parked and taxiing aircraft as the moment of the wheels is used as a countering moment for the induced rolling moment. One accident with a flying aircraft was reported, but there are few details known, and the aircraft was said to be upwind from the helicopter, which makes it difficult for Ferguson to explain, let alone calculate the cause of the accident.

C. HE (ref. 24, 1988)

In this journal article a calculation method is derived for the strength and longitudinal position of the ground vortex in front of the rotor. Comparisons are made with observations by Curtiss (ref. 17, 1982) and Sun (ref. 18, 1983) in wind tunnel tests and there is good agreement in the location, height and longitudinal position of the vortex core. The strength calculation results behaved according to the qualitative observations made, although this is not a numerical comparison. The method is based on the equilibrium of the accumulation of free single blade tip vortices in the ground vortex, while at the same time vorticity is dissipated from the ground vortex to the surrounding air.

Because nap-of-the-earth flight is investigated no ambient wind is incorporated in the model, which might lead to an underestimation of the ground vortex. The calculated values of the strength can not be compared with measured data because of the lack of those in either full scale or wind tunnel research. The strength of the vortex is only

given in front of the rotor, so the strength far behind the rotor would have to be derived by using equations governing the decay of vortices.

M. SUN (ref. 18, 1983)

This PhD thesis incorporates further research on the same subject as in the report by Curtiss (ref. 17, 1982), of which Sun was one of the co-authors, as described in the next paragraph. A calculation method is included for the ground vortex, the result of which is given in figure 21. This is the same figure as used by Ferguson (ref. 32, 1991) in the ROTWASH program. Also in the thesis are wind tunnel measurements of the location of the ground vortex, however no measurements were made of its strength. The author also describes the shear layer which is formed as the wall jet streams along the ground, as is shown in figure 17. As the sense of this shear is opposite to that of both the ground vortex and the atmospheric boundary layer, the effect of the latter might be cancelled out or at least diminished. The cause of the up float phenomenon, described by Zheng (ref 36, 1992), is also discussed. It is assumed to be due to the induction of a small, contra-rotating secondary vortex, outboard of the wake centreline and slightly under the main vortex as shown in figure 12.

E.S. LEVINSKY (ref. 7, 1970)

In this report a theoretical method is presented to determine the vortex paths and wake velocities, using lifting line theory. Formulas are also given for the decay of the vortices. The ground vortex is included for the rotor in ground effect case. The author states that there is a good correlation with available measurements, but more measurements are needed to completely validate the calculation method, which is used to develop a FORTRAN computer program, **HELIWAKE** (not included in the report). The presence of wind is included in the calculations. An important conclusion is that the vortices will float upwards if the helicopter gets closer to the ground. According to the author this effect is caused by self-induction of the trailing vortices. In the results of the calculations this upfloat was apparent when the bound vortex was below a certain height.

Z. ZHENG (ref. 36, 1992)

This report describes a program for calculating the position of the free wake vortex at any distance behind an aircraft wing when the vortex is generated near the ground. The decay of the vortex is also calculated. An important result of the calculations is that a vortex, as it reaches the ground, due to viscous effects, generates a second vortex between the ground and the main vortex itself, slightly on the outside, rotating in the opposite direction (see figure 12). This new vortex pushes the original upward and outward from the centreline. At a distance the free wake vortex becomes higher in altitude than its original position. This may explain how in the accident with the Cadet (ref. 37) the aircraft could have encountered the vortex at a greater altitude than that at which the helicopter was hovering.

Because the report is on aircraft wakes the ground vortex or disk-edge vortex will have to be derived from other sources or tests, but when a value of that vortex is found in a position near the rotor it might be possible to predict the path and strength at greater distances using the method given in this report.

H.H. HEYSON (ref. 8, 1970)

In this report a comparison is made with a theoretical calculation of the wake of a rotor in free air, in ground effect, in a closed tunnel as well as in a closed-on-bottom-only tunnel. Extensive visualisation of flow vectors for different sections and situations is included (see figure 18 for example), some of which are wind tunnel test data but the majority are the results of the theoretical calculations. Heyson shows that the limits set by **Rae** (see below) do not apply to wind tunnel tests involving ground effect (regarding minimal advance ratios to avoid wall interference). This is because the wall interference is almost identical to the ground effect, with the same ground vortex.

The calculations do not include the atmospheric boundary layer and the results might therefore underestimate the true ground vortex. As a theoretical model it might be possible to amend it, but the **ROTWASH** program is probably a better basis as it relates directly to the ground vortex and induced hazards.

W.H. RAE (ref. 5, 1967)

This article gives limits for the size of the test rotor compared to the size of the wind tunnel. It also shows that there exist minimum acceptable values for the advance ratio. This is because otherwise the rotorwash skew angle will become too small (near-vertical) and the wall interference will be too large. The last part is less important for the ground effect situation, as Heyson showed, so this report is not that relevant to the ground effect research. Information relating to the maximum permissible size of the rotor is however important for wind tunnel tests.

J.B. CRITCHLEY (REF. 31, 1991)

In this paper incidents involving wake vortices of aircraft are reviewed. Although primarily aircraft wakes are considered the report contains observations on vortices and the danger they are to other aircraft that are also relevant to the helicopter-aircraft situation. It is concluded that the decay of vortices is slow in calm atmospheric circumstances and that decaying can be through core bursting, which is a very swift decay, or through core merging, as the cores get larger in time. This is a slow decaying process occurring mainly in calm days.

G. KURYLOWICH (ref. 14, 1979)

In this report hazards from wakes and vortices of both aircraft and helicopters are investigated for improving safety in USAF operations. Formulas for the rolling moment on an aircraft flying in a vortex with a viscous core are deduced. A simple, but adequate method for estimating the strength of helicopter wake vortices and their decay rate is also described, although mainly out of ground effect. As it is aimed at operations of the USAF, it is concluded that large cargo aircraft are not the only source of dangerous wakes, but also an aircraft of equal weight as the following one, especially when manoeuvring at higher load factors. Another observation relevant to the helicopter-aircraft case is the dangerous speed difference, that makes a separation diminish very quickly (during the approach a certain separation between helicopter and aircraft can be maintained, but as the helicopter slows down to start the hover-taxi the aircraft will close in at a high rate, while the helicopter is still producing a strong wake). Also discussed is the effect of wind on the decay or removal of vortices.

F.A. DUWALDT (ref. 4, 1966)

This report uses lifting line theory and a FORTRAN computer program to calculate the wakes of rotors in ground effect and in an ambient wind, although the effect of the atmospheric boundary layer is not included. Therefore the ground vortex might again be underestimated.

ESDU Data Sheet No 82026 (ref. 38)

If a model of the atmospheric boundary layer is to be added to a computer model, this is a good reference for information on that subject.

H.H. HEYSON (ref. 16, 1980)

This is a memorandum in which the operational implications of the results of NASA research on helicopters are presented. Of particular interest are the comparisons of the wake of helicopters with that of a Boeing 747-200F, which shows that the downwash velocity at very low advance ratios of heavy helicopters like the CH-47 or the CH-53 is larger than that of the B747 at landing speeds. This shows helicopter wakes are relatively very strong. The hazard for light aircraft is mentioned in general terms, but no values are given. Some illustrations show the horse-shoe ground vortex and the velocity profile in ground effect. This report is quite useful as a general overview of the wake interaction problem.

T.A. EGOLF (ref. 19, 1983)

In this report an analytical investigation is described on the wake of a rotor in forward flight, first using the classical undistorted wake model and then with a new generalised wake model. Ground effect is not included, but the report is very useful in describing the analytical model used. Charts with wake geometries for several advance ratios and thrust coefficients are given in volume II (NASA CR 3727).

H.H. HEYSON (ref. 1, 1959)

This report deals with the influence of ground proximity on the power required by the rotor. Shown is that ground effect benefits decreases rapidly with increasing speed. Also shown is that, at a forward speed of approximately 1.5 times the mean induced velocity in the rotor, the ground effect has all but disappeared. This means that the induced velocity and the power required are initially increased when accelerating forward in ground effect, instead of the expected decrease. There is little information on the wake velocities. It also means that at that speed the disk-edge vortex would be as strong as the out of ground effect value, easing calculation as much more is known about that condition.

Bibliography

I.C. CHEESEMAN (bibl. 2, 1957)

This is a report in which the influence of ground effect on helicopter performance is estimated and measured in flight tests. As the form of the wake is not discussed in detail, it is of limited value to this study.

H.H. HEYSON (bibl. 4, 1960)

This note shows that momentum and vortex theories for calculating rotor characteristics yield the same results. Caution is needed when using the vortex theory, because when a sine variation of the blade circulation is used the axial wake vorticity has to be included to get the correct results.

I.A. SIMONS (bibl. 11, 1965)

This memorandum is on the calculation of induced velocities from the tip trailing vortices, using the Biot-Savart law. The model is used only for loads on rotor blades and therefore the situation further from the rotor is not discussed.

D.S. DOUGLAS (bibl. 12, 1968)

Although primarily a report on particle cloud induction and the limits on visibility that result, a simple method is given for the calculation of the wall jet velocity. This only applies to hovering flight with no wind, so its use is limited. The report mainly investigates tiltrotor and tiltwing aircraft.

F.H. SCHMITZ (bibl. 16, 1976)

This report deals with a take-off method that can be adopted to gain height more effectively than with the conventional method of ascending immediately after take off. Although ground effect is involved in the report, it is primarily mentioned for its effect on the helicopter as less power is required in ground effect.

H.H. HEYSON (bibl. 17, 1977)

In this report a calculation method is used to show what the effect of ground proximity is on the power required by a rotor to hover. Using vortex cylinders for hover and doublets for forward flight the wake is simplified. The ground vortex is mentioned, but not very extensively researched.

K.P. REDDY (bibl. 18, 1983)

This is a report on modelling of the wake of the Sea King helicopter, with the fuselage presence included as a finite element model, using numerical calculations. The presence of the fuselage, however, has only a limited effect on the wake in close proximity and is has negligible effect at the distances that are investigated for hazard evaluation. Ground effect and ground vortex, as well as the wake at greater distances, are not included in the report.

A.2 Literature Relating to Wind Tunnel Testing

Wind tunnel testing is an important technique in aerodynamic research, although relatively more difficult for helicopter investigations. There is considerable literature available on this subject, only that involving rotor wakes in ground effect is considered here.

References

I. KUSMARWANTO (ref. 22, 1985)

This PhD thesis deals with wind tunnel research on a rotor model above a ground board. The flow is visualised with both smoke filaments and a tuft-grid, which show the ground vortex quite well. It also features results from the measurements of direction and magnitude of the downwash using a hot wire probe. This gives a good representation of the wake and vortices in ground effect. There are measured values of the position and the strength of the ground vortex, although the author states that these are approximate.

The limitations, as far as the current study is concerned, are due to the programme being concerned primarily with the nap-of-the-earth regime, which means that the helicopter is simulated flying forwards. Therefore a ground board is used to make the wind tunnel floor boundary layer near the ground as thin as possible, which is the opposite of an atmospheric boundary layer. This means that the ground vortex might be less pronounced than in the hovering situation with an ambient wind. Another limitation is that the rotor has no cyclic pitch built in, so the wake is asymmetrical. A tail rotor, which may play a role in the hazard, was not modelled. The thrust coefficient, which is important for comparisons with full scale situations, is only determined for one pitch setting. The results from the measurements are displayed in sketches, which makes it difficult to determine the magnitude of the velocities in the wake.

E.A. BOYD (ref. 21, 1985)

This is a preliminary report giving results from the same research as the above, so it does not add to the knowledge gained from the thesis.

P. DHAR (ref. 27, 1989)

This reports on research involving wind tunnel tests of a rotor in ground effect without a ground board. These are compared with results from field trials at low to medium advance ratios. In the wind tunnel attempts were made to create a boundary layer near the ground, so in this respect this report is more useful. Recirculation, ground vortex and disk-edge vortex regimes were observed, but at different advance ratios than found

in measurements by Curtiss (ref. 17, 1982). The author presumes the atmospheric boundary layer causes the difference.

Although a ground plane boundary layer was modelled, it was small compared to the real atmospheric boundary layer. The scaling was 1/100th while the rotor was scaled 1/25th. Since the atmospheric boundary layer is more or less constant (with the same surface roughness), it is more difficult to do wind tunnel tests for small helicopters than for large ones, as the size of the layer is relatively larger for small helicopters. Again, no cyclic pitch was incorporated, which distorts the wake a little.

J.D. SINGLETON (ref. 28, 1990)

In this memorandum wind tunnel tests with 1/6-scale rotors are described. The baseline rotor is that used by the UH-60A and the other a very advanced rotor design. A dynamically scaled rotor is also tested, as well as one that is not. Unfortunately, no analysis of the results is included, but it does give a good description of the wind tunnel tests. As both air and a refrigerant medium, R-12 are used. When using R-12 greater Reynolds numbers can be reached and the tip Mach number of the model is closer to the full-scale value, which is more important at the higher advance ratios than those of interest for this study.

H.C. CURTISS (ref. 17, 1982)

In this report a description is given of a series of dynamic tests with a model rotor, which is moved over the ground on a rail to simulate a rotor in ground effect at low advance ratios. This technique was used to avoid a boundary layer near the ground, which is undesirable for the nap-of-the-earth flight regime research. Accelerating and decelerating runs were included. It is shown that three areas exist in the speed-height diagram: at very low advance ratios a recirculation occurs, at intermediate advance ratios the horse-shoe ground vortex appears and at higher advance ratios the whole wake is blown back and the wake starts to look like the one a fixed wing induces. It is also shown that in acceleration the forces, power and wake differ from those during deceleration at the same advance ratio (hysteresis).

P.F. SHERIDAN (ref. 11, 1977)

This paper gives results from wind tunnel tests of a scale model of the YUH-61 in ground effect. It includes good visualisation of the occurrence of the ground vortex which is shown to occur for a relative speed or wind velocity from approximately 10 to 30 Knots or at advance ratios of 0.023 to 0.068. With higher speed the ground vortex disappears and disk-edge vortices are formed, which can be compared to wing tip vortices of fixed wing aircraft. Again, because it is research aimed primarily at the nap-of-the-earth flight regime, the ground vortex is not the strongest possible.

V.R. STEWART (ref. 27, 1989)

Although this report is not on rotors, but on lift jets, it is shown that the effect of a jet impinging a flat plate at a forward speed results in a similar ground vortex to that generated by rotary wing aircraft. This might be useful to find the strength of the ground vortex of the helicopter, but blade tip vortices are not included and will have to be added with a theoretical method.

H.H. HEYSON (ref. 3, 1962)

This report uses simple linear theory to determine interference factors for wind tunnels. Tables containing those factors for different tunnel sizes are given by Heyson (bibl. 7 to 10) One of the conclusions is that testing in open wind tunnels at low speeds is not recommended because the jet boundary will deform.

E.J. HANKER (ref. 20, 1983)

This paper is on interactional aerodynamics and wind tunnel tests, but a section deals with the ground vortex, including a presentation of some of the values of the advance ratio at which the various types of the wake occur. This is again only in the direct vicinity of the helicopter and not at some distance. It is a good reference on wind tunnel testing of complete helicopters at a large scale (1:4.85).

A.J. LANDGREBE (ref. 10, 1974)

This note deals with the technique of velocity measurement using a laser Doppler velocimeter. The measurements are instantaneous, do not disturb the stream and there is no probe collision risk close to the rotor. It is clearly very well suited to vortex measurements.

N.J. COOK (ref. 12, 1978)

N.J. COOK (ref. 13, 1978)

ESDU Data Sheet No 82026 (ref. 38)

The first two references give possible ways of modelling the atmospheric boundary layer to an as large as possible scale. In the third reference the characteristics and values of the full scale atmospheric boundary layer are given.

Bibliography

J.L. MCLOUD (bibl. 3, 1958)

In this note full scale rotors with different aerofoil sections are tested. It is relevant because one of the conclusions is that tip speed is, at least in the configurations tested, not very important; when the rotor was slowed down by about one third, the results (with the same advance ratio) were only marginally different.

H.H. HEYSON (bibl. 5, 1960)

The contents of this note are the basis of reference 3, so it does not add anything of significance to this investigation.

R.B. GRAY (bibl. 6, 1960)

In this note a model rotor is tested at three advance ratios, 0, 0.022 and 0.030. The flow is visualised through smoke and an electromagnetic analog is studied. It is shown that the ground vortex moves under the rotor between advance ratio 0.022 and 0.030. The smoke visualisation was not very effective, as a result of which only the wake near the rotor could be visualised. The analog method might not be suited for this study, because the atmospheric boundary layer is not taken into account.

L.F. EAST (bibl. 13, 1970)

In this report the use of a ground board for simulation of ground effect is investigated. It is concerned with fixed wing aircraft, but the principle is the same for helicopters. However, the ground board is used to avoid a thick boundary layer, while simulating the wind profile that is desirable. It is therefore not directly relevant to this study.

J.L. TANGLER (bibl. 14, 1973)

In this report single blade tip vortices are visualised with the Schlieren system and their stability is investigated. An investigation of the effect of compressibility and tip shape on noise is also included, but this is not relevant to this study. Measurements were also made using a hot-wire probe rotating with a rotor blade. Comparisons are given between experiments and numerically calculated vortex paths. It is shown that tip speed is not important for single blade tip vortex paths as long as it is below $M=0.75$. This is not in ground effect though and only stability in the vicinity of the rotor was investigated, so the results can not be used directly.

P.F. SHERIDAN (bibl. 15, 1973)

This paper describes interactional aerodynamics in ground effect and includes wind tunnel tests of a helicopter model. The emphasis is on rotor wake effects on other parts of the helicopter so there is little information on the wake downstream of the rotor.

A.3 Literature Relating to Full Scale Testing in the Field

Literature involving flight tests in proximity of the ground is not very extensive, but there are some relevant reports from the FAA and NASA.

References

R.M. WEISS (ref. 25, 1989)

This report is intended for the design of heliports, providing measurements of the possible horizontal flows in critical places on the heliports. This report consists of three volumes. The first volume explains the way the measurements of the induced horizontal velocities were made and it includes results from a questionnaire among pilots on what they consider to be safe distances from objects and other aircraft, while the second and third are the results of the measurements plotted on maps. An example of the resulting plots can be seen in figure 19. These are based on measurements of speed and direction of the wake of helicopters in varying positions on several heliports in the United States. The ambient wind is also quoted in strength and direction.

The questionnaire unfortunately did not produce conclusive results, as for each question asked the answers varied considerably. Horizontal speeds are only a minor part of the wake hazard problem (no ground vortex and disk-edge vortices are measured), and the position of the helicopter responsible for the flow is not known for the measurements.

R.M. WEISS (ref. 29, 1990)

This is identical to the former report but for another heliport, Intracoastal City, U.S.

A.B. CONNOR (ref. 2, 1962)

This technical note presents results from flight-tests with a helicopter flying at an altitude of 4,000 feet and a light trainer aircraft penetrating the wake about 1,000 feet behind the helicopter with differing height separations. Rapid roll of the aircraft did occur in some cases and the pilot had to apply 90% of the maximum countering roll moment to neutralise the roll (when not countered, a roll rate of 40 degrees per second was reached, which would have been disastrous near the ground). A method for calculation of some important factors regarding the wake is also given.

Unfortunately the results do not give a general picture as only relatively few situations are tested. The fact that the helicopter is not in ground effect means it is not directly usable, and the calculations of the wake are based on a very simplified theory, that is only applicable out of ground effect.

J.J. TYMCZYSZYN (ref. 34, 1991)

In this report results of flight tests are presented. A small aircraft probed the wake of several helicopters at varying distances in the same direction and cross track. It is concluded that; (i) at low helicopter flight speeds, a relatively strong vortex is induced that decays relatively quickly - the risk created by helicopters flying at low advance ratios is therefore greatest at small horizontal separations. (ii) at high helicopter flight speeds the vortex induced is relatively weak but its lower decay rate means that the risk is apparent at larger horizontal separations.

It was also noted that at several rotor diameters behind the helicopter the individual tip vortices of each blade were still present, inducing violent flapping of the wings of the probing aircraft. The difference in the disk-edge vortex on the advancing and the retreating side was also apparent, with the strongest vortex with a small core size on the advancing side, which induces stronger upsets on the aircraft than the retreating side vortex.

A different explanation from that in the reports of Zheng (ref. 36, 1992) and Levinsky (ref. 7, 1970) is given for the ascending of the trailing vortices; it is postulated that this might be induced by the relatively high engine exhaust gas efflux levels, due to the high power settings (significantly higher than for fixed wing aircraft of the same weight). Another observation is that the wake of two helicopters of the same weight, but with a different number of blades, is not identical; the more blades there are, the sooner the vortices decay. This is similar to the alleviation of the wake with flaps extended for a fixed wing aircraft, where the flaps induce an extra vortex, while the tip vortex is weaker. The resulting vortex interaction reduces the decay time.

Unfortunately only probing of helicopters wakes at considerable heights was carried out, for safety reasons, so the wake in hover is not included in the discussion. As the author states the tests could not be measured very extensively due to the high costs (there were a number of aircraft and many personnel involved). Qualitative observations were made, as well as estimations of some of the aircraft attitude parameters.

T. SULLIVAN (ref. 15, 1979)

This report describes measurements of wake vortices of aircraft at Toronto International Airport. One section deals with measurements of the wake of a tandem rotor helicopter, a Canadian Armed Forces CH-47. These are measurements of the time taken for the wake vortices to decay and the location, relative to the helicopter, at which they are said to be completely dispersed. Unfortunately, no vortex strengths are measured, but the life span measurements are very useful for confirming decay estimates in a theoretical model.

This report is very useful to the current investigation in that many wake vortex measurement techniques are described in detail, including their advantages and disadvantages. The techniques include laser Doppler measurements, which are best suited for unobtrusive measurements, such as would be required on the runway itself

for example. This technique has a limited range, but measures velocities directly. A disadvantage is the high equipment cost. The other experimental equipment, used mainly for vortex location, is the propeller anemometer, placed in rows across the track of the vortex, enabling location and tracking of the lateral position. It might be possible to measure strengths as well, but then the height of the anemometers would also have to be variable.

J.T. WAREING (ref. 6, 1968)

In this paper some measurements of the distribution of the horizontal wake velocities in hover of specific helicopters are presented. A very important conclusion is that at some distance from the rotor centreline the velocities are virtually independent of disc loading, and only vary with thrust (which is usually equal to the weight of the helicopter). As a result of this conclusion it is stated that at some distance a jet impinging on the ground is remarkably similar to a rotor (which has a much lower disc loading) in hover. This is backed up by graphs of tests with both devices (although with a ducted fan instead of a rotor), showing very good correlation.

There is no discussion or measurement of vortices, as they would only occur in forward flight, or in wind conditions, and not during the hover in nil wind conditions, which this paper investigates.

P. DHAR (ref. 27, 1989)

The field trials are used for visualisation of the real rotor wake and no numerical measurements are made.

G.W. LEESE (ref. 9, 1974)

In this paper the results are given of measurements of several types of helicopters in hover, slow forward flight and in accelerating flight. The horizontal velocities at certain distances from the rotor are measured. No graphical data or analysis is included. Unfortunately the greatest distance is only 90 feet, which is far short of the separation distances required in this study. In forward flight only velocities perpendicular to the direction of flight are measured. No vortices are measured in the forward flight regime, where they would have occurred, making the report of limited use for the current investigation.

Bibliography

R.J. ADAMS (bibl. 19, 1992)

This report is a statistical survey of helicopter safety in the various flight phases. The hazard to other aircraft is not included though, so it is not of direct benefit to this investigation.

Appendix B: Separation Requirements Calculation Method

In this section the different segments of the calculation as described in chapter 4 will be established mathematically; as far as possible a comparison with measured data will be made for each individual section.

B.1 Shape of Wake Determination

As concluded in chapter 4 the shape of the wake has to be determined from measured data. Since this data is inconclusive, as the results differ from each other, further research should be conducted. It is possible that there are factors determining the occurrence of the different types of wakes that are not yet understood.

It is likely that three factors determine the ground vortex occurrence and strength:

- The strength of the tip vortex, which is primarily a function of tip speed.
- The mass flow of air through the disk, which can be expressed as the mean induced velocity.
- The thickness of the atmospheric boundary layer.

The first two result in a dependence on advance ratio μ and normalised advance ratio μ^* while the last factor is the atmospheric boundary layer thickness δ . This dependence is illustrated by the results of Dhar (ref. 27, 1989) with a simulated ground plane boundary layer, which differ from other wind tunnel measurements simulating nap-of-the-earth flight with as little ground plane boundary layer as possible. Unfortunately, one data set showing the effect of different boundary thickness is clearly not enough for development of a general relationship. It is, however, possible to find a relation between differing μ , μ^* and height and the type of wake which develops.

It is still possible to make an estimate of the wind velocities for which the recirculation, ground vortex and disk-edge vortex cases occur. It can be seen from figure 1 that for a typical hover taxi height of 0.5 rotor diameter the ground vortex (recirculation) begins to form at values of μ^* from 0.2 to 0.4, which means for most helicopters with a single rotor, the wind velocity ranges from 2.5 to 5 m/s or 5 to 10 knots. Its maximum strength will be reached at approximately $\mu^* = 0.8$, which is the case in a wind speed of 10 m/s or 20 knots. The disk-edge vortex is formed at a μ^* of 0.9 or 22 knots according to Curtiss (ref. 17, 1982) and Sun (ref. 18, 1983), but Sheridan (ref. 11, 1977) and Dhar (ref. 27, 1989) found far larger values of μ^* typically 1.2 to 1.4, which is a wind speed of approximately 30 knots. In the case of transition from the wall jet case to the recirculation or ground vortex case, the exact value of μ^* is not that important, since the strength of the ground vortex will be shown to increase gradually up to a maximum, and then slowly decrease until the disk-edge vortex is formed. The onset of the disk-edge vortex is important in that its strength will be

shown to be greatest at the lowest advance ratios. The vortex decay rate for this case will be very strong as the core radius and turbulence are both very large.

B.2 Determination of the Strength of the Ground Vortex

The method given by Ferguson (ref. 32, 1991) is based on a calculation of the tip vortex trailing each rotor blade and the use of the data in figure 21 to determine the amplification factor to give the ground vortex. The data in figure 21 is presented as a function of advance ratio and non-dimensional rotor height. Since the normalised advance ratio is not used this could be a source of inaccuracy, but as the thrust coefficient is more or less identical for most helicopters at maximum take-off weight, this might not be very significant.

The calculation of the strength of the vortex trailing each blade is based on the assumption that the strength of the lifting line vortex is constant along the blade, which effectively assumes a triangular radial lift distribution. This is an inaccurate assumption, particularly towards the rotor tip, but this might not be a significant source of error after roll-up of the real trailing vortex sheet. The equation for the strength of the tip vortex then is:

$$\Gamma_{tip} = \frac{2 \cdot \Pi \cdot R \cdot V_{tip} \cdot C_T}{b} = \frac{2 \cdot W}{\rho \cdot R \cdot V_{tip} \cdot b} \quad (1)$$

where

- R = blade radius
- V_{tip} = tip speed of the rotor
- C_T = thrust coefficient
- b = number of blades
- W = helicopter weight
- ρ = density of the air

The strength of the ground vortex can then be calculated using figure 21.

Sun (ref. 18, 1983) assumed a two-dimensional wake, as shown in figure 20, in which the strength of the mirror image of the ground vortex is calculated such that the resulting speed, at the centre of the ground vortex, is zero relative to the rotor. The helical tip vortices are represented as 2D line vortices on the outside of the downwash and their images are also included. The horizontal induced velocity due to these vortices is cancelled out by the image of the ground vortex.

The results of such a 2D simulation are given in figure 21 and can be used directly to calculate the ground vortex. However, there would appear to be a discrepancy between this additive method for multi bladed rotors and simple reasoning. If for example a two bladed and a four bladed rotor were compared the number of trailing vortices would be twice as many for the latter but the trailing vortex strength would be

only half of that for the two bladed rotor. Therefore the induced velocities at the centre of the ground vortex for both rotors would be virtually the same which leads to near identical ground vortex strengths. This example indicates that the ground vortex strength may be independent of the number of blades, yet the use of figure 21 leads to stronger ground vortices for helicopters with less blades. Unfortunately the number of blades used by Sun to calculate the ground vortex is unclear.

The method developed by He (ref. 24, 1988) is a more complex approach to that of Sun since it allows for the circular shape of the tip vortices. It is assumed that the vortices from the rotor blades can be presented as vortex rings, and that these rings are carried down at the skew angle of the wake, without change of the initial rotor diameter. At the height of the ground vortex, as calculated earlier, the vortex ring expands, while staying at the same altitude, this principle is visualised in figure 22. As with Sun's method He uses the steady state of the ground vortex location to calculate the strength of the mirror image, but more accurately in his case since rings are used for the tip vortices instead of straight lines.

Results using He's method are given in figure 23 and seem to be comparable to those of Sun, except for the actual values of the rotor height. In this figure the recirculation vortex is also included, which is important for the hazard evaluation since its strength may be the same magnitude as the ground vortex.

Both figures indicate that the maximum ground vortex strength is 6 to 7 times the tip vortex strength, which is useful for comparison with the disk-edge vortex. It is also clear that the strongest vortex, at a typical hover taxi height of 0.4 to 0.5 rotor diameters, is twice the tip vortex strength according to Sun's method, but is six times the tip vortex strength according to He's method. Therefore a factor of six is assumed in order not to underestimate the hazard.

B.3 Determination of the Strength of the Disk-Edge Vortex

For the disk-edge vortex Ferguson (ref. 32, 1991) assumes that the rotor disk acts as a wing of circular planform with a constant vortex strength along the diameter. The value of the trailing vortex can then be calculated:

$$\Gamma_{\text{disk edge}} = \frac{W}{2 \cdot \rho \cdot R \cdot V_F}$$

where

V_F = true airspeed, i.e. the ambient wind speed plus the forward speed of the helicopter

This value may be suspect close to the rotor, but after roll-up it is a reasonable assumption (although vortex decay has to be included at a distance). In most theoretical models it is stated that the rotor disk acts as an elliptical wing with uniform downwash at a distance. The bound vortex then varies elliptically along the 'span', resulting in a slightly higher trailing vortex strength as a factor $4/\pi$ is included for the ideal elliptical wing, resulting in:

$$\Gamma_{\text{disk edge}} = \frac{2 \cdot W}{\pi \cdot \rho \cdot R \cdot V_F} \quad (2)$$

This equation is inaccurate if the wake downwash angle gets very large. Ferguson (ref. 32, 1991) mentions a maximum of 45 degrees, which means that the forward speed equals the induced velocity (if the rotor has an angle of attack of zero degrees). For most helicopters the induced velocity through the disk in hover is 10 to 13 m/s, and slightly lower at higher speeds, so the minimum speed for which the formula can still be used is of this magnitude. Since this is also the speed where the disk-edge vortices are formed this formula covers the whole range of this type of wake. However, it is important to consider that at these angles a very strong wake may not persist since the turbulence and core size, as well as vortex instability, are very large.

The value of the disk-edge vortex strength can be divided by the tip vortex strength to make a comparison with the ground vortex strength possible. This ratio can be calculated for a typical tip speed of 200 m/s and the lowest possible speed where the disk-edge vortex exists, to show what the difference in strength at the transition region is.

$$\frac{\Gamma_{\text{disk edge}}}{\Gamma_{\text{tip}}} = \frac{2 \cdot W}{\pi \cdot \rho \cdot R \cdot V_F} \cdot \frac{\rho \cdot R \cdot V_{\text{tip}} \cdot b}{2 \cdot W} = \frac{b}{\pi} \cdot \frac{V_{\text{tip}}}{V_F} \approx \frac{b \cdot 200}{3.1415 \cdot 15} = 4.2 \cdot b$$

where

b = the number of blades.

In simple terms this means that a two bladed rotor would generate a disk-edge vortex 8.4 times as strong as its tip vortex, and for 4 or more blades this gets larger than 16 times the tip vortex. This is clearly far stronger than the ground vortex which is a maximum factor of 6, and perhaps only 2 for typical hover heights, stronger than the tip vortex.

B.4 Calculation of the Induced Horizontal Velocities

The calculation of the induced horizontal velocity at hover, or the wall jet velocity, is described many times in the literature. As can be seen in figures 24, 25 and 26 the wall jet velocity in nil wind conditions decreases very rapidly. It should be negligible at distances in excess of 50-100 meters, so at the typical separation distances considered here it is of no influence.

Ferguson (ref. 32, 1991) also includes an ambient wind, enabling calculation of the induced horizontal velocities at low advance ratios. This is achieved by superposition of the wind multiplied by an empirical factor on the wall jet profile:

$$V_{i \text{ wind}} = V_{\text{wind}} \left(-0.5 \cdot \frac{h}{R} + 2.5 \right) + V_{i \text{ nil wind}}$$

At heights greater than 5 rotor radii the factor is unity.

This would mean that at the typical hover height of one rotor radius twice the wind velocity should be added to all downwind locations, which could be correct close to the rotor since, as a result of the downwash skew a relatively higher portion of the mass flow will be blown downwind. At larger distances however, where the wall jet velocity as calculated in nil wind conditions to be virtually zero, it does not seem logical that the wake velocity will still be twice the wind velocity. It is likely that the measurements were made up to a limited distance behind the helicopter, and the empirical relation is based on that range only. It does not seem possible that such a strong velocity would remain at more than 50 meters since the wash of a propeller, which is directed in one direction in a much more direct way, and also involves higher induced velocities, is diffused at those large distances. Since no other source is available on the effect of an ambient wind on horizontal velocities in the wake more research in this area is needed.

B.5 Calculation of the Decay of the Vortex

Vortex decay can occur in two ways: (i) a slow decay in which the viscous core increases in size, therefore decreasing the total vortex energy, and (ii) a rapid decay which can occur through the bursting of the core. An instability known as Crow instability can cause self destruction of the vortex, or merging of two counter rotating vortices, resulting in the disappearance of both.

Decay through Core Radius Growth

Several formulae exist for predicting this form of core growth. Kurylowich (ref. 14, 1979) gives two core radius formulae, one for fixed wing aircraft vortices and one for helicopter vortices. These are both based on measured data, and the helicopter values are much larger. Kurylowich postulates that this is to be expected, since the turbulence level in a rotor is higher and therefore the effects of viscosity are greater.

The equation for aircraft is:

$$R_{\text{core}} = 36.2 \cdot \sqrt{\nu \cdot t}$$

For helicopters it is:

$$R_{\text{core}} = 244 \cdot \sqrt{\nu \cdot t}$$

where

R_{core} = core radius

ν = viscosity of air, which is approximately $1.44 \cdot 10^{-5} \text{ m}^2/\text{s}$

t = age of the vortex in seconds

V_F = ambient wind speed plus the forward speed of the helicopter

Levinsky (ref. 7, 1970) does not give the radius directly, but it is possible to estimate it from the calculation he describes. The resulting formula is:

$$R_{\text{core}} = 2 \cdot \sqrt{\frac{v_t \cdot t}{1.26}} \quad \text{with } v_t = \Lambda \cdot \sqrt{\Gamma \cdot v} \text{ and } 0.2 < \Lambda < 0.6 \text{ for most data} \quad (3)$$

Finally, Squire (bibl. 1, 1954) gives the radius as:

$$R_{\text{core}} = \sqrt{5.04 \cdot 1.5 \cdot 10^{-4} \cdot \Gamma \cdot t}$$

The results of these different equations are plotted in figure 27 from which it is clear that there is considerable scatter. Only one of these methods was specifically for helicopters and that is the only one that does not include a vortex strength dependence. It may be that the measurements were for one type of helicopter only and therefore the strength did not vary. Of the other two methods, Squire takes the square root of the circulation strength while Levinsky uses the fourth root of the circulation strength.

It is clear that more research in this area is required as the core radius and the vortex decay rate are of paramount importance for the determination of separation minima. The method of Levinsky will be adopted for the theoretical approach to be developed here, since it closely predicts the core radius given from the measurements of the wake of a CH-54, see figure 15. The results with this core radius and the disk-edge vortex strength as in (3) and (2) can be seen in figure 29. The core is reasonably well represented, but the strength is overestimated. Comparing the measured data to the calculated values, it seems that the wake might not have been rolled up entirely, as the downwash is far less curved. The calculation is safe and does not overestimate the strength too much, so it can be used in the theoretical model. Later, when more measurements are available, the model can perhaps be more closely matched to the real wake.

Decay of the Strength of the Vortex Circulation

Kurylowich (ref. 14, 1979) gives an equation for a decrease in vortex strength that occurs after a time due to the interaction of several trailing vortices, like the flap and tip vortices of a fixed wing aircraft on approach. He assumes this will also occur with helicopter wakes, because of the higher turbulence levels, but does add that more research is needed to validate this assumption.

The equation for the decayed vortex strength is:

$$\Gamma_{\text{disk edge decayed}} = 9.58 \cdot \left[\frac{4 \cdot \rho \cdot V_F \cdot R^3}{t \cdot W} \right] \cdot \Gamma_{\text{disk edge}} \quad , \quad \text{if } \left[\frac{4 \cdot \rho \cdot V_F \cdot R^3}{t \cdot W} \right] < \frac{1}{9.58} = 0.1044$$

If the term in brackets is larger than 0.1044 the undecayed value of the vortex strength is used. When this formula is implemented the strength of the disk-edge vortex decreases too sharply so the predicted upset bank angles are far too small compared to Tymczyszyn (ref. 34, 1991 and fig. 25 and 26). Therefore in the current model this equation is not directly included. Later research might well indicate that an equation

resembling the above is desirable, but to be conservative this cannot be confirmed with the current knowledge.

Little is known on the effect of the proximity of the ground on vortex decay. If a secondary vortex near the ground were to be induced, an additional decay would occur.

Rapid Decay

Unfortunately there is little known about the rapid decay of vortices. Even for fixed wing aircraft the knowledge is limited and for helicopters it is almost nil. Kurylowich (ref. 14, 1979) mentions that for most of the flight tests described in ref. 2 the vortex could not be detected by the following aircraft after one minute, but also states that this could have been because the pilots were unable to find the centre of the vortices (smoke used for visualisation had already dispersed). The results of the flight tests by Tymczyszyn (ref. 34, 1991) seem to indicate that, at least for larger types of helicopters, the vortices can exist for much longer than one minute (up to four minutes). It is probably identical to fixed wing aircraft vortices in that their persistence depends mainly on the strength of the ambient wind, as seen in figure 28 for fixed wing aircraft.

B.6 Prediction of the Path of the Vortex

As has been stated before, the practical value of an exact prediction of the vortex path is limited for this investigation. Therefore, this paragraph will be confined to an evaluation of the up float of the vortices in order to try to indicate a minimum height above the hovering helicopter, above which no vortices can be encountered. A short discussion of approximate lateral spread of the ground and disk-edge vortices will also be included. The calculation methods for vortex path prediction do exist, but require long calculation time and, because the wind direction is likely to fluctuate, have little practical value.

Up Float of the Vortices

Zheng (ref. 36, 1992) calculated the up float for aircraft wake vortices with a complex numerical model, the results from which are given in figure 30. The aircraft height is not varied, so it is difficult to assess if the maximum possible up float is predicted. The value of the maximum height is approximately 1.3 times the rotor height.

Levinsky (ref. 7, 1970) has a similar calculation, the results of which can be seen in figure 31. This is for helicopters at several heights, and it can be seen that for normal hover taxi heights (approximately 0.5 rotor diameter) the up float should not be very strong for disk-edge vortices. Ground vortices are closer to the ground and might have relatively more up float. The actual height they could reach might however still not exceed the rotor height, as can be seen in figure 31.

Although the effect of some parameters, like the strength of the vortex and atmospheric conditions are not discussed, it seems a safe assumption that the vortex of a hovering helicopter will not exceed approximately 1.3 times the hover height, and in reality may even remain below the rotor height altogether.

As stated in chapter 4, the effect of the exhaust heat on the up float is not known, and should be addressed in later research.

Lateral Spread of the Vortices

For the disk-edge vortex case the spread would be very small, as for fixed wing aircraft, until the ground is reached. At this point the mirror image of each vortex induces outward velocities, resulting in a larger spread. When the up float occurs, the induced counter rotating extra vortex will, as it is next to as well as slightly under the vortex, not only make it go up, but also dramatically increase the lateral spread. This can be seen in the results of the calculations by Zheng (ref. 36, 1992) in figure 30, where the final lateral location is three to four times the initial distance to the centreline of the wake. This would mean that the lateral movement for a vortex of a CH-53 with a rotor radius of 12 meters would be up to 48 meters. As concluded earlier, the up float calculated by Zheng (ref. 36, 1992) is probably not so strong for hovering helicopters, as their rotor height is relatively large, so the extreme spread would also be a smaller.

In the case of the ground vortex, lateral spread is expected to be very large, not only because of up float effects, but mainly because of the nature of the ground vortex itself, which is formed in front of the rotor and curves around the downwash. This can be seen in some of the wind tunnel test results, such as the ground vortex position found by Sun (ref. 18, 1983), which is given in figure 32. Although this is only a small segment, it indicates how wide it is likely to be.

Implications of Lateral Speed

It is clear that the lateral spread is quite large for both the ground vortex and disk-edge vortex cases, so to ensure that the runway is clear, particularly in a crosswind is relatively difficult. It would appear that, particularly in the case of a ground vortex, a very strong crosswind would be needed to keep the runway free from the effects of the vortex.

B.7 Calculation of the Roll Angle of the Aircraft

An estimate of the roll angle induced on an aircraft entering the wake vortex can be made using a method derived by Kurylowich (ref. 14, 1979). This approach uses the velocities induced by the vortex to calculate the increase in local angle of attack on a section of the aircraft wing. A linear variation of lift coefficient with incidence is assumed which does not take account of the aerofoil stall. Only roll is considered, yaw and pitching moment are considered negligible. These simplifications, as well as the assumption that there are no three dimensional effects, make the value of the rolling moment higher than it really is, giving a safety margin.

The lift on a wing section of width dy is:

$$dL = \frac{1}{2} \cdot \rho \cdot V_{\infty}^2 \cdot c(y) \cdot dy \cdot C_{l_{\alpha}} \cdot \frac{V_{\text{vortex}}}{V_{\infty}}$$

$$dM_{\text{roll}} = \frac{1}{2} \cdot \rho \cdot V_{\infty} \cdot c(y) \cdot y \cdot dy \cdot C_{l_{\alpha}} \cdot V_{\text{vortex}}$$

where

dL = lift increase on wing segment

V_{∞} = true airspeed (approach or landing speed) of the aircraft

$c(y)$ = chord in station y

dy = width of wing segment

$C_{l_{\alpha}}$ = lift coefficient slope on 3-dimensional wing

V_{vortex} = vertical velocity induced by the trailing vortex of another aircraft

dM_{roll} = roll moment induced on the wing segment

y = distance from the centreline of the aircraft.

Integration gives:

$$M_{\text{roll}} = \int_{-b/2}^{+b/2} \frac{1}{2} \cdot \rho \cdot V_{\infty} \cdot c(y) \cdot y \cdot C_{l_{\alpha}} \cdot V_{\text{vortex}} \cdot dy = \frac{1}{2} \cdot \rho \cdot V_{\infty} \cdot C_{l_{\alpha}} \cdot \int_{-b/2}^{+b/2} c(y) \cdot y \cdot V_{\text{vortex}} \cdot dy$$

where

b = span of the aircraft

An untapered wing has a constant chord and therefore it will be most affected by the vortex as the extra lift works at a greater distance from the aircraft centreline. Since this estimation method aims to predict a worst possible induced rolling moment, this type of wing planform is considered here.

$$M_{\text{roll}} = \frac{1}{2} \cdot \rho \cdot V_{\infty} \cdot C_{l_{\alpha}} \cdot c \cdot \int_{-b/2}^{+b/2} (y \cdot V_{\text{vortex}} \cdot dy)$$

The vortex the aircraft encounters is assumed to be made up of a non-rotational inviscid exterior, with a viscous core in which linear velocities are assumed from the centre to the core radius, so:

$$V_{\text{vortex}} = \frac{\Gamma}{2 \cdot \pi \cdot r} \quad r \geq R_{\text{core}}$$

$$V_{\text{vortex}} = \frac{\Gamma \cdot r}{2 \cdot \pi \cdot (R_{\text{core}})^2} \quad r < R_{\text{core}}$$

where

Γ = strength of vortex induced by helicopter

r = distance from centreline of vortex

R_{core} = core radius

When the above expressions are substituted in the integral equation for the induced rolling moment it is possible to solve the expression analytically. In order to check the position at which the aircraft encounters the strongest effect, the position of the aircraft centreline to the centre of the vortex was varied, as well as the core radius. The results can be seen in figure 33, where it can be seen that the worst case is for the aircraft displaced slightly from the centre of the vortex if the core radius is very small.

The figure also shows that the hazard to an aircraft, which is flying parallel to the vortex outside the core, is in the form of a rolling moment making it roll in the opposite sense to the vortex, away from the core. This is caused by the differences in the local angle of attack on the wings. The wing closest to the core has a greater increase in angle of attack than the other. The reaction of the pilot may be to counteract this roll and inadvertently penetrate of the centre of the vortex, inducing a far stronger rolling moment.

Since some measurements in the literature indicated that the core radius at a distance is significantly larger than one tenth of the half-span of a light aircraft, it can safely be assumed that the aircraft will encounter the largest moment in the centre of the vortex. It can also be seen that the additional moment from the second arm of the trailing vortex - which usually is at least one span away from the other in ground effect - is very small and can therefore be neglected. It is also evident that the core size has only a relatively small effect on the induced moment; therefore a safer underestimation of the core size will not have a major effect on the results.

The following formulae can be used for the induced rolling moment of an aircraft with an untapered wing, located at the centre of the vortex, with both a core radius smaller than one half-span and one larger than a half-span:

$$M_{\text{roll}} = \frac{\rho \cdot V_{\infty} \cdot C_{L_{\alpha}} \cdot c \cdot \Gamma \cdot (b/2 - \frac{2}{3} \cdot R_{\text{core}})}{2 \cdot \pi} \quad (\text{Core radius smaller than half-span}) \quad (4)$$

$$M_{roll} = \frac{\rho \cdot V_{\infty} \cdot C_{l_{\alpha}} \cdot c \cdot \Gamma \cdot (b/2)^3}{6 \cdot \pi \cdot (R_{core})^2} \quad (\text{Core radius larger than half-span}) \quad (5)$$

In order to estimate the angle rolled by the aircraft in one second a simplification that is sometimes used is that the rolling moment will be constant, giving the following expressions:

$$I_{xx} \cdot \ddot{\phi} = M_{roll} \quad \Rightarrow$$

$$I_{xx} \cdot \dot{\phi} = M_{roll} \cdot t \quad \Rightarrow$$

$$I_{xx} \cdot \phi = \frac{1}{2} \cdot M_{roll} \cdot t^2$$

where

I_{xx} = moment of inertia around the longitudinal aircraft axis

t = time expired after the vortex encounter

ϕ = roll angle of aircraft in radians

In reality the actual induced moment will be less than that given above because the roll rate will induce a decrease in local angle of attack on the wing. Because the roll rates are quite high in this investigation, the resulting decrease in the induced moment is significant. Therefore a more accurate solution can be found by inclusion of the countering moment resulting from the roll rate:

$$M_{roll_{\phi}} = \int_{-b/2}^{b/2} \dot{\phi} \cdot y^2 \cdot C_{l_{\alpha}} \cdot \frac{1}{2} \cdot \rho \cdot V_{\infty} \cdot c \cdot dy$$

so the total roll moment is:

$$M_{roll_{total}} = M_{roll} - M_{roll_{\phi}} = M_{roll} - \dot{\phi} \cdot \frac{b^3 \cdot C_{l_{\alpha}} \cdot \rho \cdot V_{\infty} \cdot c}{24}$$

This leads to a differential equation with $\dot{\phi}$ and $\ddot{\phi}$:

$$I_{xx} \cdot \ddot{\phi} = M_{roll_{total}} = M_{roll} - \dot{\phi} \cdot \frac{b^3 \cdot C_{l_{\alpha}} \cdot \rho \cdot V_{\infty} \cdot c}{24}$$

The solution of this differential equation is, with as boundary conditions that roll angle and roll rate are zero at $t = 0$:

$$\phi = \frac{24^2 \cdot I_{xx} \cdot M_{roll}}{(b^3 \cdot C_{l_{\alpha}} \cdot \rho \cdot V_{\infty} \cdot c)^2} \cdot \left(e^{\frac{-b^3 \cdot C_{l_{\alpha}} \cdot \rho \cdot V_{\infty} \cdot c}{24 I_{xx}} \cdot t} - 1 \right) + \frac{24 \cdot M_{roll} \cdot t}{b^3 \cdot C_{l_{\alpha}} \cdot \rho \cdot V_{\infty} \cdot c} \quad (6)$$

For $t = 1$ second the roll angle must not be larger than a certain value depending on the altitude for safe operation. The maximum moment allowed, as a function of the maximum bank angle, at $t = 1$, is:

$$(M_{\text{roll}})_{\text{max}} = \varphi_{\text{max}} \left(\frac{1}{\frac{24^2 \cdot I_{xx}}{(b^3 \cdot C_{l_\alpha} \cdot \rho \cdot V_\infty \cdot c)^2} \cdot \left(e^{\frac{-b^3 \cdot C_{l_\alpha} \cdot \rho \cdot V_\infty \cdot c}{24 \cdot I_{xx}}} - 1 \right) + \frac{24}{b^3 \cdot C_{l_\alpha} \cdot \rho \cdot V_\infty \cdot c}} \right)$$

So at the minimum separation distance, if core radius is smaller than the half-span:

$$\Gamma \cdot \left(1 - \frac{2}{3} \cdot \frac{R_{\text{core}}}{b/2} \right) = \varphi_{\text{max}} \left(\frac{1}{\frac{24^2 \cdot I_{xx}}{(b^3 \cdot C_{l_\alpha} \cdot \rho \cdot V_\infty \cdot c)^2} \cdot \left(e^{\frac{-b^3 \cdot C_{l_\alpha} \cdot \rho \cdot V_\infty \cdot c}{24 \cdot I_{xx}}} - 1 \right) + \frac{24}{b^3 \cdot C_{l_\alpha} \cdot \rho \cdot V_\infty \cdot c}} \right)$$

When core radius is larger than the half-span:

$$\Gamma \cdot \left(\frac{1}{3} \cdot \left(\frac{b/2}{R_{\text{core}}} \right)^2 \right) = \varphi_{\text{max}} \left(\frac{1}{\frac{24^2 \cdot I_{xx}}{(b^3 \cdot C_{l_\alpha} \cdot \rho \cdot V_\infty \cdot c)^2} \cdot \left(e^{\frac{-b^3 \cdot C_{l_\alpha} \cdot \rho \cdot V_\infty \cdot c}{24 \cdot I_{xx}}} - 1 \right) + \frac{24}{b^3 \cdot C_{l_\alpha} \cdot \rho \cdot V_\infty \cdot c}} \right)$$

The term on the right hand side of the above expression is only dependent on the characteristics of the light aircraft and since air density, approach or landing speed and sectional lift curve slope are approximately identical on most light aircraft, it is possible to make this term solely dependent on aircraft weight, (W) and wing span(b). It can be shown that I_{xx} is estimated by the following expression:

$$I_{xx} = \frac{W}{g} \cdot (0.2 \cdot b/2)^2$$

This is assuming that the mass can be concentrated at 20% of the semi-span, which is a good approximation for most conventional light aircraft.

Comparing with values for the Navion, a light aircraft for which parameters are readily available, with a W of 12.24 kN and a half-span of 5 m, the moment of inertia about the x axis, I_{xx} is 1313 kg.m², while the above equation yields approximately 1248 kg.m², which is acceptable. It has a chord of 1.7 m, a lift curve slope of 4.44, which is a typical value for the three-dimensional situation, and an approach speed (high to be on the safe side, as the rolling moment increases with speed) of 60 knots = 30 m/s. The highest value of air density at sea level in standard atmospheric conditions of 1.225 kg/m³ is taken, giving the term on the right in the above equation as:

$$\left(\frac{1}{\frac{24^2 \cdot W \cdot b^2 \cdot 0.01}{9.81} \cdot \left(e^{\frac{-b^3 \cdot 4.5 \cdot 1.225 \cdot 30 \cdot 0.17 \cdot b}{24 \cdot W \cdot b^2 \cdot (0.01/9.81)}} - 1 \right) + \frac{24}{b^3 \cdot 4.4 \cdot 1.225 \cdot 30 \cdot 0.17 \cdot b}} \right) =$$

$$\left(\frac{1}{\frac{7.4 \cdot 10^{-4} \cdot W}{b^6} \cdot \left(e^{\frac{-1149 \cdot b^2}{W}} - 1 \right) + \frac{0.873}{b^4}} \right) \quad (\text{with } W \text{ in Newtons and } b \text{ in meters})$$

In this formula it is assumed that the aspect ratio is approximately identical for most light aircraft (hence the $c = (1.7/10)b$, as for straight, untapered wings aspect ratio is b/c).

With this factor, which is constant for a certain type of aircraft, the allowable vortex strength can be calculated for any small conventional aircraft.

B.8 Evaluation of the Method with Measured Upset Angles

The results of the method can be compared to the upset bank angles as observed by Tymczynszyn (ref. 34, 1991, see figure 34 and 35) during wake penetration flight tests. There should be some caution when comparing the measured and calculated values, as the measured values are of total upset, and include pilot correction. The theoretical method gives uncorrected bank angles after one second. Another source of difference may be that in the flight tests, especially when at large separation distances, the exact centre of the vortex might not always have been penetrated.

Theoretical predictions of upset angle can be compared with the actual measurements since the pilot is unlikely to correct the upset in the first 0.6 second, due to his reaction time and after that the aircraft probably would have left the centre of the vortex, as the

induced lift is no longer simply equating the aircraft weight. The comparison can therefore still be very valuable.

When compared to the upset bank angles observed by Tymczyszyn (ref. 34, 1991, see figure 34 and 35) during the wake penetration flight tests the method with only Levinsky's vortex decay estimate (ref. 7, 1970) formula (3) is reasonably accurate for the magnitude of the roll in the first thirty seconds. After this period the actual decay of the vortex is greater. A correction factor, as used by Kurylowich (ref. 14, 1979), may be the solution in principle, but the actual values suggested are not valid for helicopters since the estimates of bank angle are far lower than those measured if this factor is included. In practice, the vortex intensity appears to start to decay at a constant value of forward speed (V_F) multiplied by time (t), based on constant helicopter weight and rotor radius, so a dimensionless factor for helicopters, based on this value, would appear appropriate. Using the measurements by Tymczyszyn (ref. 34, 1991 and fig. 34 and 35) for the UH-60 the value of this factor can be determined as:

$$K = 0.0095 \frac{V_F \cdot t}{R} \quad (7)$$

So the strength is then:

$$\Gamma_{\text{disk edge decayed}} = \frac{\Gamma_{\text{disk edge}}}{K} \quad (\text{for } K \geq 1) \quad (8)$$

$$\Gamma_{\text{disk edge decayed}} = \Gamma_{\text{disk edge}} \quad (\text{for } K < 1) \quad (9)$$

with speed in m/s, time in seconds and radius in meters.

A physical explanation for the existence of this factor is that the location of the point behind the rotor in rotor radii at which roll up is completed and the location of the point where merging occurs may not be dependent on the strength of the vortex, but they are approximately constant. This means, for a large helicopter, merging of the vortices occurs further away in actual distance than for smaller helicopters, which is to be expected. The predicted larger decay for vortices that are formed at low speeds occurs in the form of a larger core radius, this is included in formula (3). A possible problem is that formula (3) underestimates the core radius after the vortex circulation has started to decay, so it has to be assumed that near the core the formula can be applied with the undecayed vortex circulation strength, even after the circulation decreases.

The results of the use of this proposed factor have to be validated extensively, but the correlation with the existing measured data is good, as can be seen in figures 36, 37, 38 and 39. The theoretical data used in these figures are calculated with the formulae numbers (1) to (9) for two classes of helicopter, medium weight (20,000 lbs) and heavy (70,000 lbs). The aircraft is the same as that used by Tymczyszyn (ref. 34, 1991), the T-34C, but the parameters are virtually identical to those of the Piper PA-28 (the only difference is the higher moment of inertia of the heavier T-34C, but as this only has effect on the accelerating phase, which lasts only for a fraction of a second, the difference is not more than a small percentage). When the empirical decay

factor is used on the 747 wake, the results are close to those with the empirically determined factor of Kurylowich (ref. 14, 1979).

Figures

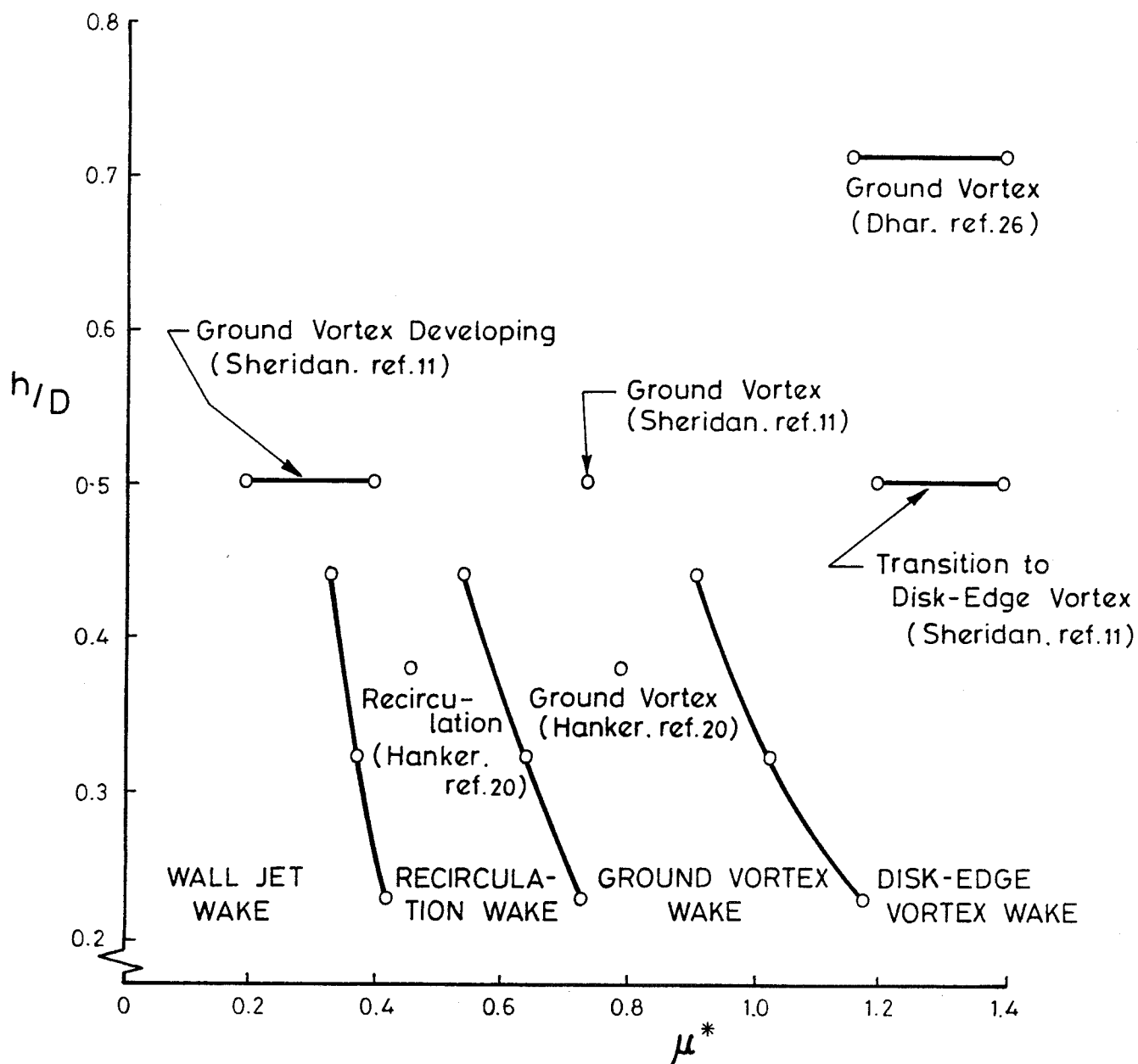
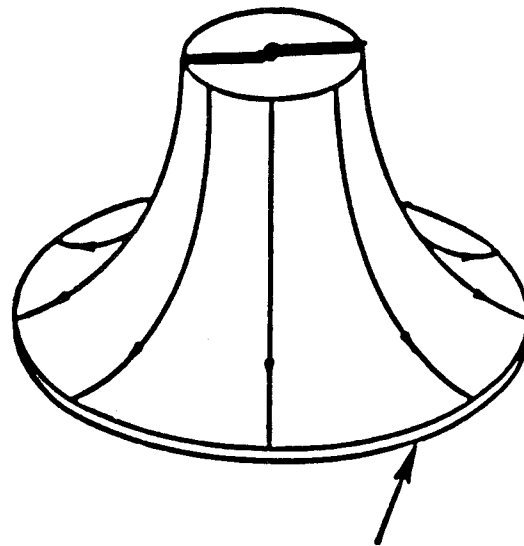


Figure 1. Summary of wake type occurrence with relative rotor height and normalised advance ratio. (Sun, ref. 18)



**RADIAL FLOW
WALL JET**

Figure 2. Downwash in nil wind conditions (Ferguson, ref. 32)

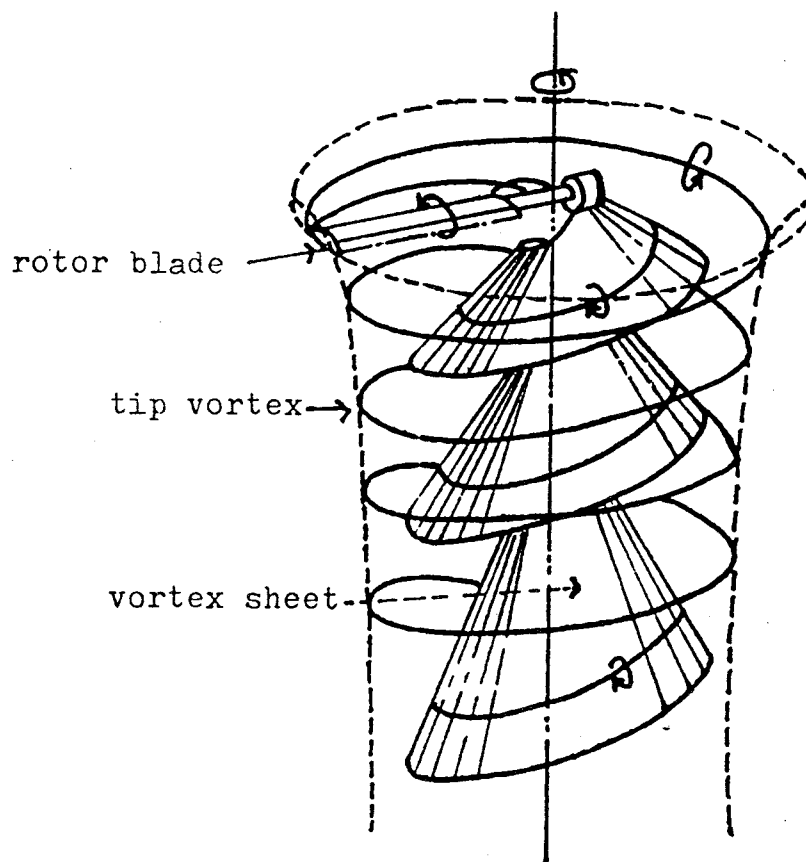
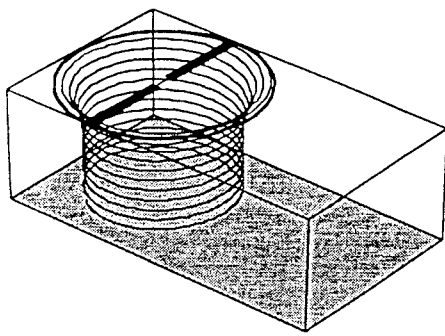
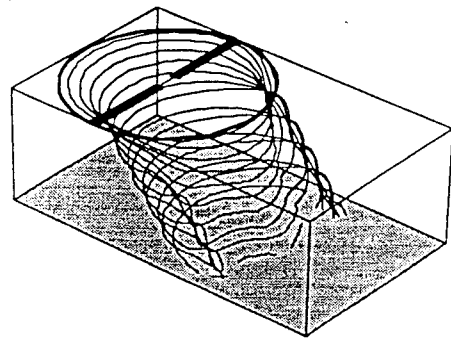


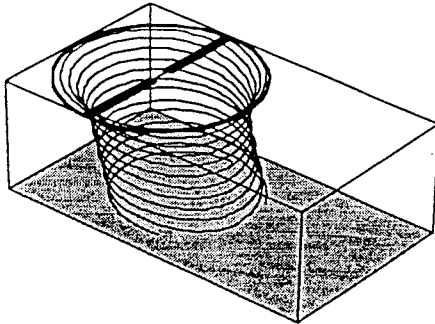
Figure 3. Rotor wake structure: vortex representation (Kusmarwanto, ref. 22)



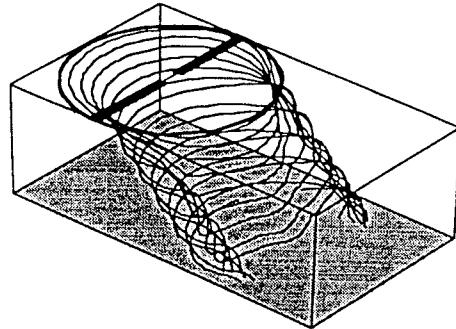
Periodic wake at $\mu = 0.0$ (hover).



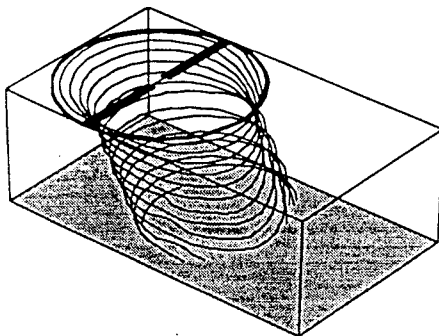
Periodic wake at $\mu = 0.0275$.



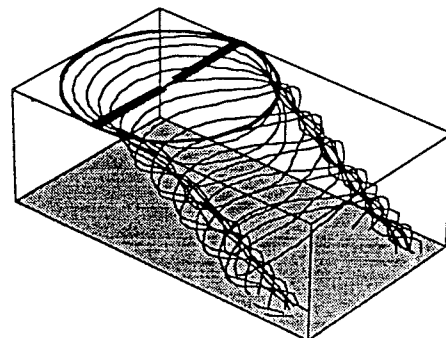
Periodic wake at $\mu = 0.01$.



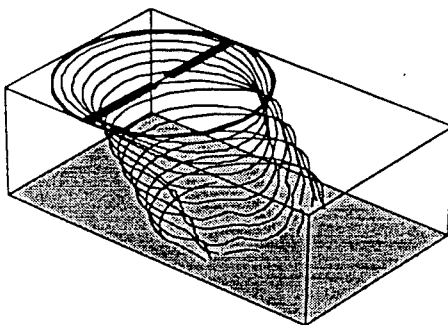
Periodic wake at $\mu = 0.03$.



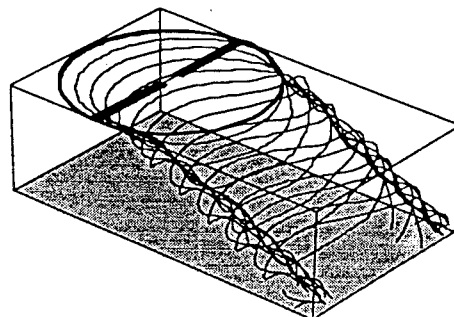
Periodic wake at $\mu = 0.02$.



Periodic wake at $\mu = 0.04$.



Periodic wake at $\mu = 0.025$.



Periodic wake at $\mu = 0.05$.

Figure 4. Skewing of the rotor wake at increasing forward speed (advance ratio (μ) indicated), (Miller, bibl. 20)

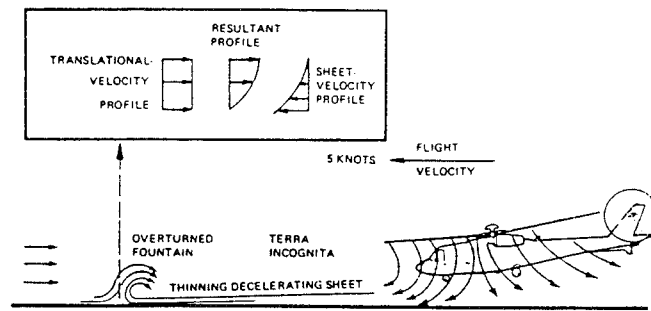


Figure 5. Wake development in light wind conditions (Sheridan, ref. 11)

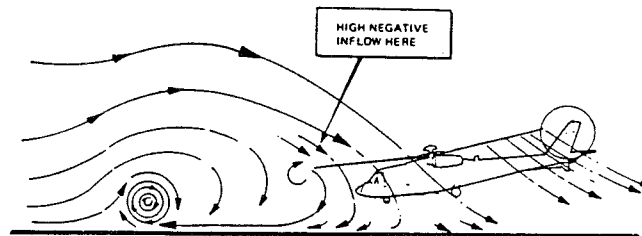


Figure 6. Wake recirculation formation (Sheridan, ref. 11)

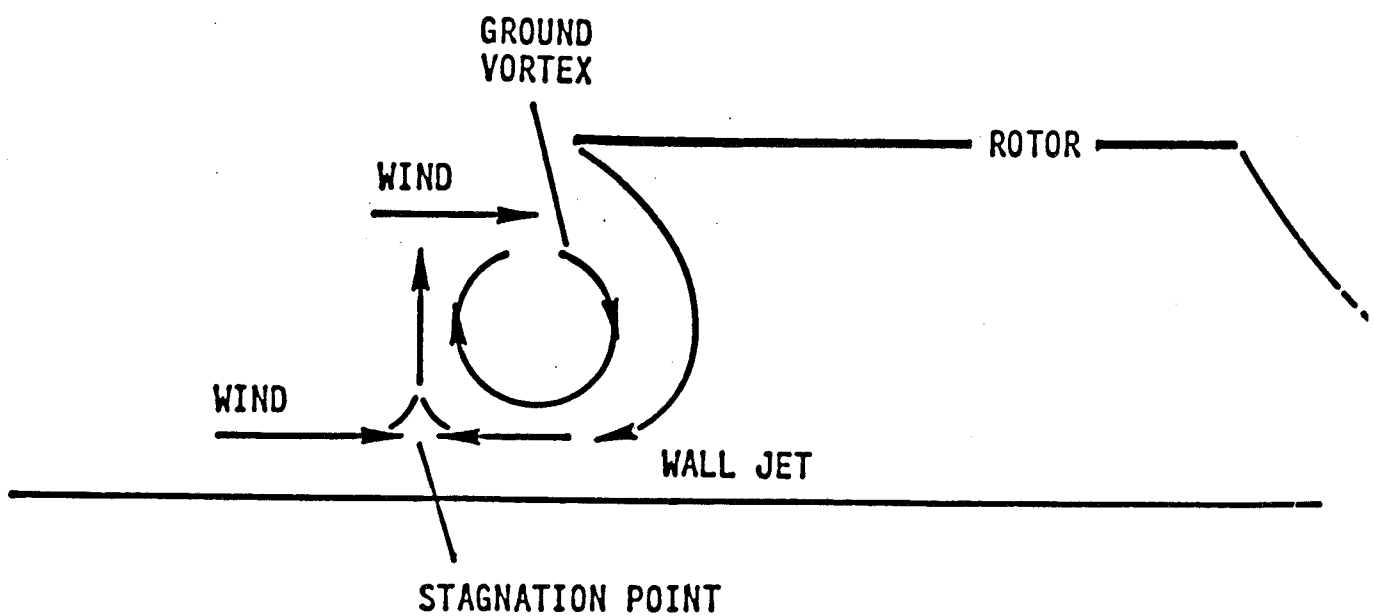


Figure 7. Schematic of the ground vortex formation mechanism (Ferguson, ref. 32)

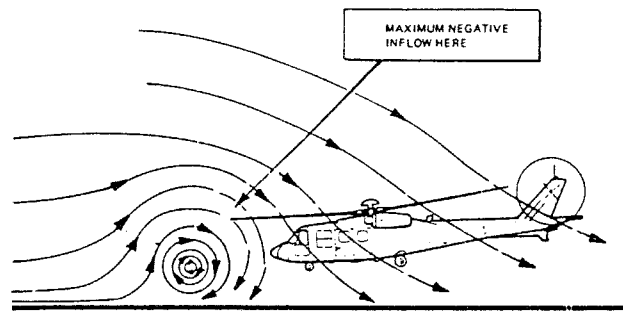


Figure 8. Geometry of the ground vortex at advance ratio $\mu = 0.04$ (Sheridan, ref. 11)

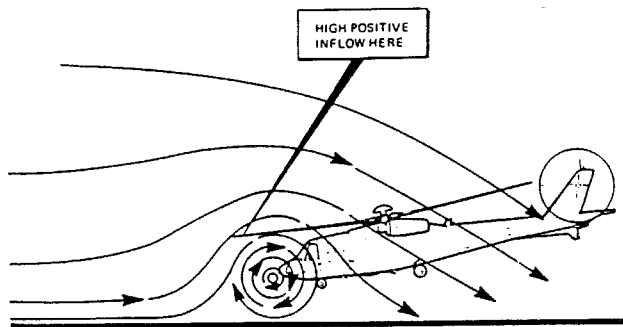


Figure 9. Geometry of the ground vortex at advance ratio $\mu = 0.05$ (Sheridan, ref. 11)

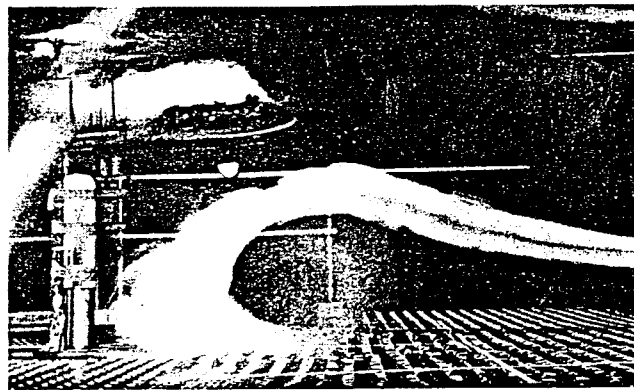


Figure 10. Flow visualisation of ground vortex at advance ratio $\mu = 0.05$ (Sheridan, ref. 11)

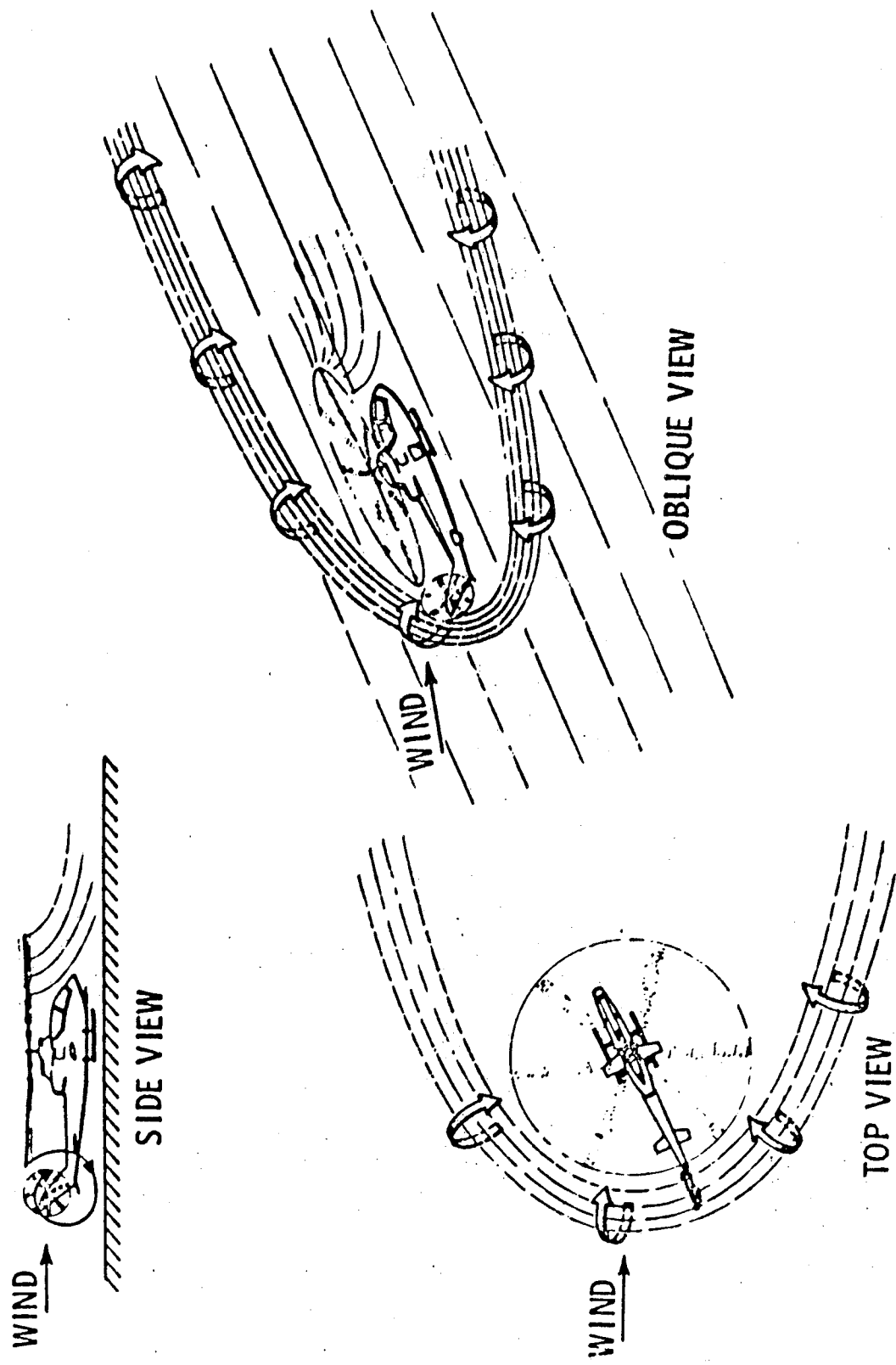


Figure 11. Schematic representation of the ground vortex with the helicopter in rearward flight (Heyson, ref. 16)

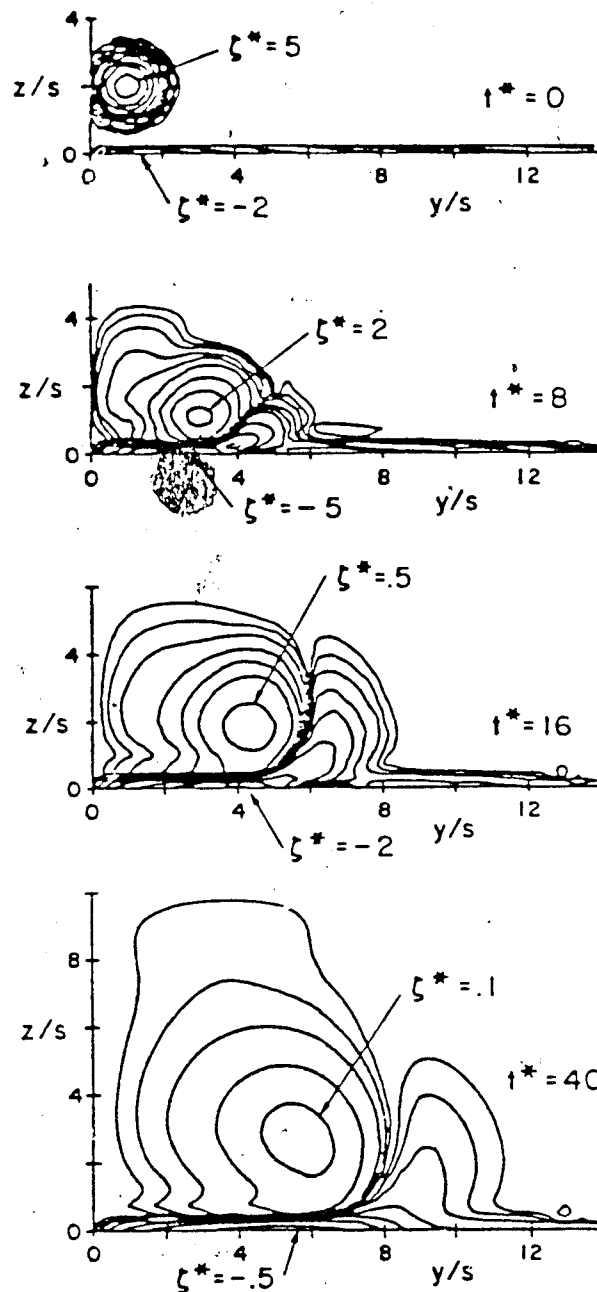


Figure 12. Secondary vortex induced when primary vortex reaches the ground (Sun, ref. 18)

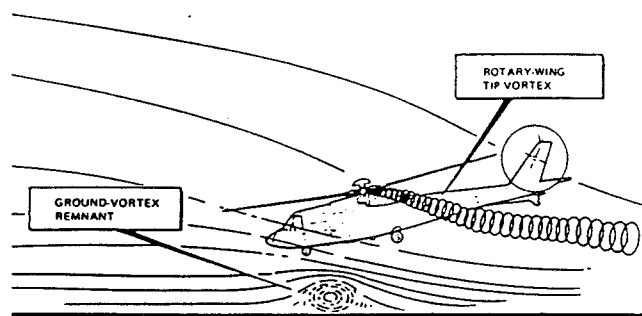


Figure 13. Schematic representation of the formation of disk-edge vortices at advance ratio $\mu = 0.08$ (Sheridan, ref. 11)

T-34C ILLUSTRATES PARALLEL PROBE TECHNIQUE
DECATHELON ILLUSTRATES CROSS TRACK PROBE TECHNIQUE
(OBVIOUSLY CONDUCTED AT DIFFERENT TIMES BY EITHER AIRPLANE)

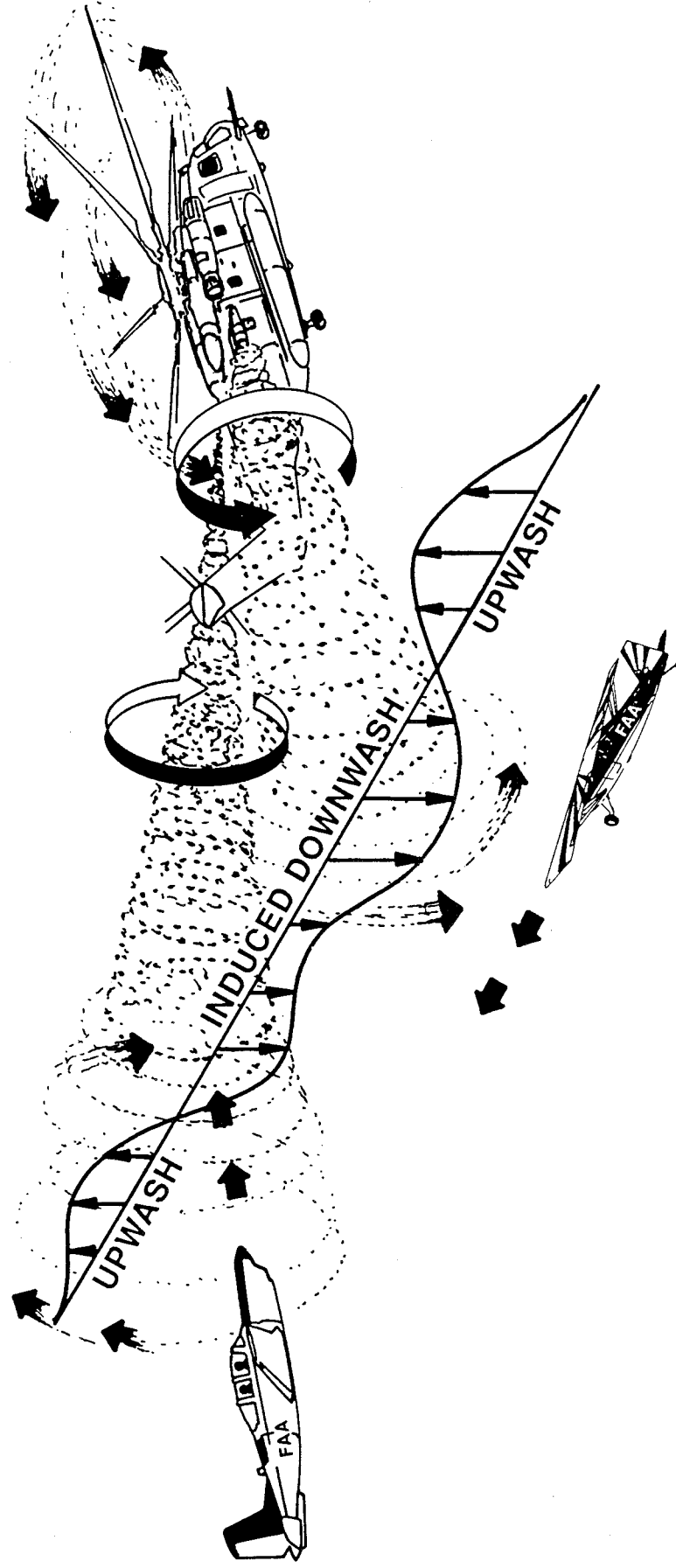


Figure 14. Schematic arrangement of the 3-dimensional disk-edge vortex wake (Tymczyszyn, ref. 34)

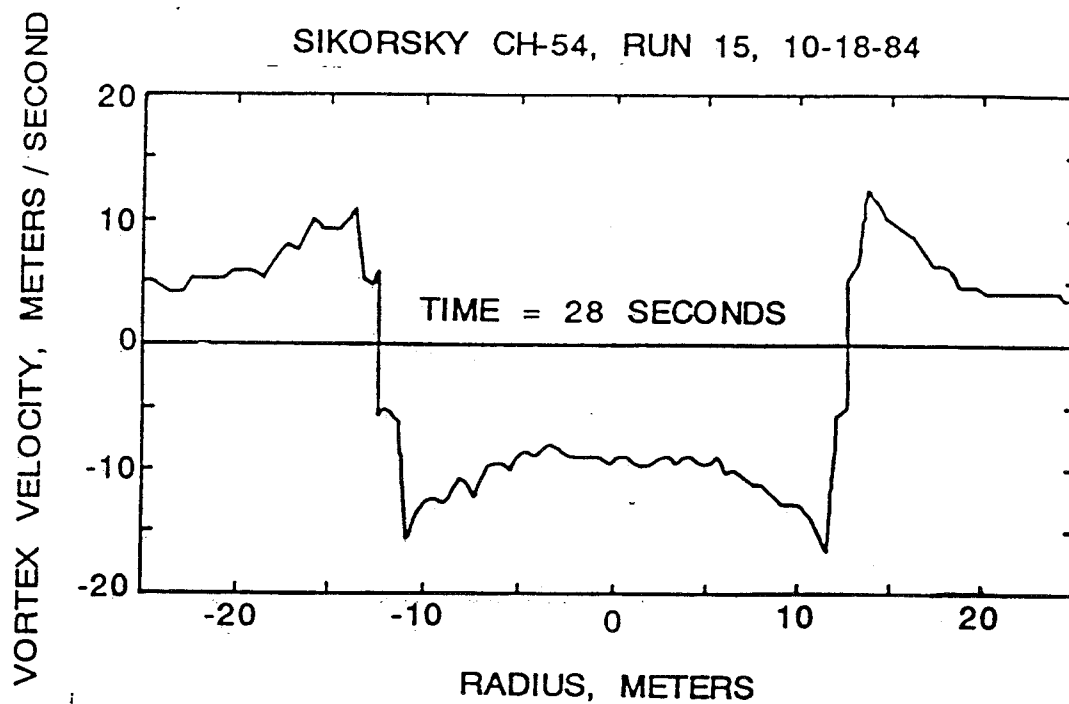


Figure 15. Measurement in the wake of a CH-54 with a weight of 38,000 lbs at 30kts, 28 seconds after the aircraft has passed the measurement point (Ferguson, ref. 33)

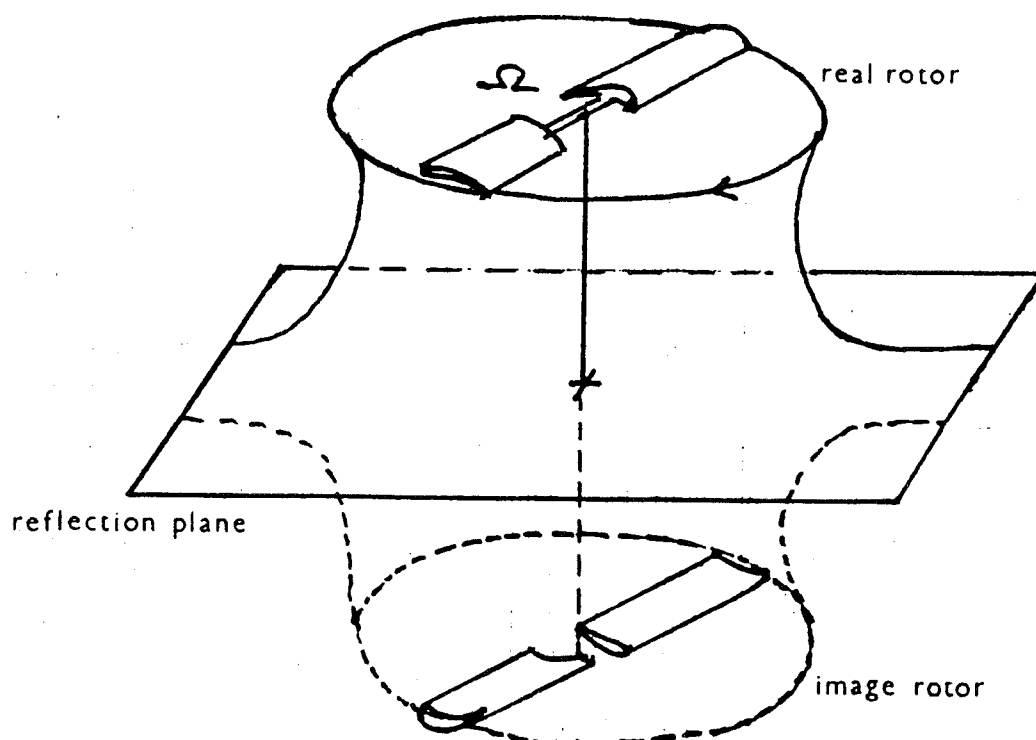
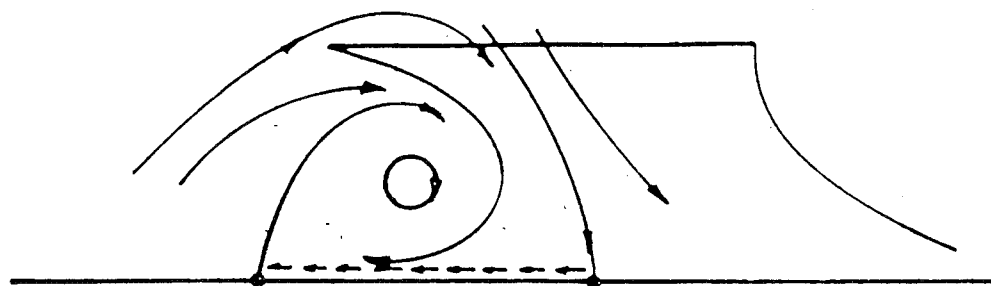


Figure 16. Representation of ground effect using a mirror image rotor (Kusmarwanto, ref. 22)



S, Ground Boundary Layer



Vorticity in Ground Boundary Layer



Vorticity in Rotor Wake

Figure 17. Schematic of the shear layer formed as the wall jet streams along the ground. (Sun, ref. 18)

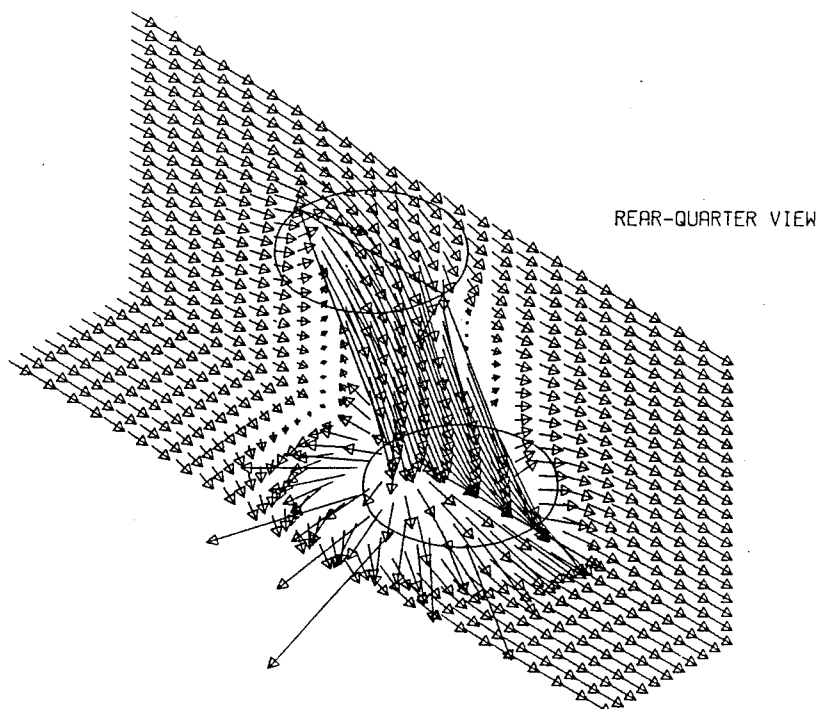


Figure 18. Example of flow velocity vector visualisation for a rotor in ground effect at low advance ratio. (Heyson, ref. 8)

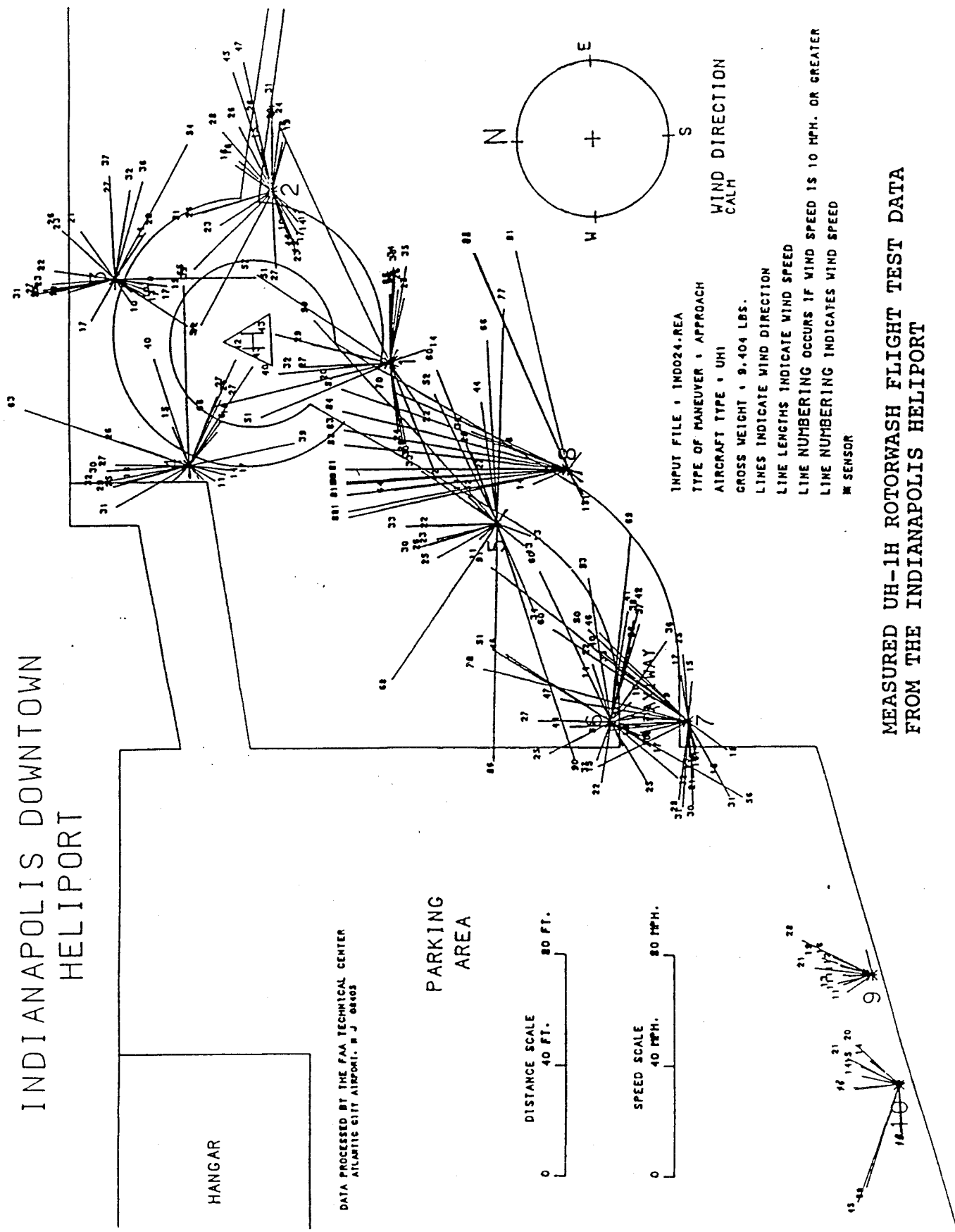


Figure 19. Example of measured rotorwash flight test data from Indianapolis Heliport (Weiss, ref. 25)

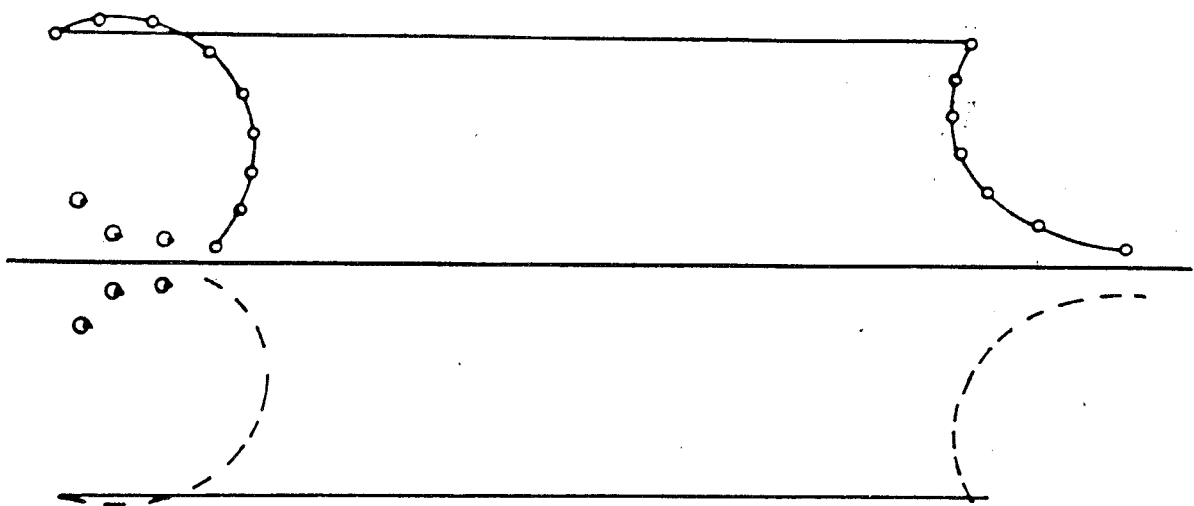


Figure 20. Schematic of the principle of the model used by Sun to calculate the ground vortex (Sun, ref. 18)

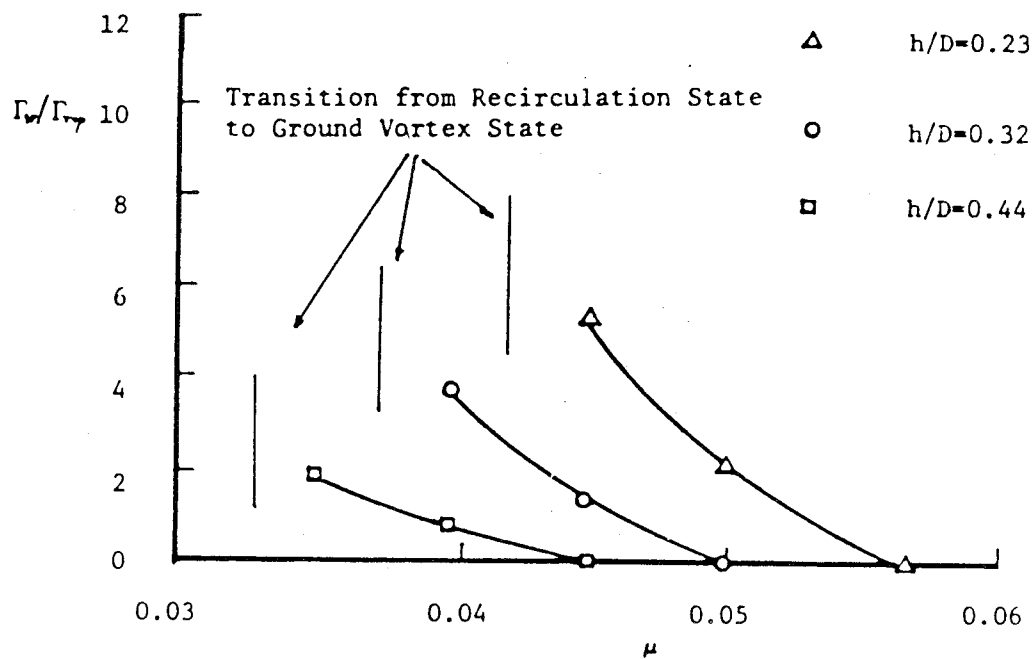


Figure 21. Ratio of ground vortex to tip vortex strength. (Sun, ref. 18)

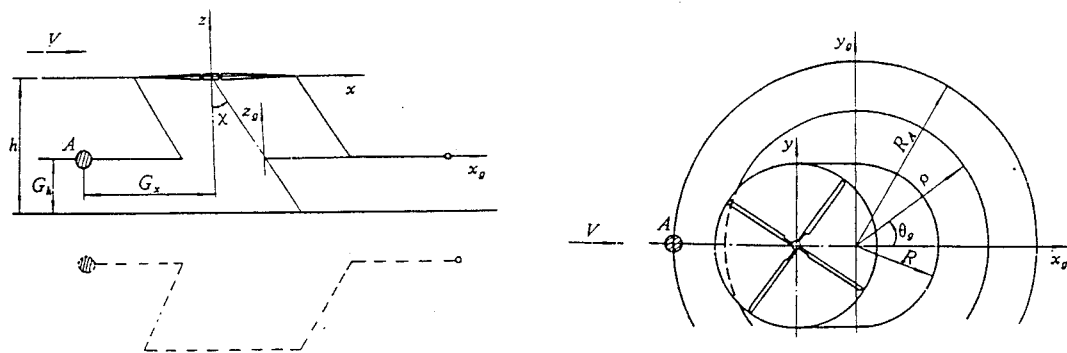


Figure 22. Principle adopted for the calculation of the ground vortex by He. (He, ref. 24)

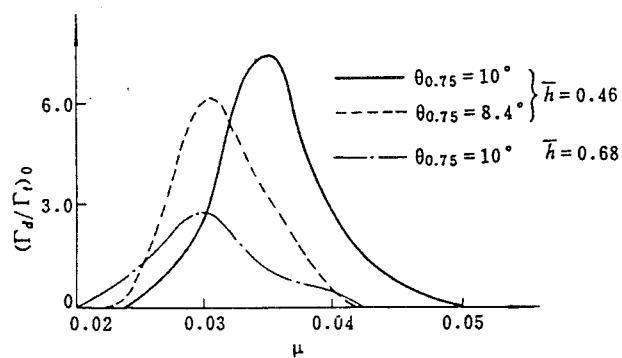


Figure 23. Ratio of ground vortex to tip vortex strength. (He, ref. 24)

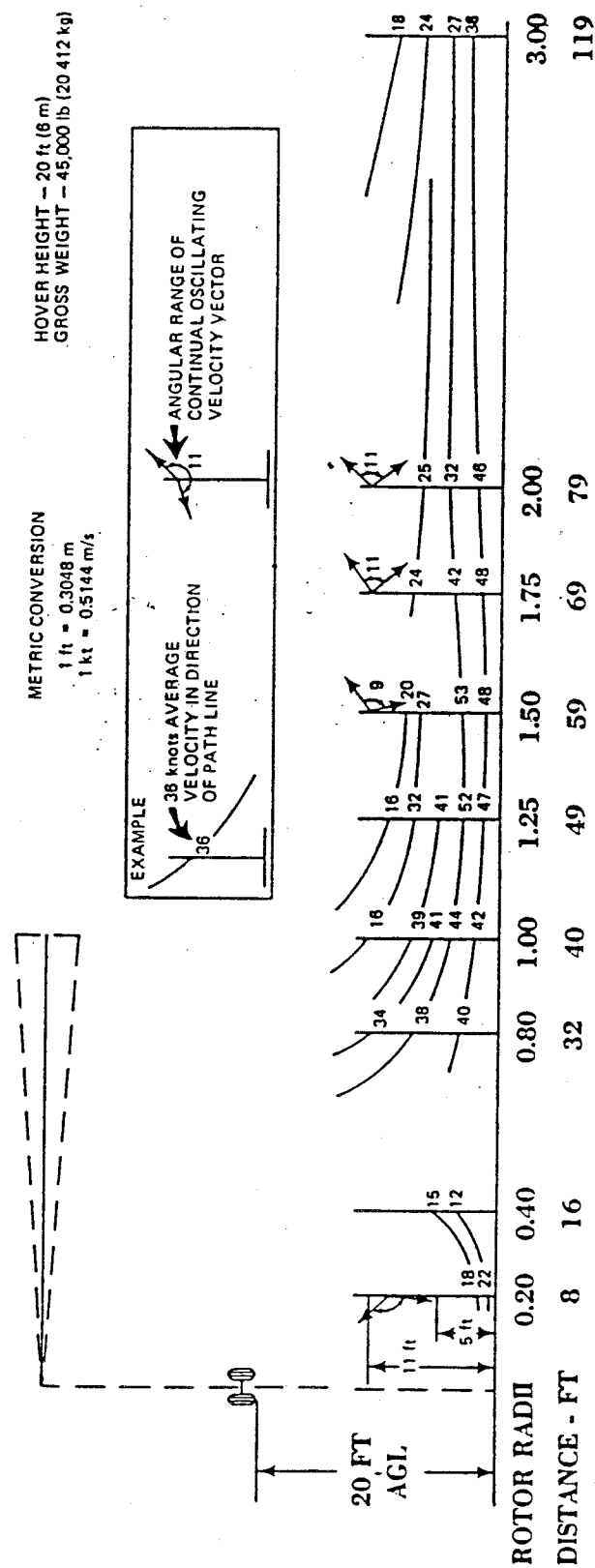


Figure 24. Measurements of the wall jet velocity decay for a CH-53 in hover - case 1. (Ferguson, ref. 33)

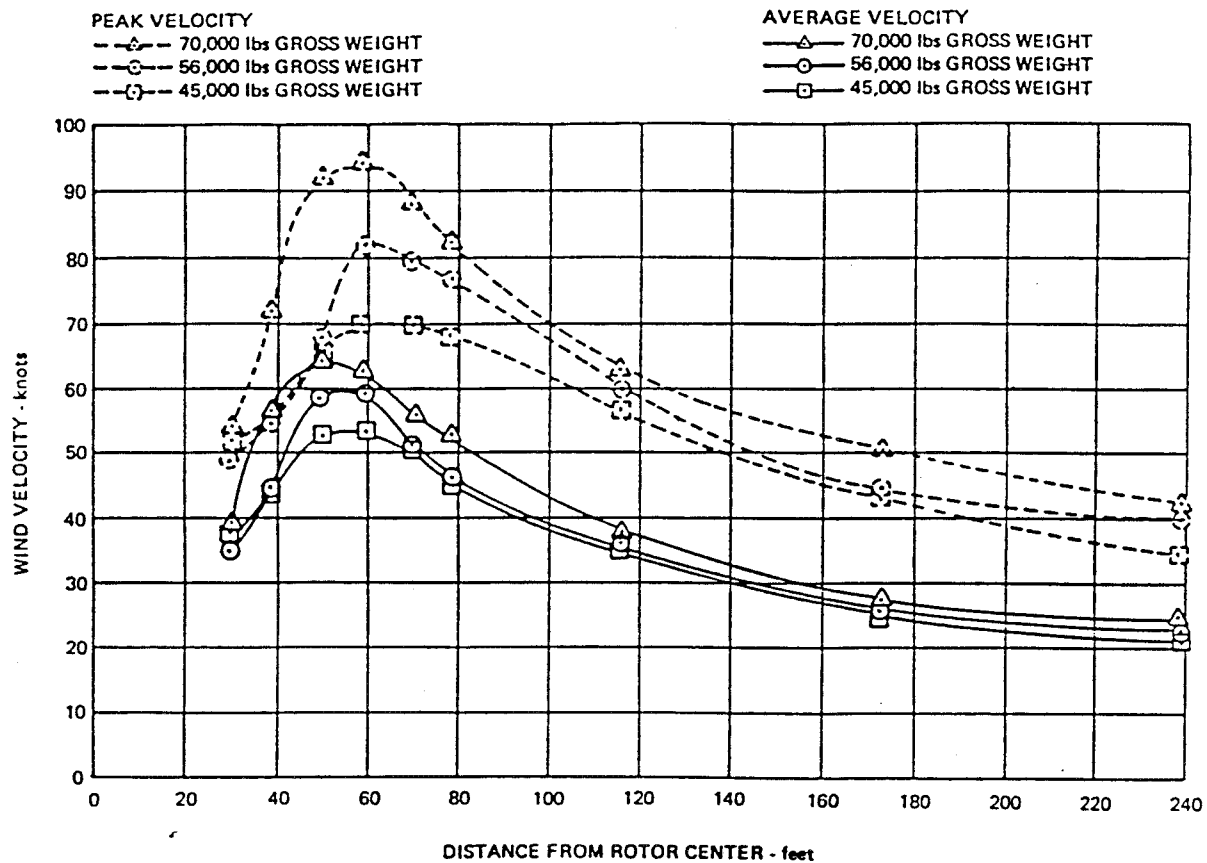


Figure 25. Measurements of the wall jet velocity decay for a CH-53 in hover - case 2. (Ferguson, ref. 33)

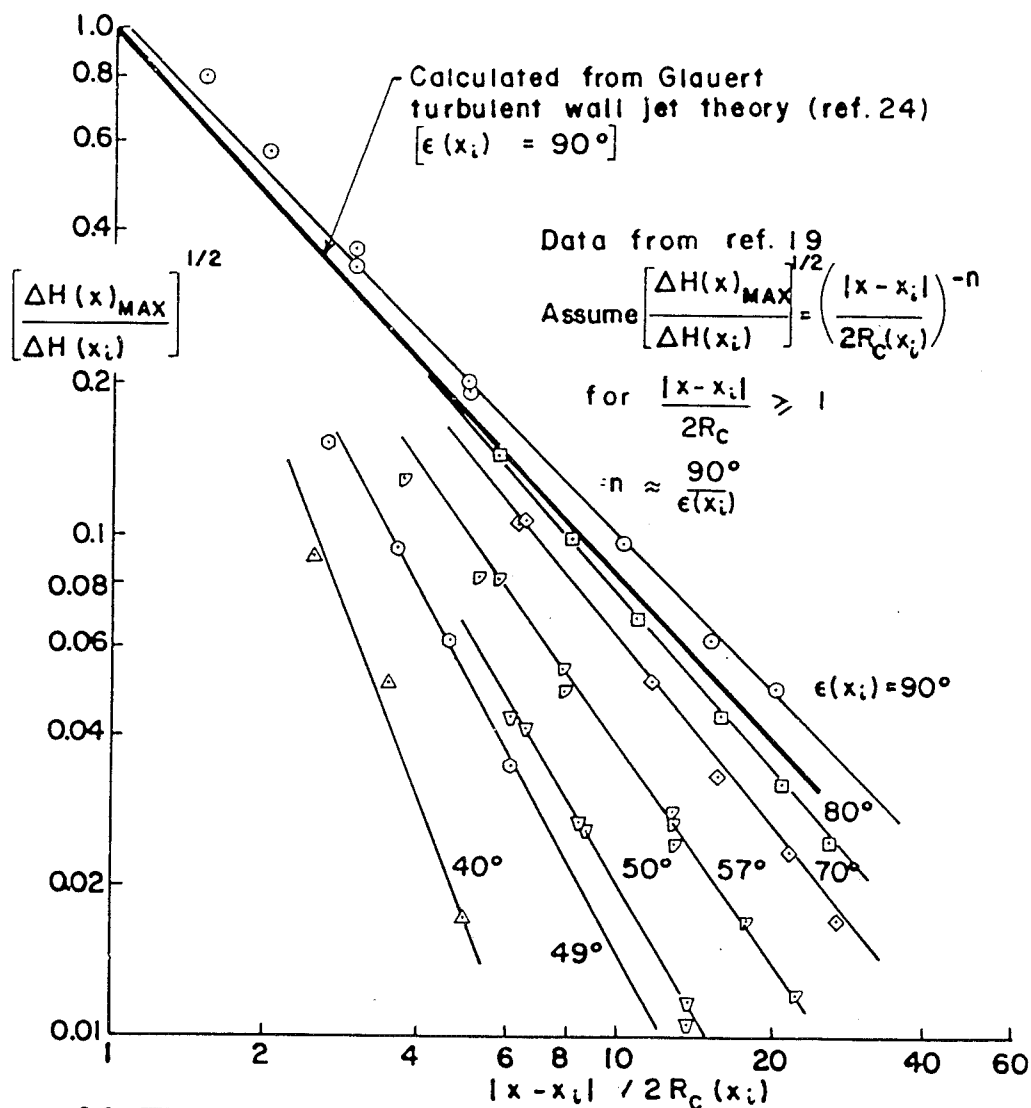


Figure 26. The wall jet velocity presented on a logarithmic scale (Levinsky, ref. 7)

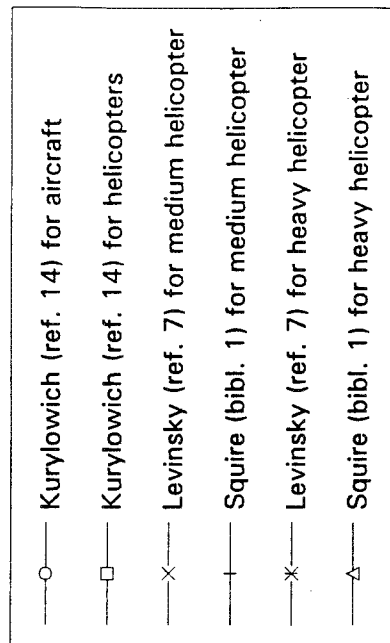
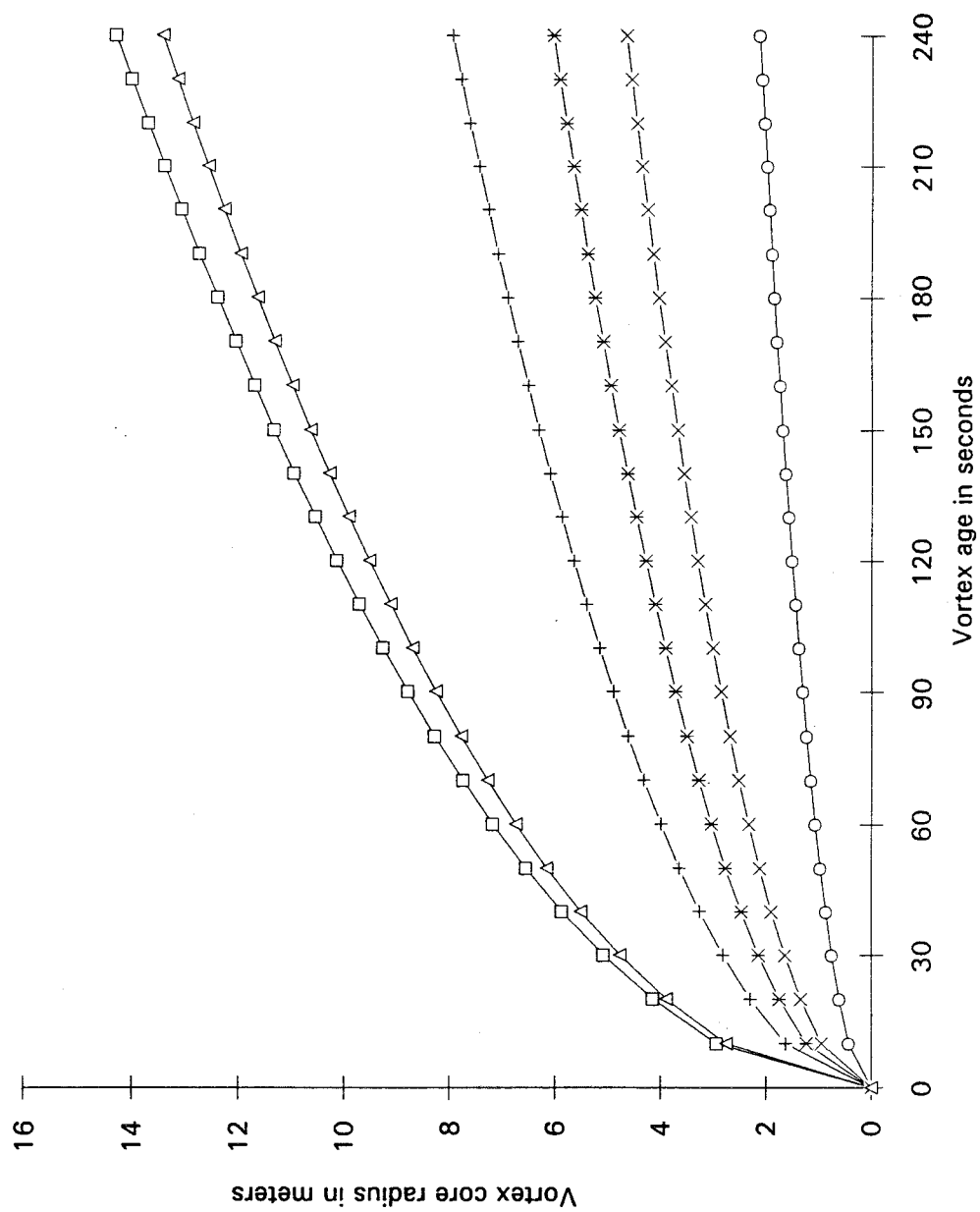


Figure 27. Comparison of the results from different calculation methods of vortex core radius

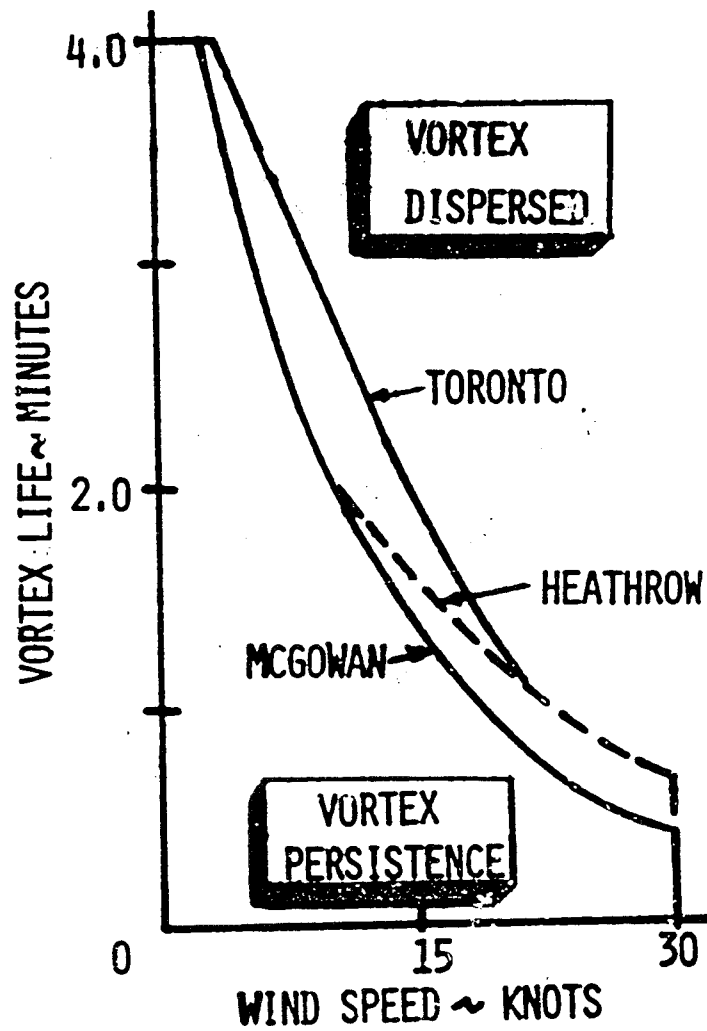


Figure 28. Measurements of vortex persistence for aircraft wakes as a function of the ambient wind. (Kurylowich, ref. 14)

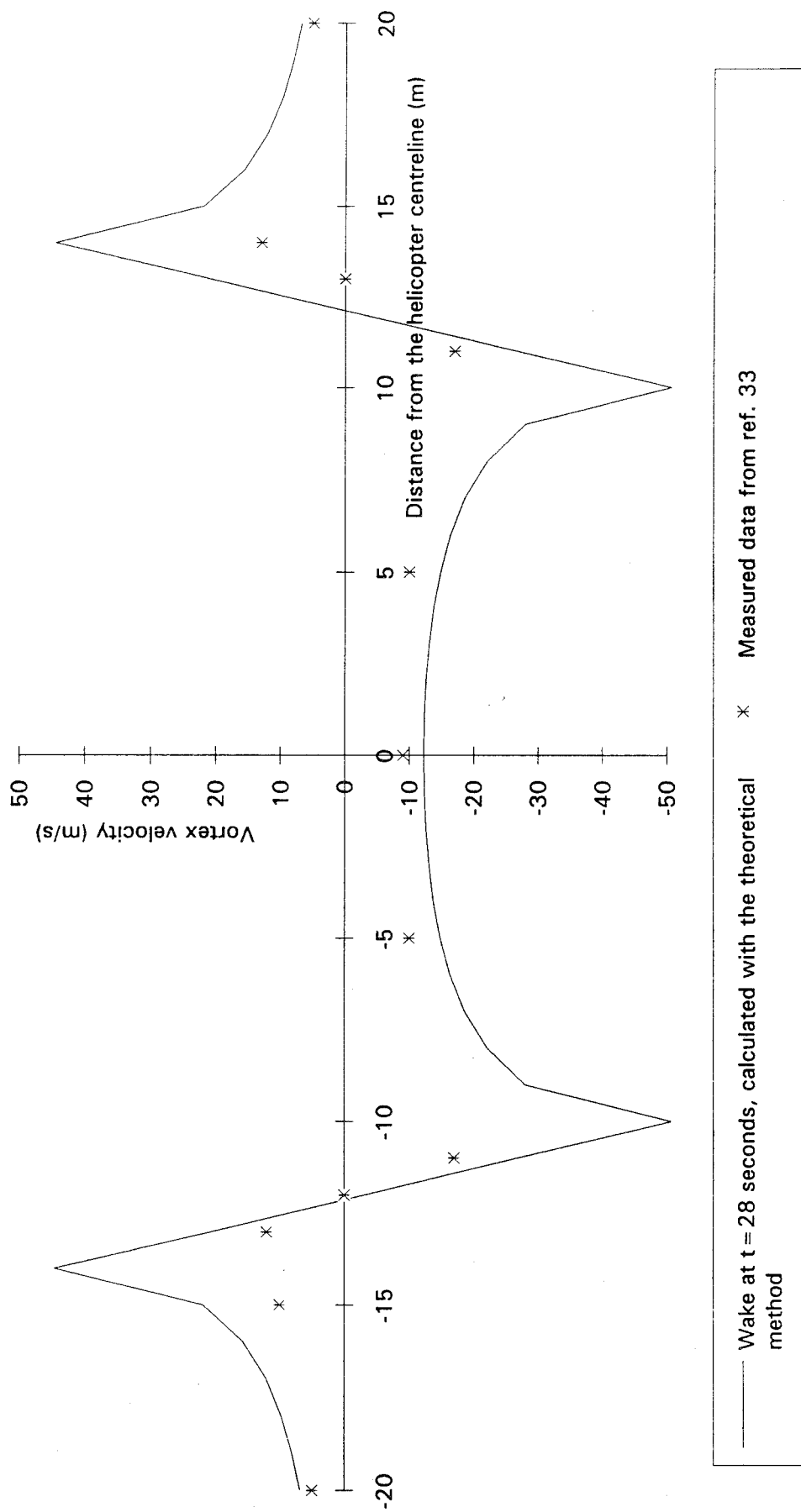


Figure 29. Comparison of the theoretically predicted wake vortex velocity with measured data, at $t = 28$ seconds behind a CH-54 at a speed of 15 m/s.

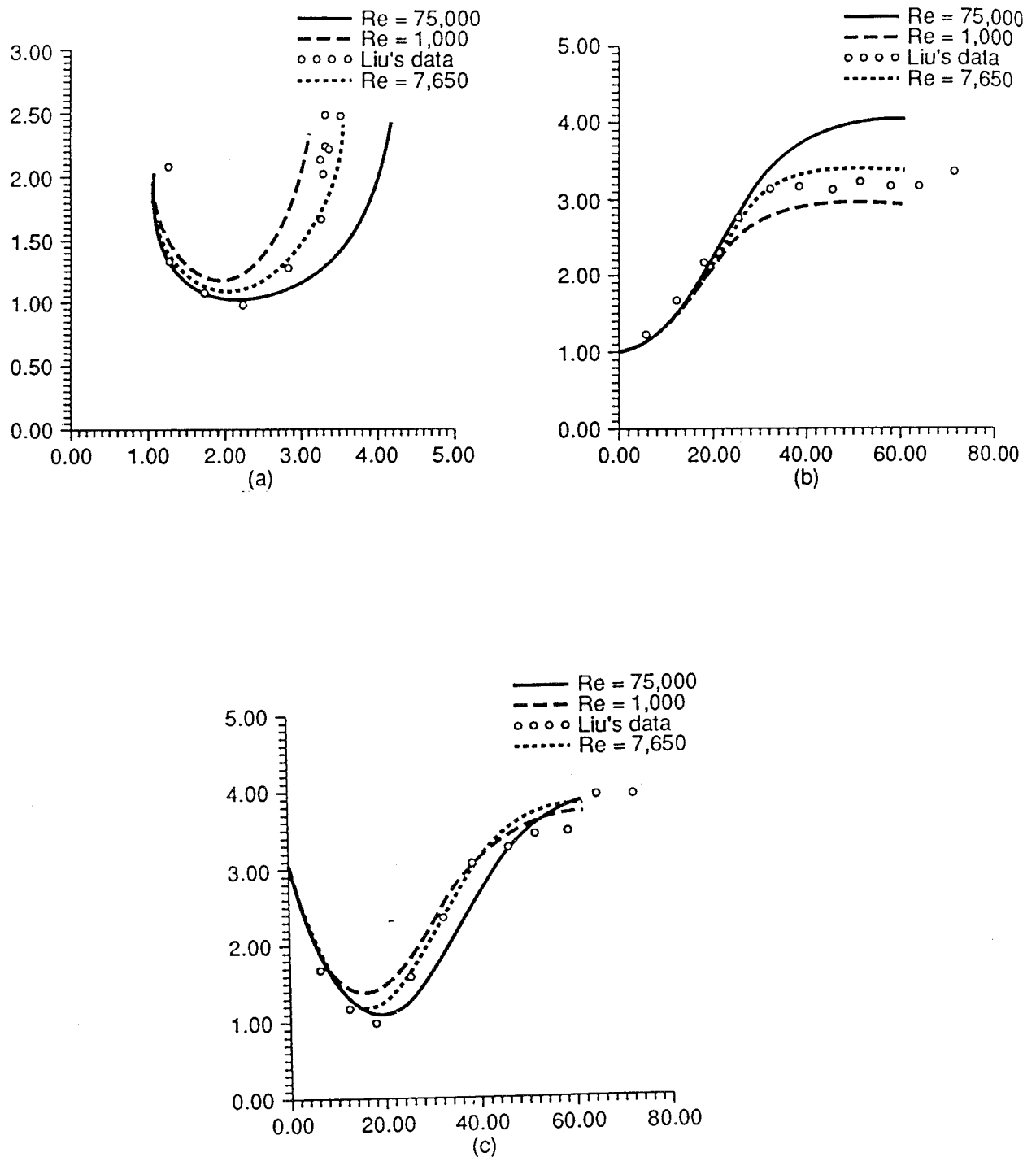


Figure 30. Measured and calculated (a) vortex trajectories, (b) lateral vortex position histories, (c) vortex elevation histories, at various Reynolds numbers in ground effect (Zheng, ref. 36)

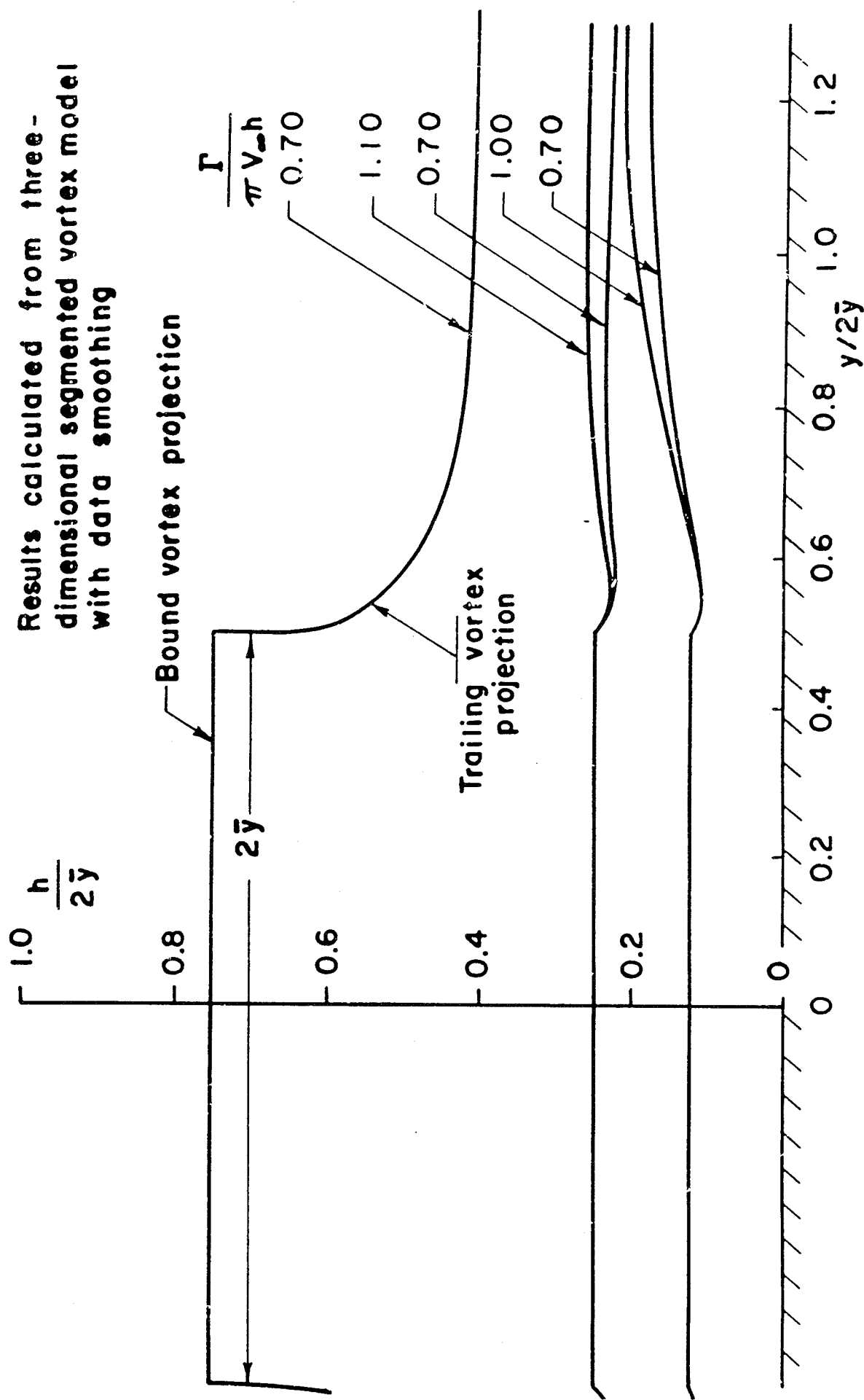


Figure 31. Theoretical prediction of the 'up float' of the wake vortex for various rotor heights above the ground plane (Levinsky, ref. 7)

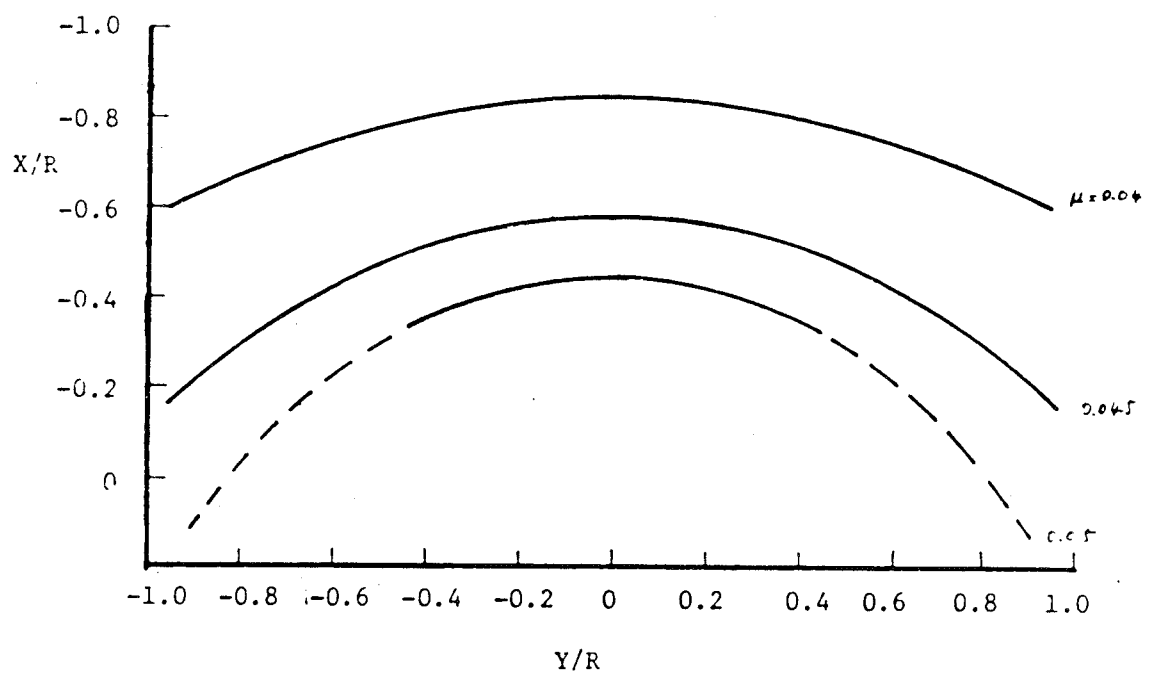


Figure 32. Wind tunnel measurements of ground vortex location indicating the lateral spread (Sun, ref. 18)

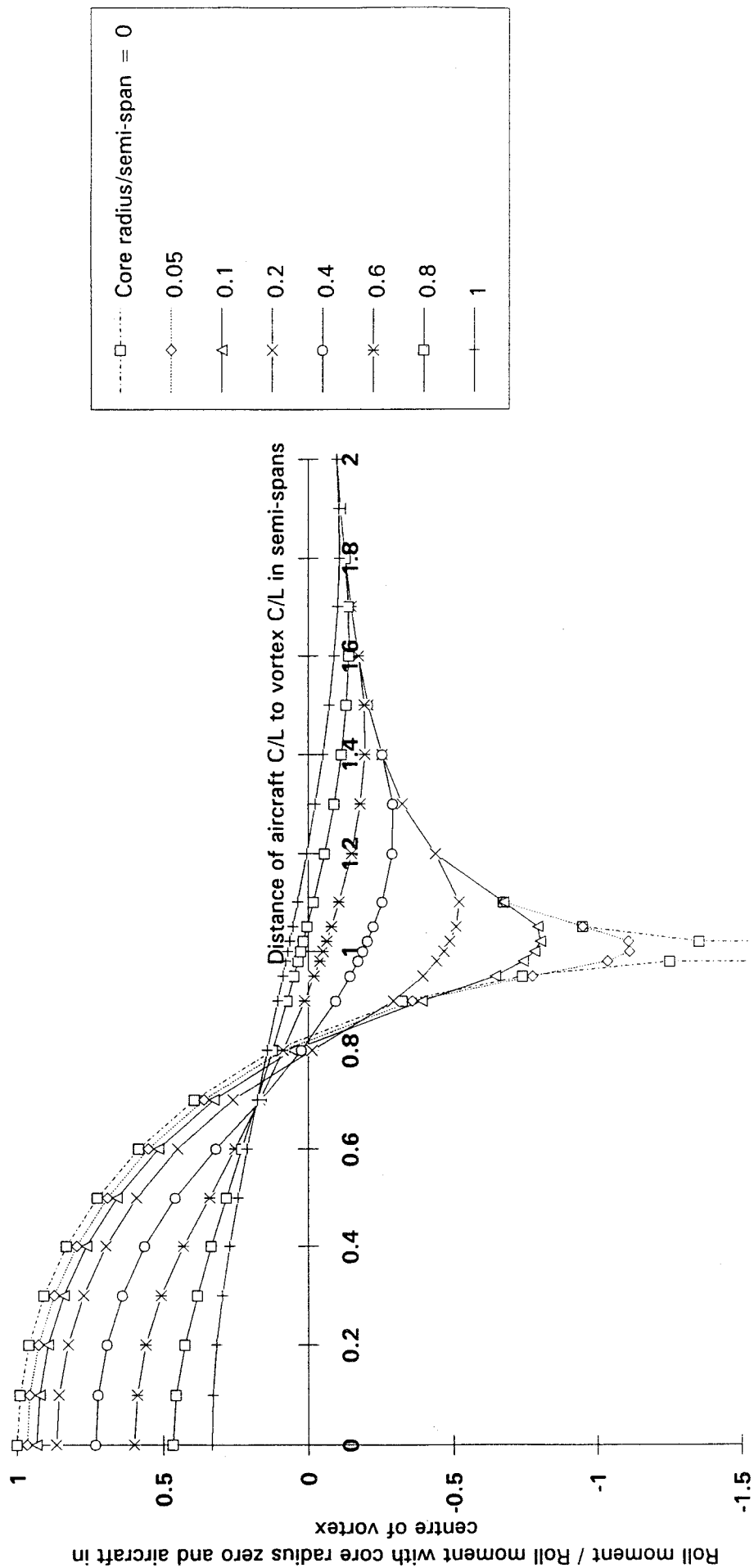


Figure 33. Theoretical prediction of the effect of the relative position of a light aircraft to the vortex centre and of the core radius on induced rolling moment

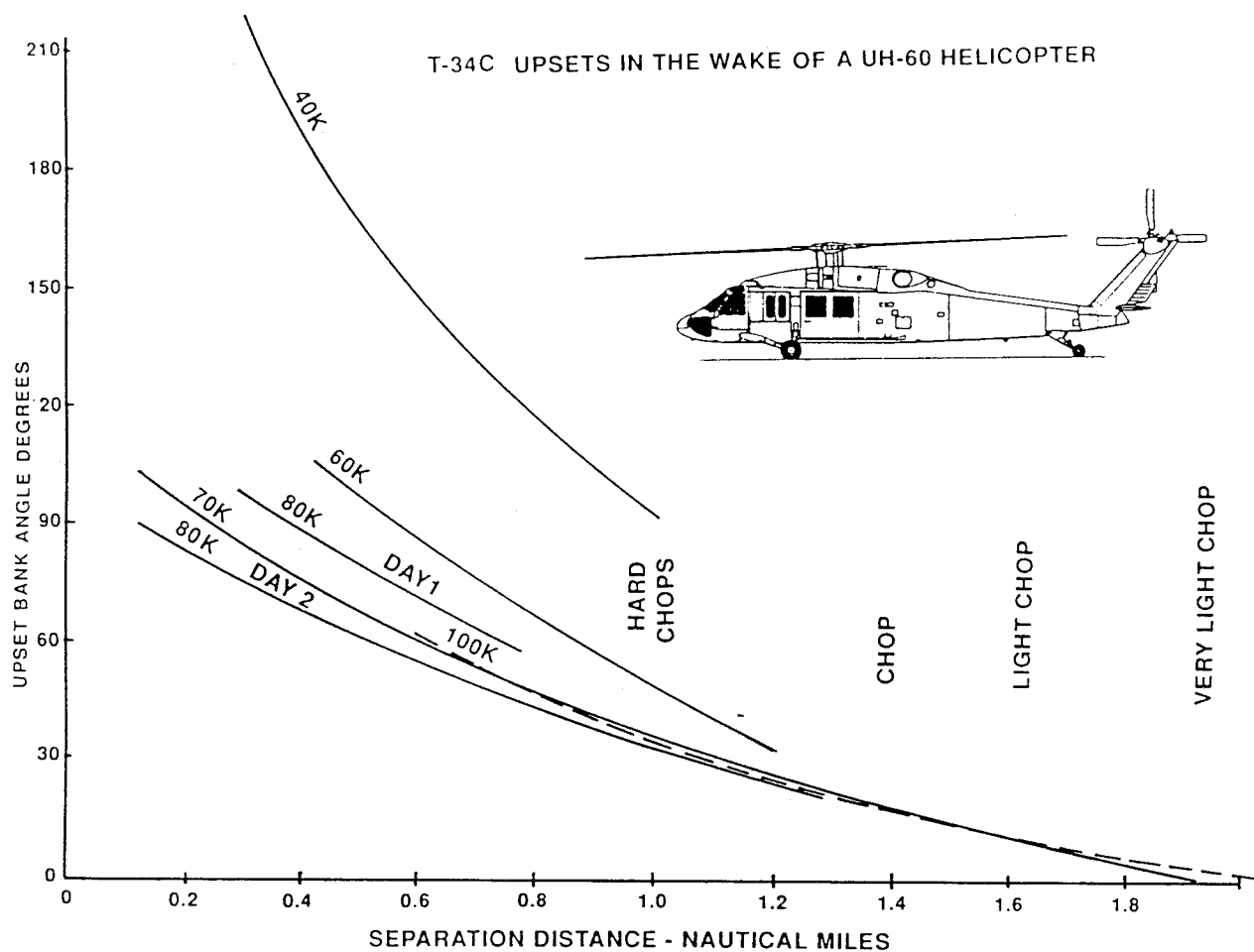


Figure 34. Variation of upset bank angle with separation distance between a T-34C and a UH-60 helicopter (Tymczyszyn, ref. 34)

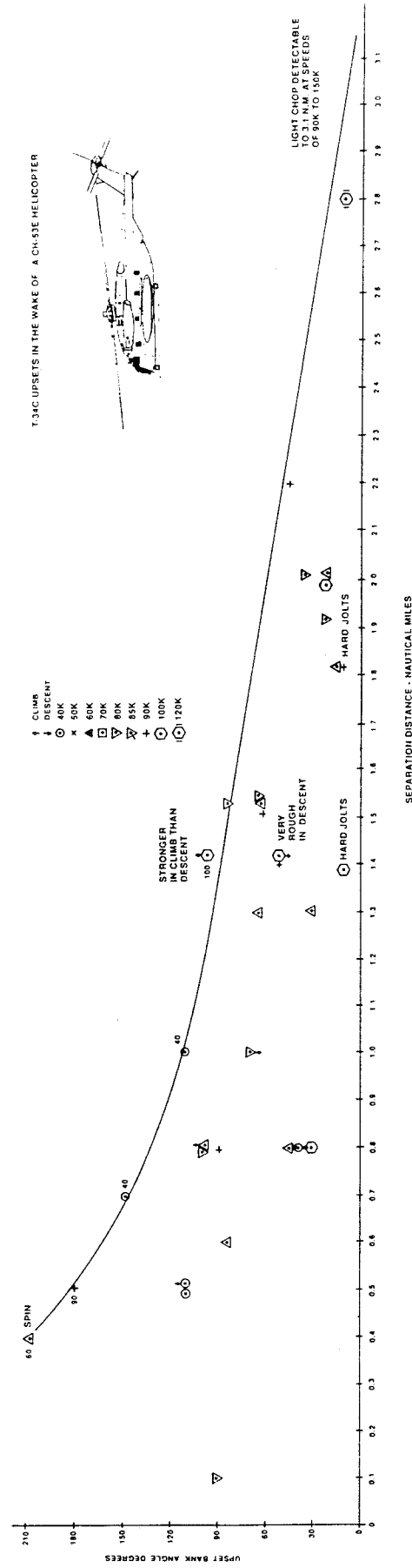


Figure 35. Variation of upset bank angle with separation distance between a T-34C aircraft and a CH-53E helicopter.
(Tymczyszyn, ref. 34)

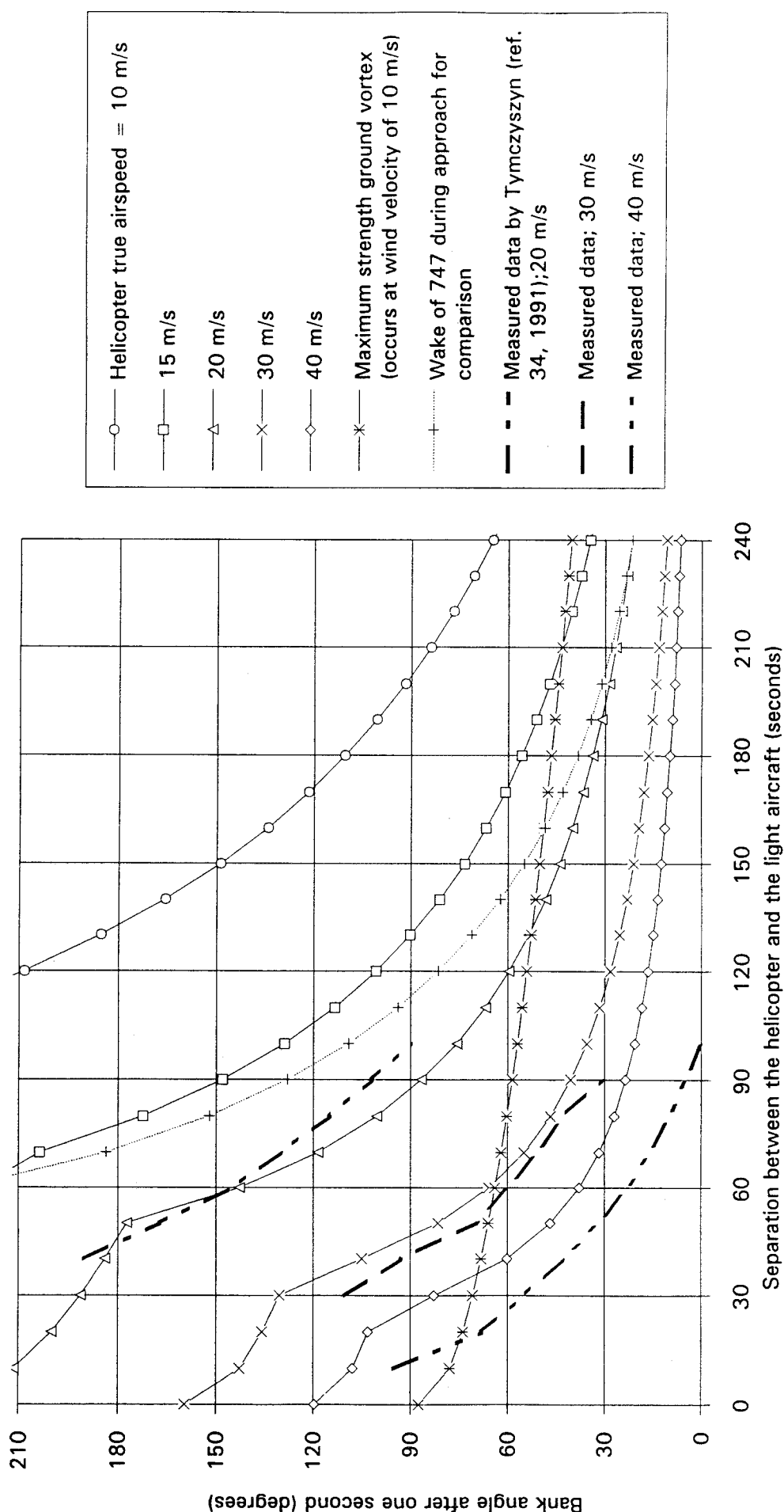


Figure 36. Comparison of the results of the developed method with measured data (ref. 34) for a T-34C penetrating the wake of a typical 20,000 lbs helicopter (such as the S-61 and the UH-60), as a function of separation time

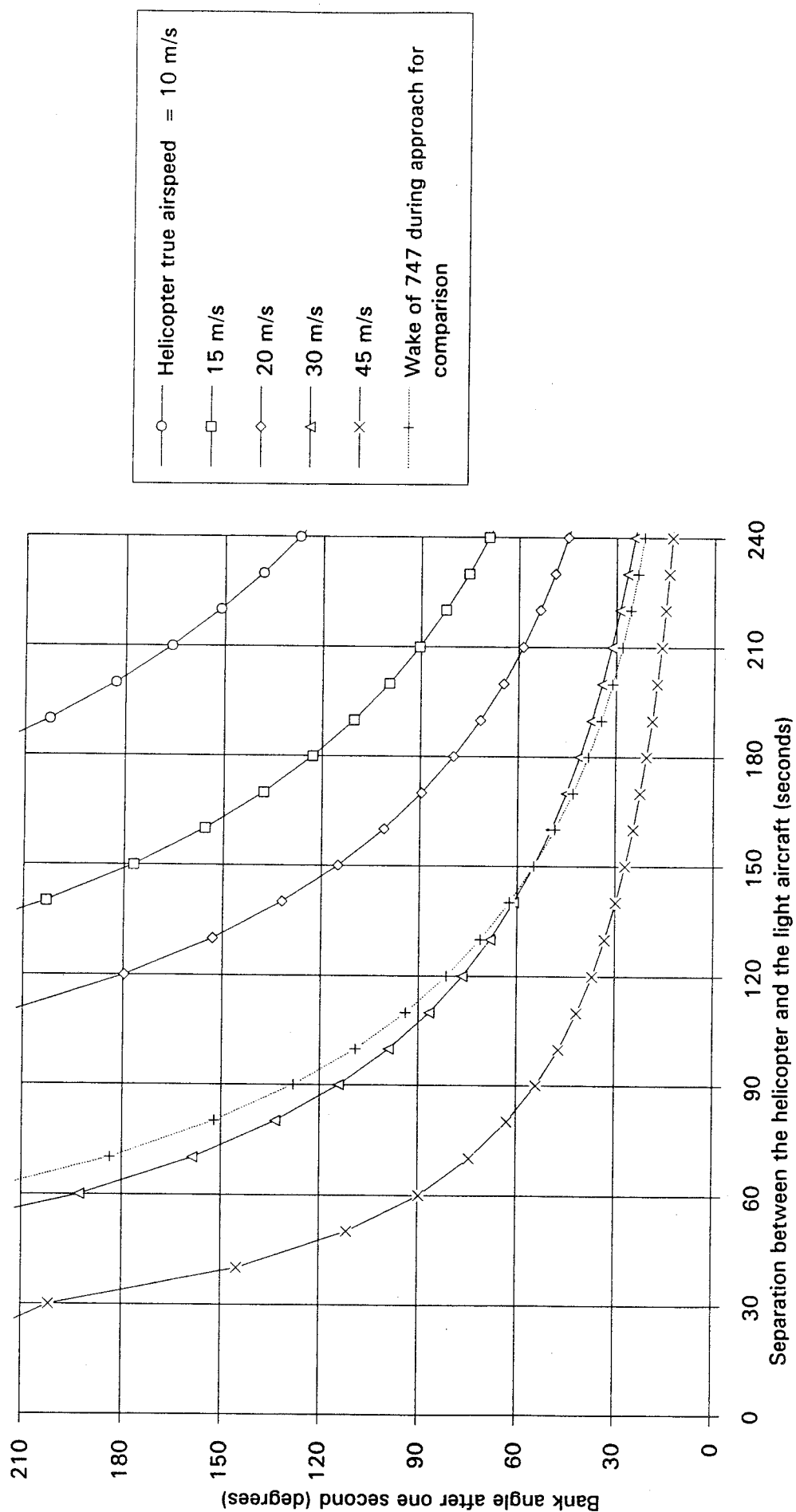


Figure 37. Comparison of the results of the developed method with measured data (ref. 34) for a T-34C penetrating the wake of a typical 70,000 lbs helicopter (such as the CH-53E), as a function of separation time

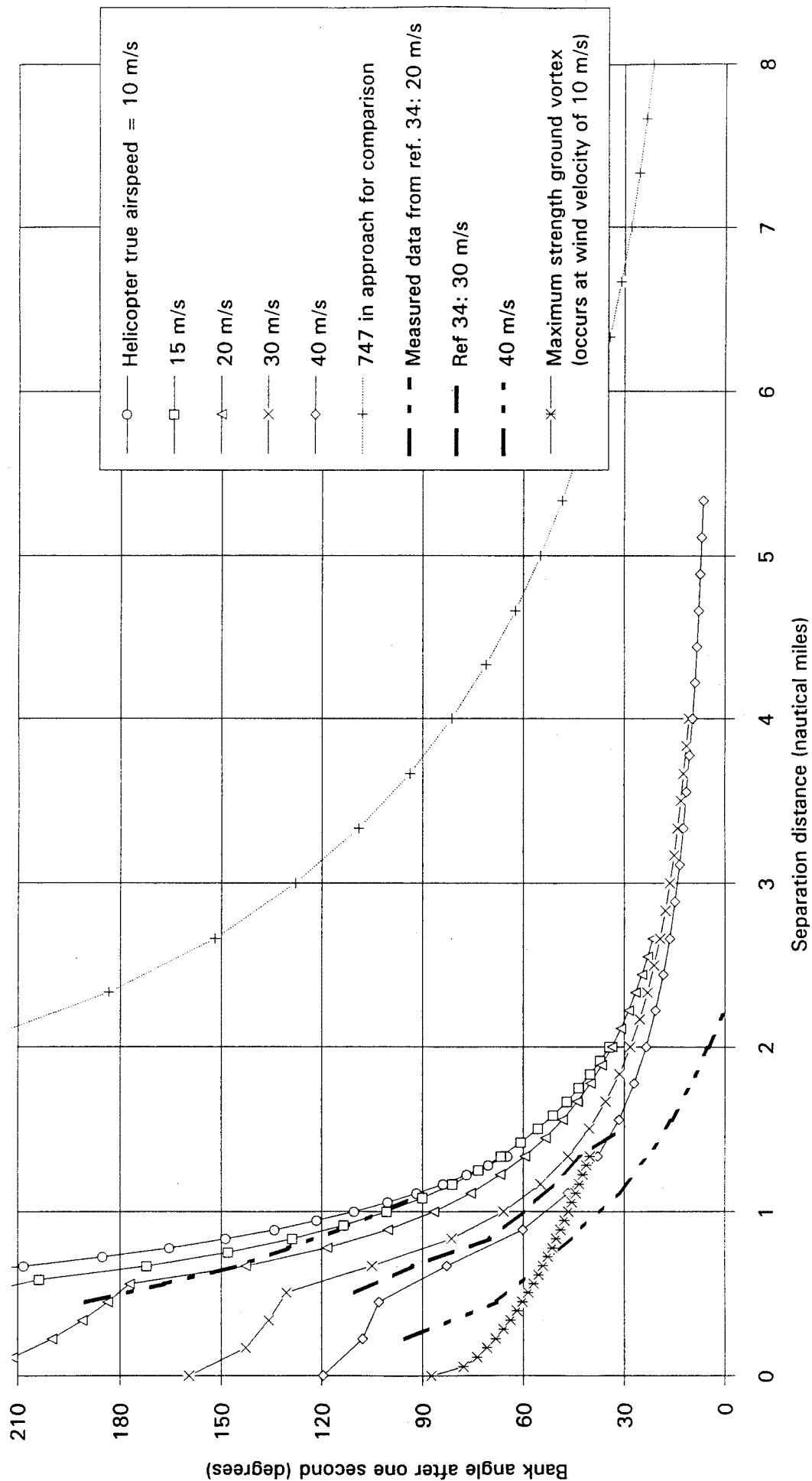


Figure 38. Comparison of the results of the developed method with measured data (ref. 34) for a T-34C penetrating the wake of a typical 20,000 lbs helicopter (such as the S-61 and the UH-60), as a function of separation distance

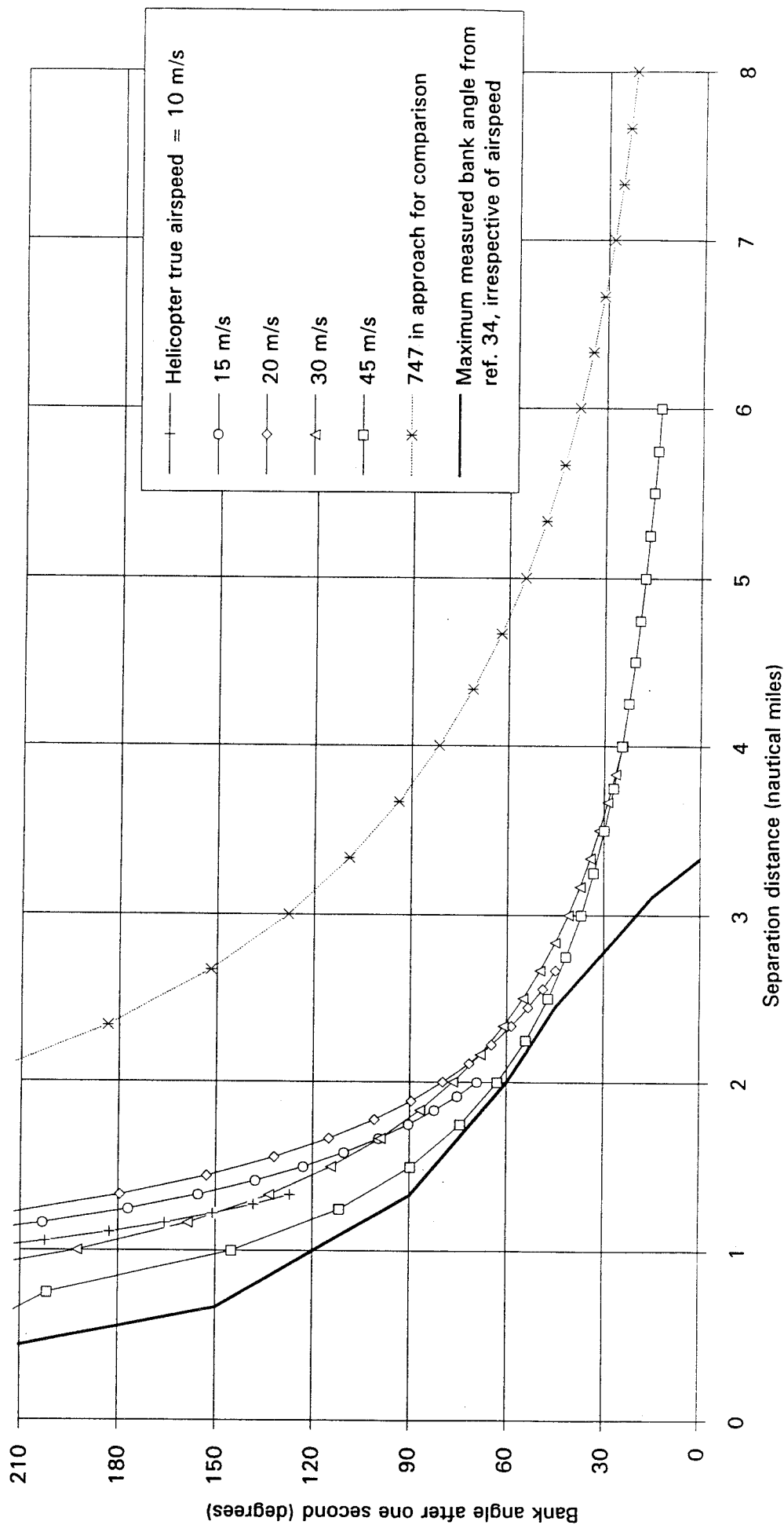


Figure 39. Comparison of the results of the developed method with measured data (ref. 34) for a T-34C penetrating the wake of a 70,000 lbs helicopter (such as the CH-53E), as a function of separation distance

TYPE: PA-28 WARRIOR

SPECIFICATION	28-151	28-161 II
Engine	150 hp Lycoming O-320-E3D	160 hp Lycoming O-320-D3G
Engine TBO (hrs)	2000	2000
No. of Seats	4	4
Wing Span (ft / ins)	35/0	35/0
Length (ft / ins)	23/10	23/10
Height (ft / ins)	7/4	7/4
Useable Fuel Capacity (US gal)	48	48
Gross Weight (lbs)	2325	2325 (77 - 82) 2440 - 2447 (83 & later)
Empty Weight (lbs)	1301 - 1315	1344 - 1348
Useful Load (lbs)	1010 - 1024	972 - 1099
PERFORMANCE		
Max Speed	118 kts	127 kts
Cruise Speed	117 kts	126 - 127 kts @ 75% 94 kts @ 55%
Efficiency (gph)	9.2 @ 75% 8.4 @ 55%	10 @ 75% 7.8 @ 55%
Stall Speed with Flaps/Gear down	51 kts	50 kts
Climb @ Sea Level (fpm)	649	644 - 710
Range with reserves	605 nm @ 75% 632 nm @ 55%	525 nm @ 75% 640 nm @ 55%
Service Ceiling (ft)	12,700	11,000 - 14,000
Take Off (Ground Run) (ft)	1065 - 1410	975
Take Off (over 50 ft obst) (ft)	1760	1490 - 1650
Landing (Ground Roll) (ft)	595	595
Landing (over 50 ft obst) (ft)	1115	1115



Figure 40. Geometry, performance and appearance of the PA-28-161 Cadet

OXFORD KIDLINGTON AIRPORT

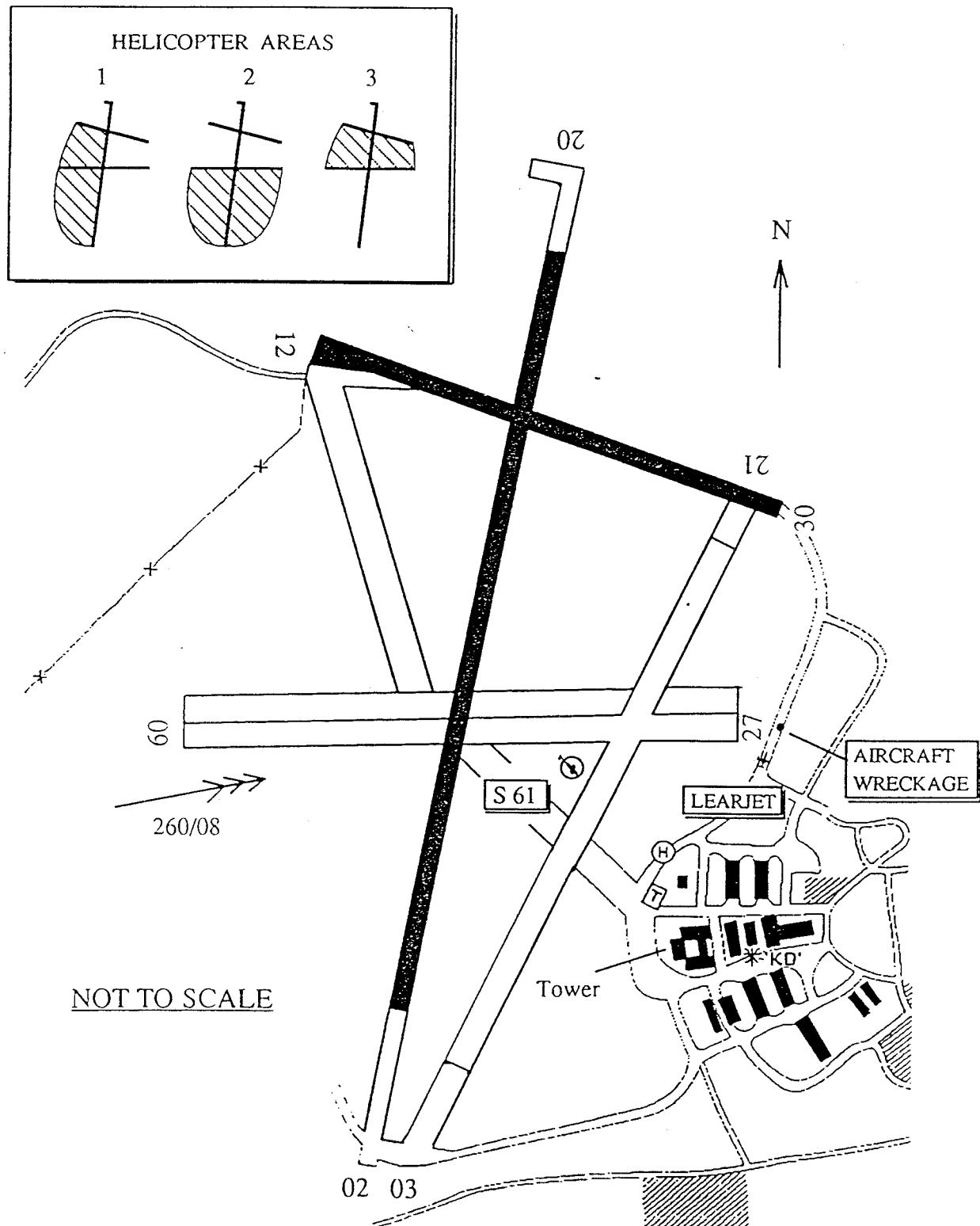
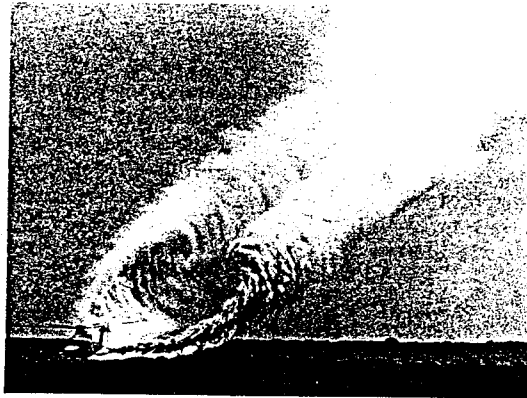


Figure 41. Map of the situation at the time of the accident at Kidlington airport (AAIB, ref. 37)



Sikorsky S76 – Photo FAA Technical Center, Mr J Sackett

Figure 42. Smoke visualisation of the wake of a S-76 during the transition to hover in a similar fashion as at Kidlington (FAA Technical Centre, Mr J. Sackett)

