EUR RVSM PROGRAMME RESPONSE
to the recommendations in the report

En-route encounters with Wake Vortices, and the implications of Reduced Vertical Separation Minima (RVSM)

[Woodfield Aviation Research Report No. 9901, March 1999]

The following describes the response of the EUR RVSM Programme to the recommendations provided in the report on Wake Vortex encounters and their implications on RVSM, developed under a EUROCONTROL contract by Alan A. Woodfield, Woodfield Aviation Research. Following this response, a copy of the full report can be found.

Each of the recommendations, copied from Chapter 9 of the report, is provided followed by the EUR RVSM Programme response to that specific recommendation, which has been agreed by the 6th meeting of the RVSM Programme Steering Group in May 2000.

RECOMMENDATION 1:

RVSM is not expected to increase the probability of a hazardous encounter with wake vortices, but pilots and air traffic should be informed that nuisance encounters would increase.

Programme Response:

The prognosis is that the introduction of RVSM within European airspace is not expected to increase the probability of hazardous encounters. The report recognises, however, that vortex encounters are totally unpredictable and that passengers should keep a seat belt loosely fastened whenever possible. As nuisance encounters are forecast to increase, this element will be included within our planned Functional Hazard Analysis of the introduction of RVSM. It is our intention to reproduce the Summary from the Report on the RVSM web site and the full Report will be made available for download.

RECOMMENDATION 2:

A change of flight level, a tactical heading or a track offset of 1 n.m. should be made available on request from ATC as a contingency procedure to remove aircraft from persistent nuisance encounters with wake vortices when they occur.

Programme Response:

Air Traffic Control can react directly to a pilot’s notification of encountering persistent wake vortices, therefore, the RVSM programme will not be recommending an introduction of an established off-set procedure. Indeed only the more sophisticated FMS are capable of flying offsets and the use of upwind offsets for specific pairs of aircraft will be very difficult to implement in practice within European airspace. The variety of aircraft types and performance, route directions and changing weather patterns will make this “solution“ almost impossible to interpret. The resultant increase in lateral or longitudinal separation standards of a permanent offset would also result in a loss of airspace capacity in the Core Region.

Doc 7030/4 (EUR SUPPS), however, recognises wake turbulence as being one of the factors that could lead ATC to resort to the application of current lateral or vertical separation standards during RVSM operations. The ATC RVSM Guidance Manual includes the option of suspending RVSM operations. There is sufficient flexibility within Doc 7030/4 (EUR SUPPS) for pilots and ATC to be able to resolve any need for flight deviation or even to introduce increased separation standards, depending on the traffic situation. This flexibility is possible on a tactical basis in the European environment, unlike the NAT region, due to the existence of Direct Controller Pilot Communications (DCPC). The relevant extracts follow:

Proposed Amendment to the EUR Regional Supplementary Procedures (Doc 7030/4)

- Para X.1.2. The pilot shall inform air traffic control as soon as possible of any circumstances where the vertical navigation performance requirements for the EUR RVSM airspace cannot be maintained . In such cases, the pilot shall obtain a revised air traffic control clearance prior to initiating any deviation from the cleared route and /or flight level, whenever possible. Where a revised air traffic control clearance could not be obtained prior to such a deviation, the pilot shall obtain a revised clearance as soon as possible thereafter.
- Para X. 3.1. When an aircraft operating in the EUR RVSM airspace encounters severe turbulence due weather or wake vortex that the pilot believes will impact the aircraft's capability to maintain its cleared flight level, the pilot shall inform ATC. Air traffic control shall establish either an appropriate horizontal separation or an increased minimum vertical separation.

RECOMMENDATIONS 3 & 4:

Before the introduction of RVSM, an effective system should be established for reporting, collecting and analysing reports from pilots and air traffic of significant wake vortex encounters.

After the introduction of RVSM, a study should be made of the received wake vortex reports, together with details of any other major wake vortex report above 5000ft in recent years, and this should be included as part of the Monitoring Post Implementation (Safety Case).

Programme Response:

It is agreed that the introduction of wake vortex reporting is a Programme responsibility. Wake vortex report forms are already an established feature of the NAT RVSM programme. A similar version will be introduced to collect information reports of wake turbulence encountered within European RVSM airspace. These reports will be fully analysed by the RVSM Programme and taken into account both within the Detailed Functional Hazard Analysis and the pre-implementation Safety Case. Wake vortex reports will continue to be gathered both prior and following the introduction of RVSM. These reports will be introduced, therefore, into the Safety Domain so that there is a continuing process in being. Thus, if required, it would become a Safety Domain responsibility to provide follow up studies and analysis for the future.

RECOMMENDATIONS 5 & 6:

Pilots and air traffic should be better informed of the character of wake vortices and typical encounters. Confirmation should be sought that recovery from unusual attitudes on instruments as a result of a major upset, such as a wake vortex encounter, is included in pilot simulator training schedules.

Programme Response:

The need for the awareness of wake vortex within RVSM airspace is recognised by the RVSM Programme. The contents of the Report will be made available through the RVSM web site. It is a condition of the RVSM approval requirements as specified in Doc.7030/4 that Operators intending to conduct flights within European RVSM airspace have instituted flight crew procedures. Confirmation will be sought from representative commercial pilot flying schools that adequate practice in recovery from unusual attitudes as a result of wake vortex encounters is a feature of their training. It should be noted, however, that the fidelity of all flight simulators cannot be assumed with regard to the dynamics of a wake vortex encounter. The national trainers briefings provided by EUROCONTROL have included relevant information and experience gained from the introduction of RVSM over the NAT and the NAT/EUR transition airspace. INSTILUX will be provided with a copy of the Report and its recommendations for their subsequent action with regard to the basic ATC syllabus.

[END OF PROGRAMME RESPONSE]

For full report **"En-route encounters with Wake Vortices, and the implications of Reduced Vertical Separation Minima (RVSM)"**, see following pages.

Woodfield Aviation Research

Woodfield Aviation Research Report No. 9901
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En-route encounters with Wake Vortices, and the implications of Reduced Vertical Separation Minima (RVSM)

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Summary

Wake vortices are shed downstream by all aircraft and can be a potential hazard in en-route flight conditions as well as in the terminal area close to the ground. Introduction of Reduced Vertical Separation Minima (RVSM) bring aircraft closer together and it is important to assess whether or not this will significantly increase the risk of a hazardous encounter with wake vortices. Operations under RVSM in Oceanic airspace provide some practical experience with which to make an initial assessment of the likely effects of introducing RVSM in the more complex environment of European airspace.

The characteristics of wake vortices and typical encounters by aircraft are described. Heavy or Medium aircraft changing flight level within less than 2-3 minutes and through that of an encountering aircraft generate the greatest risk of a hazardous encounter. Data from reports to the UK CAA and NATS of wake vortex encounters in Oceanic airspace under RVSM are studied, and also some earlier data from en-route wake vortex encounters. It is noted that there were no significant wake vortex encounter incidents in the first nine months of RVSM operations over the North Atlantic, which is estimated to cover about 100,000 flights. However, there were several nuisance encounters and a contingency procedure was introduced to allow lateral upwind track offsets to move an aircraft safely away from continuing nuisance encounters with a wake. This seems to have eliminated wake vortex incident reports, although there is no doubt that nuisance encounters still occur. It is noted that the largest incidents with about 17° of roll occurred when an aircraft climbed or descended through the flight level of a following aircraft, which is not related to RVSM. This same scenario was responsible for the largest recorded disturbance of 70° of roll when a BAC 1-11 encountered the wake of a B747 that descended through its flight level 16-20 nm ahead, which demonstrates that en-route encounters may be hazardous.

Particular relevant features in European airspace that do not occur in Oceanic airspace are a wider mix of aircraft sizes, a greater number of aircraft changing flight levels, the presence of traffic on reciprocal tracks in airways, the intersection of airways, and the presence of up and down draughts at high altitudes as a result of winds passing over mountain ranges. These effects have been considered and it is concluded that the presence of mountain ranges and the wider mix of aircraft sizes will increase the probability of encountering wake vortices with RVSM compared with Oceanic airspace, but the encounters should remain a nuisance rather than a hazard. When wake vortex encounters occur and persist then a change of flight level, heading, or a track offset of 1 n.m. will usually prevent further encounters.

An effective system for reporting, collecting, and analysing significant wake vortex encounter situations identified by pilots and air traffic should be established so that any significant issues relevant to European airspace can be effectively monitored and appropriate action taken when necessary. It is also recommended that pilots and air traffic controllers should be better informed of the character of wake vortices and typical encounters.

Contents

1. Introduction

Aircraft produce wake vortices in all flight conditions as energetic swirls of air, or vortices, trailing downstream of each wing. The vortices can persist for several minutes and can induce large roll or normal acceleration disturbances if another aircraft passes through the wake before they decay. These wake vortices are small in diameter and in most conditions they descend gradually. The chances of an encounter are small unless aircraft are constrained to follow other aircraft on similar tracks and at similar heights. This occurs regularly when aircraft operate to or from an airport, and roll disturbances can be particularly hazardous near the ground. Thus regulations exist to enforce enough horizontal separation (in time or distance) between adjacent aircraft while landing or taking off so that the probability of a significant disturbance from the wake of a preceding aircraft is acceptably low. However, it is possible to encounter vortices whenever tracks intersect at similar altitudes and the time separation between aircraft is less than about two minutes.

Large disturbances can also occur as a result of wake vortex encounters during climb, cruise and descent and most of these arise when an aircraft encounters the wake of an aircraft that has recently climbed or descended through the same altitude. The use of specified Airways to manage civil air traffic increases the probability of these encounters by keeping aircraft on similar or reciprocal tracks. However, the minimum vertical and horizontal separation requirements that have been used to avoid collisions between aircraft on the same or reciprocal headings ensures that there is a very low probability of encountering the wake vortex of another aircraft cruising at a fixed height. True airspeeds are about 3 or 4 times higher in these flight phases than during approach or take off and vortices decay with time. Thus vortices typically persist for distances of 20 nm (40 Km) in climb, cruise or descent compared with 5-6 nm (10 Km) during approach or take off in calm conditions.

Improvements in aircraft sensors and operating procedures have allowed reductions in minimum vertical separation and Reduced Vertical Separation Minima (RVSM) were introduced in North Atlantic Oceanic airspace in March 1997. The reduction from 2000ft to 1000ft applied to operations by specific aircraft between Flight Levels 285 and 420 in the Minimum Navigation Performance Specifications Airspace of the North Atlantic Region. It is planned to introduce similar RVSM in European airspace.

One consequence of RVSM could be an increase in the probability of wake vortex encounters, and anecdotal reports of such encounters have arisen since the introduction of RVSM over the North Atlantic. A theoretical assessment of the likely effects of RVSM on wake vortex encounters[i] concluded that there was not likely to be a significant problem for the variety of aircraft types and infrequent changes in Flight Level expected over the North Atlantic.

RVSM operations over Europe will differ significantly from those over the North Atlantic because of, among other things, the wider mix of aircraft types, more frequent height changes, reciprocal tracks within airways, intersecting airways and greater traffic density. EuroControl wish to assess the experience gained during North Atlantic RVSM operations and general knowledge of wake vortex characteristics to determine any significant problems that may arise from wake vortex encounters as a result of applying RVSM in European airspace. If there are problems, then advice is required on possible techniques to alleviate problems. There is also a need to review the possible hazards from wake vortex encounters in the climb, cruise and descent phases of flight as traffic density and the range of aircraft sizes continues to increase.

This report describes the general characteristics of wake vortices and the effects on an aircraft encountering them. Descriptions of the results of encounters with wake vortices at significant altitudes and away from airport terminal areas are provided, reports from North Atlantic RVSM operations are summarised, and preliminary indications of possible acceptable encounter limits are presented. Some alleviation techniques are then discussed before presenting Recommendations and Conclusions relating to RVSM and, separately, for general en-route operations.

2. Wake Vortex characteristics

All bodies that produce lift when a fluid passes over them will generate circulation, i.e. a greater velocity over the upper surface than over the lower surface for positive lift. Wings are designed to be efficient lift producers and have particularly strong circulation. Wherever there is a rapid change in the spanwise distribution of lift across a wing then circulation will be shed downstream. This occurs at the wing tips, the ends of flaps (when deployed), and at the junction of the wing and fuselage. These regions of circulation usually amalgamate within about 10 wingspans downstream to form a pair of contra-rotating wake vortices. This is an energetic and stable type of flow which can persist for several minutes.

Decrease in pressure at the centre of a vortex maintains air in a vortex motion because the pressure gradient opposes the centrifugal force on each portion of the vortex. High tangential velocities in a vortex also reduce static air temperature. This lower temperature can make vortices visible in humid conditions at low altitude when moist air condenses in the high tangential velocity regions near the core. At higher altitudes the water vapour in jet engine exhausts is often entrained into the wake vortices and the vortices become visible as condensation trails.

If another aircraft encounters these vortices before they decay, then it can experience a large roll disturbance if it is following a similar track; a large normal acceleration pulse if its track is at a right angle, and a combination of these effects on other tracks. The size of disturbance depends on the vorticity of the wake, the vortex core diameter, lateral separation between vortices (which is related to the wing span of the generating aircraft), decay of the wake (which is related to time and local levels of atmospheric turbulence) and the span and roll control power of the aircraft encountering the wake. The probability of encountering the wake depends on the relative position of the following aircraft to that of the aircraft generating the wake and the age of the wake.

The following parts of this section briefly summarise the main parameters that determine the characteristics of wake vortices, and their motion. These all relate to aircraft in cruise conditions. Details of mathematics are provided in Appendix A.

2.1 Initial vorticity and separation between vortices

Circulation, or vorticity, of the amalgamated vortices in inviscid flow is the sum of all the circulation generated by the wing. There may be some circulation that is not captured by the main vortices, such as vortices from the tailplane, and viscous effects may result in other small vortices that do not amalgamate. However, for most aircraft, the total vorticity is related to the net lift (= weight, in steady flight). This assumes that the tailplane vortices do not merge and viscous losses are about the same as the tailplane vorticity, which has the opposite sense to wing vorticity.

The total vorticity is

$$\Gamma = f(\text{Wing planform}).\frac{\text{Lift}}{(\text{Air density}).(\text{Wing span}).(\text{True airspeed})}$$

where the ‘Wing planform’ function depends mainly on the taper ratio and varies between unity for a rectangular planform and about 2 for a triangular planform. The function is 1.27 for a classic elliptical lift distribution.

It will be shown later that the magnitude of vorticity that is relevant in relation to the size of a disturbance is the non-dimensional vorticity, $\Gamma_n = \Gamma / ((\text{Wing span}).(\text{True airspeed}))$, and

$$\Gamma_n = f(\text{Wing planform}).\frac{2.\text{Lift}}{(\text{Indicated airspeed})^2.(\text{Wing span})^2}$$

It is relevant to note that a Mach number of 0.8 at Flight level 360 is an indicated airspeed of 250 knot. Thus non-dimensional vorticity in cruise may typically be around 50% of that during landing because of the combined effects of higher weight (Lift) and higher indicated airspeed in cruise conditions.

2.2 Vortex core diameter

The influence of a vortex on another aircraft depends, among other things, on the relative size of the vortex compared with the wing span and chord of that aircraft. Vortex size is usually described by the radius where tangential velocity is greatest, and the vortex core is within this radius with zero velocity at the centre. The character of the vortex core depends on the size of the generating aircraft and on the extent of any amalgamation of vortices. In cruise conditions the vortices are usually very compact and laboratory experiments suggest that typically[ii,iii] the core radius will be no larger than

$$\frac{\text{Core radius}}{\text{Wing span}} = (0.011).\sqrt{\Gamma_n.\frac{\text{Downstream distance}}{\text{Wing span}}}$$

For a B747-400 cruising at FL 360 the radius at about 25 Km (13 nm) downstream (c. 90 seconds) would be about 3 m, which compares reasonably well with the data from Bisgood’s observations[iv] on B747-100 of 2.4 m. However, both Bisgood and many full scale measurements at low altitude suggest that there is little change in core diameter with age. Thus a better estimate of core radius may be

$$\frac{\text{Core radius}}{\text{Wing span}} = 0.2.\sqrt{\Gamma_n}$$

If the vortex changes state by bursting then the radius will increase dramatically.

2.3 Tangential velocity distribution

Various mathematical forms have been proposed to describe the distribution of tangential velocity with radius from the centre of wake vortices. Iversen[ii] has shown that about 40% of total vorticity is in the core for the high vortex Reynolds Numbers that are typical of aircraft wake vortices. Most formulae have a much higher proportion of vorticity within the core, and this affects the rolling moments induced by vortices on another aircraft. Measurements of actual wake vortices[v] support Iversen’s proportion and a mathematical formula has been developed[v] with 37% of vorticity within the core and that formula is used in Appendix B and throughout this report when deriving vortex induced rolling moments.

Tangential velocity equation: $$v_r = \frac{2.\Gamma}{\pi^3.r}.\arctan\left(1.392.\frac{r}{R}\right)^2$$

where $\Gamma =$ total vorticity

$R =$ core radius (= radius for maximum tangential velocity)

$r =$ radius from the centre

This reduces to the usual $$v_r \approx \frac{\Gamma}{2.\pi.r}$$ at large radii

2.4 Decay

In describing the decay of vortices it is the change of character of the discrete large vortices that is important. Small eddies are still technically vortices but will have negligible effect on another aircraft. Vortices have energy and momentum which are conserved, but large discrete vortices can decay by creating smaller less energetic eddies and by amalgamating with vortices of opposite rotation. It should be noted that vortices shed by an aircraft are contra-rotating sets of nominally equal pairs with a total angular momentum of zero.

Creation of smaller eddies and cancellation by amalgamation will reduce the vorticity of the discrete large vortices. Another relevant change is any redistribution of circulation within the vortex, which will affect tangential velocities, and consequently the disturbances caused to another aircraft. Such redistribution may not change the overall vorticity.

The decay of vortices has been the subject of many studies and can occur in different ways, and at different rates, depending on several parameters. There seem to be significant differences between decay in laboratory conditions and in flight, particularly near the ground which has been the focus of most work. Donaldson & Bilanin describe decay as exponential with a time constant inversely proportional to atmospheric turbulence in their classic AGARDograph[vi].

Experience of incidents and accidents in the vicinity of airports suggests that the decay of vortices is sensitive to very low levels of atmospheric turbulence and is also affected by atmospheric thermal stability (temperature gradient with height), but only recently, with the advent of Computational Fluid Dynamic methods using Direct Numerical Simulation or Large Eddy Simulation techniques, have any theoretical studies shown significant influence of these parameters on full scale vortices.

At higher altitude there can be regions with very low levels of turbulence, and in such conditions it is likely that decay may be somewhat similar to that observed in high Reynolds number laboratory tests. (Reynolds number is a particularly important aerodynamic similarity factor including size and is high for full-scale aircraft.)

An important study of the persistence of wake vortices at cruise altitudes was reported by Bisgood[iv], who studied 37 condensation trails. These trails are created by the water vapour in the jet engine exhaust, which is entrained into the wake vortices. They can only be observed from the ground in clear conditions when the turbulence at the cruise altitude is very low. If there is noticeable turbulence at cruise altitude it will tend to disperse the water vapour. Thus Bisgood's study was associated with conditions that encourage vortices to persist. The maximum age of visible vortices was around 120 seconds and by this time there were usually noticeable changes in the form of the wake.

Wake vortex pairs change with age in three different ways. In the absence of significant turbulence they can develop a sinusoidal wave pattern between the two vortices that eventually leads to the two vortices joining at intervals to form lozenge shaped loops, which are known as Crow loops after the scientist who described the theoretical basis[vii]. These loops then decay by one of the other two types of ageing which are bursting or dissipation.

Bursting is seen as a sudden increase in vortex radius followed by rapid dissipation.

Dissipation appears to be a consequence of turbulence, which may be either present in the atmosphere or within the aircraft wake, and leads to the disappearance of the wake.

2.4.1 Crow loops

The development of sinusoidal waviness is common when wakes persist for longer than about 30 seconds, and the vortices can join to form a series of closed loops between about 50 and 100 seconds after generation. However, the vortices are still potent when the loops are formed, which is contrary to the impression sometimes given that the formation of loops is the end of the wake as a potential hazard. This persistence in potency is shown by the lack of dissipation in condensation trails and was also noted by Pinsker[viii] from one of his encounter examples where a series of normal acceleration bumps were experienced as a TriStar (L1011) passed through a sequence of loops.

An example of Crow loop development observed by Bisgood[iv] is shown in Fig.1. Another important feature of Crow loops is their tendency to broaden across track and increase the chance of encounter by a following aircraft. Sarpkaya & Daly[ix] describe how the formation of Crow loops is dependent on atmospheric turbulence even at very low intensity.

The loops appear to dissipate in the same way as parallel vortices.

2.4.2 Bursting

This is the most dramatic and visually obvious evidence of the decay of vortex potency. It is seen by the rapid formation in portions of a wake of bellmouth shapes where the vortex seems to have suddenly grown about 3 or 4 times in diameter and caused the wake just ahead to disappear (Fig.2). The bellmouth then seems to dissipate very rapidly. However there may be short filaments of apparently potent wake between bursting regions, and it is not unknown for one wake of a pair to dissipate through bursting while the other remains intact.

The cause of the bursting is not known, although it may be influenced by variations in velocities along the vortex axis and the effects of turbulence on these velocities. Although bursting can significantly shorten the potency of wake vortices, it does not seem possible at present to predict the occurrence of this phenomenon. Thus all estimates of potential hazard ignore this feature and concentrate on the worst case of gradual dissipation.

2.4.3 Gradual dissipation

This is a slower decay process seen as the gradual loss of coherent vorticity in the main vortex to smaller insignificant eddies and there is some indication that this may be accompanied by diffusion of vorticity outward from the core (the same evidence indicates that there would be little change in core radius with age). The report of

Donaldson & Bilanin[vi] suggests a linear relationship between rate of decay and atmospheric turbulence, which is generally supported by a range of full scale evidence that this process is accelerated by the presence of even very light atmospheric turbulence. However, there is insufficient data to confirm a quantitative relationship between turbulence and rate of decay of vortices, and the linear relationship is used at present.

There are two important consequences of the effect of turbulence:

1. Regions of high shear such as the edges of a jet stream, mountain waves, the tops of strong temperature inversions and thermally active clouds are all associated with significant turbulence and this will rapidly dissipate vortices. Thus it is very unlikely that a wake vortex encounter will occur in these regions, and the chance of wake vortex encounter in combination with other turbulence encounters is very remote.
2. Turbulence is often very low in other cruise conditions and wake vortex encounters are possible for periods of up to 3 minutes after the wake was generated.

2.5 Motion

Wake vortices move vertically relative to the generating aircraft. They tend to move downwards because each is influenced by the downdraught created by the other. Initial rates of descent depend on vorticity and vortex separation and are typically around 3 m/s, which corresponds to an initial descent angle of the vortex cores of around 1° in cruise conditions.

Vortices decay exponentially with time and in proportion to turbulence intensity. Increasing pressure will compress the vortex as it descends, which will increase the air density and reduce vorticity as angular momentum is conserved. Both these effects will reduce the rate of descent of the vortices, and the descent will stop when the vortices dissipate completely.

Vortices are also affected by any gradient of crosswind velocity with height, which increases the descent rate of one vortex and reduces it for the other. As the line between the vortex cores tilts from the horizontal so the mean rate of descent of the pair is reduced.

Finally, vortices can be moved up and down by vertical movements of the air in which they are immersed. The up or down draughts from thermal effects, or airflow over mountain ranges, can easily exceed the small downflow velocities of the vortices. Thus upstream of mountains, or over the tops of cumulus clouds, vortices may rise above the flight level of the generating aircraft. Whereas downstream of mountains they may descend much further than would be expected in other regions.

Greene[x] developed an approximate method of calculating motion and decay where the pair of vortices are treated as a single solid shape with buoyancy and drag and this was used by the author of this report in ref.i to make an estimate of vortex wake motion in the absence of wind shear or up/downdraughts. Estimates of vorticity as a function of downstream distance and vertical descent for a B747-400 are presented in Fig. 3 and for an A310-200 in Fig. 4. Note that, although the maximum weight of an A310-200 is only half that of a B747-400, the non-dimensional vorticity is about 75% of that of the B747 because the A310 wing span is lower. The vortex descent rate for the A310 is lower than the B747 but there is not a great difference because the separation between the vortices is less with the lower wingspan. It should be noted that there is a level of vorticity below which there is no significant hazard and this will be considered later. This is important because it is not necessary to avoid wake vortices once they become insignificant.

For these two aircraft cruising at the tropopause the vortices are estimated to descend about 500ft for the B747 and 400ft for the A310 when the horizontal separation from the generating aircraft has reached about 20 nm (c. 40 Km).

It is important to remember that vortices will be transported up and down by local up/downdraughts and vertical motion will be affected by crosswind changes with height. These affects may be greater than the inherent downward motion of vortices in relatively calm conditions.

Although vertical motion is particularly important when considering RVSM, vortices are also advected by the local wind and will move across track if there is a crosswind component. However a 17 knot crosswind will only move the vortices 1 Km across track in 2 minutes, and under most wind conditions vortices will remain within an airway while they decay. It is always best to move upwind when offsetting from a wake so as to remain in an airway.

3. Encounter behaviour

As mentioned at the start of Section 2, depending on the angle between aircraft tracks, an aircraft encountering a wake vortex can experience either a roll or a normal acceleration disturbance, or a combination of both. Where aircraft are on similar or reciprocal tracks then the disturbance is mainly in roll and can be large (> 20° of bank). This is likely to be the most frequent cause of incidents. Some normal acceleration disturbances can be experienced in flight on similar tracks, particularly if the vortices have formed ‘Crow loops’, but usually the effects will be less severe and much rarer than moderate clear air turbulence and need not be considered as a potential hazard. Occasionally aircraft tracks may be approximately at right angles and larger normal acceleration excursions of typically ± 0.6 ‘g’ and short duration can be experienced. The duration is not usually long enough to produce much movement. However, if an aircraft is manoeuvring near to structural limiting acceleration, then increases in structural loads such as wing root bending moment during a wake encounter could cause damage. This combination is likely to be extremely rare for civil aircraft, although it is a real concern for military fighter aircraft in air to air combat where they need to keep close together and manoeuvre near structural limits in the same airspace.

The most critical cases are roll disturbances, and estimation of aircraft response in roll to an encounter with wake vortices is reasonably straightforward. Roll disturbances develop over several seconds and quasi-steady aerodynamic calculations can be used to estimate aircraft motion. However, it takes a fraction of a second to cross a single vortex at right angles and requires knowledge of the transient changes in flow over a wing in response to large and rapid vertical velocity changes caused by a vortex to estimate the details of a normal acceleration disturbance. This section only considers roll responses. The size of roll disturbance for a particular combination of wake vortices and encountering aircraft depends on the characteristics of both, but is also very dependent on the position of the encountering aircraft relative to the vortices when it first starts to be affected by the vortices. The next section considers typical aircraft motion for a variety of 'in-line' encounter situations.

3.1 Typical aircraft behaviour for 'in-line' encounters

When the track of a following aircraft is similar or reciprocal to the generating aircraft, i.e. 'in-line', then the aircraft will slowly converge on a vortex pair. Usually the convergence will be from above if the generating aircraft has climbed through the flight level of the following aircraft; from below if the generating aircraft is cruising just above the flight level or descends; and could be from one side in any of these cases. However, the effects of up/downdraughts can result in a variety of different encounter situations.

To estimate typical aircraft trajectories and angular motion it is necessary to include a pilot/autopilot control strategy as well as calculating the moments induced by the vortices. Control actions will attempt to reduce roll excursions, as well as heading and height changes, and will have a significant effect on trajectory and deviations from the desired flight path. The author of this report has developed an unpublished method for estimating trajectory and deviations[xi] for NATS (UK) that includes a simple control model. Aircraft motion is primarily related to the ratio between the vortex induced rolling moment and the maximum available roll control moment, which will be shortened to RollRatio in this report. This RollRatio is a function of the vortex characteristics and the wing geometry of the encountering aircraft. It varies with position and roll attitude of the aircraft in relation to the vortex pair. RollRatio has the largest magnitude when the encountering aircraft is at the centre of either of the vortices. The examples in this section have been estimated for an aircraft with a wingspan of 62% of the generating aircraft encountering a pair of vortices with a maximum RollRatio of 3.8, which is large but not unusual.

3.1.1 Aircraft descending from above a vortex pair

Consider the motion of an aircraft descending steadily (c. 350 ft/min) through the region of the vortex, Fig. 5. The position and bank angle of the aircraft is shown from behind at 3 second intervals with additional dashed outlines at one second steps when the motion is rapid. If the aircraft starts far enough outside the vortices to starboard, Fig. 5a, then there is a gentle tendency to roll starboard that is easily resisted and the small deviation to starboard is easily recovered.

However, there is a point starboard of the nearest vortex, Fig. 5b, where the normal action of retaining wings level will result in the aircraft being drawn closer to the vortex and passing through the core. In this example the largest RollRatio is encountered as the aircraft passes near to the core and transiently reaches 3.4 times the moment available with full roll control, but the large roll disturbance accelerates the aircraft away from the core and control is soon regained. The peak roll angle in this example is 44° port wing down.

If the aircraft descends from above the starboard vortex, Fig. 5c, then the rolling moments and control responses take the aircraft down between the two vortices and the largest RollRatio only reaches 1.5 times the maximum roll control moment. The peak roll angle is 18° port wing down.

If an aircraft descends over the mid-point between the vortices then it could avoid any roll disturbance, but in practice the situation is similar to balancing a ball on top of a sphere and any deviation will result in some roll disturbance, although it will be relatively small.

Behaviour for descent on the port side is a mirror image of that on the starboard side.

The critical distance beyond which there is no significant effect from the vortices is about twice the distance from the vortices to the plane of symmetry in this case. It is a useful rule of thumb to say that encounters with vortices can be significant if the follower is inside a region of about twice the span of the generating aircraft. This describes the size of the disturbance region and can be useful if vortices are visible as condensation trails, although normally they will be invisible. The largest disturbances occur if the following aircraft is inside the critical region and outside the nearest vortex. Between the vortex and the plane of symmetry the disturbance is less than half the worst case.

3.1.2 Aircraft climbing from below a vortex pair

The behaviour of an aircraft climbing steadily (c. 350 ft/min) towards a pair of vortices is shown in Fig.6. Again there is a critical distance from the plane of symmetry where, Fig. 6a, the aircraft experiences a small rolling moment to starboard but no significant disturbance. Only a small distance closer to the vortex, Fig. 6b, and the aircraft is drawn through the core of the vortex and reaches a maximum roll angle of 42° port wing down. In this case recovery is more rapid than the descent case because the aircraft passes closer to the port vortex during recovery.

Starting below a vortex is a more complex case, Fig. 6c. Initially the downdraught reduces the climb and induced roll is easily countered by control inputs. The crossflow draws the aircraft towards the plane of symmetry. Once in this region the aircraft can follow a range of trajectories that is critically dependent on control actions. If the starboard wing is kept down to correct heading to starboard as it is at 12 seconds then the aircraft will pass very close to the core of the starboard vortex and experience a large roll disturbance. If, on the other hand, this recovery is relaxed then the aircraft will climb between the vortices and experience only a small roll disturbance. In practice vortices are usually invisible and pilots are not able to choose an appropriate strategy and occasionally there will be large roll excursions when an aircraft climbs from below in any position between the vortex and the plane of symmetry.

3.1.3 Aircraft converging on a vortex pair from the side

When an aircraft converges slowly on a pair of vortices from right to left at a closure rate of about 3.5 knots then motion is as shown in Fig.7. If the aircraft is 10m above the vortices, Fig. 7a, it is only slightly affected by the nearest vortex, but sufficient to draw it down close to the second vortex where it experiences a maximum roll disturbance of 45° starboard wing down. Starting only 5m above the vortices, Fig. 7b, shows an increase in the effect of the first vortex and the aircraft does not get so close to the second vortex. Again the maximum roll is starboard wing down but reduced to 33°.

If the closure is at the same level as the vortices from starboard, Fig. 7c, then the vortices try to roll the aircraft to starboard, which, if it were not resisted, would prevent an encounter. However it is natural to counter the induced roll and the aircraft will initially move upwards and then continue downwards and to port through the core of the vortex and experience a large roll disturbance with a peak value of 44° port wing down.

Starting 5m below the vortices, Fig. 7d, the aircraft is raised over the first vortex and passes back down between them with a maximum roll angle of 30° port wing down. Starting at 10m below, Fig. 7e, is sufficient to avoid much of the disturbance as the aircraft remains below the vortices and the maximum roll angle is 17° port wing down.

In practice encounters are likely to arise from a combination of convergence situations, but all encounters have many features in common.

1. The maximum roll angle that could be induced depends on the maximum RollRatio and this worst case will occur when the aircraft passes through the vortex core. In general the roll angle in an encounter is approximately proportional to the largest RollRatio that is experienced.
2. The largest disturbances occur when the initial track of the aircraft passes outside the nearest of the vortex pair by no more than about the distance from the vortex to the midpoint between the pair
3. If the track is outside this distance there will be negligible effect from the vortices
4. If the track is between the vortex and the mid-point between the pair then the roll disturbance will usually be less than half the maximum
5. Induced rolling moments only exceed available rolling moments for a short time and recovery is always possible unless a pilot exceeds other limits during recovery. However, the disturbance can result in large roll angles and require pilots to recover from unusual attitudes, where many may have very little experience to call upon.

The variation of maximum roll angle with starting position for the descent and climb situations shown in Figs. 5 & 6 are shown in Fig. 8. This shows the sharp edge of the critical region and the small range of distance before the roll disturbance reduces significantly. However, as the vortices are invisible there is a real possibility of encountering the largest disturbance, but disturbances of less than 60% of the worst case will be about five times more common. A consequence of this variation of roll angle disturbance is that it is difficult to ascertain the maximum roll disturbance in flight tests using smoke to mark vortex cores, as has been attempted on some occasions, because of the difficulty in finding a starting position that will take the test aircraft through the core. It is likely that most disturbances experienced in such tests will be less than half the possible maximum.

3.2 Effects of altitude and aircraft configuration

In Appendix B it is shown that the maximum ratio of vortex induced roll moment to available roll control moment is:

$$RollRatio = \frac{V_g}{V} \cdot \frac{\Gamma_n \cdot f\left({}^{b_g}\!/\!{}_{b}\, , {}^{b_g}\!/\!{}_{R}\, , tr \right)}{C_{l\xi\max}} \quad \text{where suffix } g = \text{Generating aircraft}$$

V = True airspeed

b = Wing span

R = Vortex core radius

tr = Wing taper ratio

$C_{l\xi\max}$ = Non - dimensional maximum roll control moment

The non-dimensional maximum roll control moment is very similar for all civil aircraft in the cruise; cruising speeds will be similar for many aircraft with the exception of a few high altitude turbo-prop aircraft (which will be slower than jet aircraft), and the function of wingspan/vortex radius and taper ratio does not vary greatly between most civil aircraft. Thus

RollRatio varies most strongly with the non-dimensional vorticity, Γ_n, which is defined in section 2.1 above, and with a function of the ratio between the wing spans of the two aircraft. The non-dimensional vorticity is a function of Lift (Weight), indicated airspeed and the wing span of the generating aircraft, and is the main parameter in determining safe separation distances between aircraft.

Variation of the Induced Roll Factor, $f\left({b_g}/{b}, {b_g}/{R}, tr \right)$, with the ratio of the span of the generating aircraft to that of the encountering aircraft is shown in Fig. 9 for typical values of $b_g/R = 200$ and $tr = 0.25$. At high altitude the factor for a vortex pair is usually most appropriate, although there are occasions where one vortex decays and the other persists. The Induced Roll Factor is multiplied by the non-dimensional vorticity to form the main part of the maximum RollRatio. This factor peaks at 1.8 for a span ratio of 4.5, which is about the ratio for an executive jet encountering the wake of a B747-400. It is important to note that encounters between aircraft of similar wing span can be significant.

Generally civil aircraft prefer to operate at around the minimum drag condition. This occurs at an almost constant value of indicated airspeed for a given weight and configuration, and is independent of altitude. This indicated airspeed gives the best climb performance and cruise economy. At minimum drag the non-dimensional vorticity for a particular configuration, such as the clean configuration used en-route, will be independent of altitude. Cruise at high subsonic Mach numbers tends to be at a slightly different indicated airspeed because of the affects of Mach number on the zero lift and induced drag of an aircraft, but this is not a major effect.

For landing, and for take-off, the emphasis is on generating lift at the lowest practical airspeed. Aircraft deploy flaps to increase lift, and, for landing, to increase drag. Indicated airspeeds are below that for minimum drag because of the need to reduce touchdown and take-off speeds. Thus non-dimensional vorticity during landing and take-off will be significantly higher than in the clean configuration for other phases of flight. However, it is usually necessary to increase the maximum non-dimensional roll control moment to provide adequate roll manoeuvrability at the lower speeds during landing and take-off, whereas roll control in cruise is often restricted because of structural limitations. Thus the maximum RollRatio will tend to be similar for aircraft in landing and cruise.

3.3 Summary of important features of vortices and encounters

a) Initial Vortex strength that is relevant when encountered by another aircraft is proportional to the non-dimensional vorticity, which is

$$\Gamma_n = \frac{\Gamma}{\text{(True Airspeed).(Wing span)}} = f\text{(Wing planform)}.\frac{2.\text{Lift}}{\text{(Indicated airspeed)}^2.\text{(Wing span)}^2}$$

b) Vortex core diameter is proportional to $b_g/R = 200$ and $tr = 0.25$

c) Decay of vorticity is mainly a function of time and atmospheric turbulence, and is commonly taken to have an exponential time constant inversely proportional to the atmospheric turbulence rms. Evidence indicates that core diameter remains constant.

d) ‘Crow loops’ often form under low turbulence conditions, but these are still active vortices

e) Regions of high shear where other large atmospheric disturbances, e.g. clear air turbulence, storm turbulence, etc., occur will cause rapid vortex decay. Significant wake vortices will not be encountered in these conditions.

f) Vortices inherently move downwards initially and the descent rate reduces as the vorticity decays. Typically they descend initially at about 3 m/s (600 ft/min) and decay sufficiently to become only a nuisance in about 400-500 ft. Downward movement can be significantly increased or decreased by down or up draughts caused by flow over mountains or meteorological conditions.

g) Aircraft on a track passing outside a pair of vortices by more than about half the wing span of the generating aircraft will not be significantly affected.

h) Aircraft on a track passing outside the vortices but by less than half the span of the generating aircraft can be drawn towards the nearest vortex and will experience the largest roll disturbance when drawn through the core of the vortex.

i) Aircraft descending from above a vortex or between a pair will experience less than half the maximum potential roll disturbance.

j) Aircraft may temporarily be unable to control roll if they pass near the core of a vortex, but they are always thrown clear of a vortex and control is regained. It is not possible to stay in or near the core of a strong vortex.

k) Aircraft crossing a vortex at right angles will experience a sudden ‘jolt’ in normal acceleration, but there will be no significant effect on flight trajectory or pitch attitude.

l) The magnitude of roll disturbance is proportional to the maximum vortex induced Roll Ratio (ratio of induced to maximum roll control moments). This ratio is primarily dependent on indicated airspeed and the ratio between the speed of the two aircraft, which is often close to unity. There is no direct effect of altitude on the roll moment ratio.

4. Encounter scenarios

4.1 Encounter reports

Reports of encounters with wake vortices are one of the sources of incident reports in Oceanic airspace and all the incidents recorded by the UK CAA have been examined for the period 27th March 1997 to 16th December 1997. RVSM was introduced in Oceanic airspace from 27th March for approved aircraft. Another important event on 24th September 1997 was the formal introduction of the use of lateral track offsets as an in-flight contingency procedure in the event of reports of encountering wake vortices from a preceding aircraft. No reports of wake vortex encounter incidents were received after the introduction of the offset procedure and up to the 16th December 1997. This does not mean that aircraft no longer encounter wake vortices, but now there is an effective procedure to move away from the encounter conditions when it is needed. Only significant encounters would be reported after 24th September. It should be noted that airways in Oceanic airspace are uni-directional in contrast to most airways where reciprocal tracks are used with appropriate vertical separation. There are also no intersecting airways in Oceanic airspace.

The UK CAA review all reports by pilots or air traffic controllers and log those which merit incident status, and in addition the UK National Air Traffic Services (NATS) receive specific reports of wake vortex encounters. Reports are not always received by both agencies, because not all wake vortex encounters are regarded as incidents but some are still sufficiently noteworthy to be reported as a wake encounter. It is informative to note the range of causes of the 47 incidents in Oceanic airspace logged as incidents by the UK CAA during the period of the survey and these are summarised below.

Type of incident	Number in period	Comment
Flight level error	8	Aircraft operating at a Flight Level different from air traffic clearance, but not as a result of an emergency
Navigation error	8	Aircraft not following cleared route or gross error in time
Military conflict	6	Unexpected conflict between military and civil aircraft
Unable to hold cleared Flight Level	5	Aircraft unable to hold flight level because of non-emergency performance problems or turbulence
Emergency change of Flight Level	5	Emergency declared following engine, pressurisation, and similar problems. Normally a descent is made, although may climb to move out of severe turbulence.
Collision avoidance manoeuvres	4	Manoeuvres following TCAS warnings, which usually included visual contact.
Communications problems	4	Communication difficulties and misunderstandings between ATC and aircraft
Wake vortex encounters	4	(Discussed in detail in this report)
Procedural errors between neighbouring Air traffic Control Centres	2	Flight clearances not received or understood
Non-RVSM aircraft given RVSM flight clearance	2	An aircraft type may appear frequently on the approved list but a particular aircraft of that type may not be equipped to the necessary standard. On one of the occasions the pilot told ACC that he was not equipped for RVSM.

It is outside the scope of the present report to comment on the significance of all the different reasons for incidents. However it is important to note that 40% of the incidents involve changes in Flight Level (Unable to hold cleared Flight Level, Emergency change of Flight Level, and Collision avoidance manoeuvres), which will increase the probability of following aircraft encountering a wake vortex.

In addition to the 4 wake vortex encounter incidents logged by the CAA, they received 5 other reports in the period that were not significant enough to log. NATS received 6 reports of which 2 were also reported to CAA, and the author has access to flight data records of one other encounter that, as it happens, was not reported to the CAA or NATS. These 14 events should be considered in the context of overall traffic levels for the 6 months between the introduction of RVSM and the provision of the offset contingency. From IATA statistics[xii] of passengers carried, average load factors, and assuming an average passenger capacity of 300, there were approximately 140,000 passenger flights between Europe and North America in 1996. If all of these flights used Oceanic airspace, then the wake turbulence reports would be 1 in 10,000 flights during the six months before provision of the offset contingency, and logged incidents only about 1 in 35,000 flights. It is likely that encounters are not particularly uncommon, but the lack of any major incident report suggests that severe incidents will be much less frequent.

It is noticeable that of these 14 wake vortex encounters there are two occasions where more than one report comes from the same date, and three reports come from three consecutive dates. This suggests that there may be particular meteorological conditions when encounters are more likely. This could be as simple as the wind being approximately along the track with a negligible or small crosswind component, because crosswinds will advect vortices away from following aircraft; it may relate to downflow that is associated with some weather systems, or there may be other meteorological causes.

4.1.1 Wake vortex encounters

The following table summarises relevant aspects of the reported encounters:

Date	Source	Encounter aircraft & FL	Lead aircraft & FL	Separa-tion	Event description
1/4/97	Airline internal	B767 Climbing to FL350	(Unknown) (340)	10 nm	Wake turbulence encounter between FL340 and FL350 during cruise. Unknown aircraft type 10 nm ahead on FL340. (see Flight Data Records in Fig. 11)
4/4/97	CAA (Incident Logged)	B747 (340)	B747 (350)	20 nm	Experiencing severe turbulence due to the vortex wake of the B747 ahead, and had been for some considerable time. The captain further advised that in his opinion the turbulence was so rough that there was considerable danger to his passengers at the rear of the aircraft. The captain intended to submit a report through his company *(but none was received). This report was from ATC.*
24/6/97	CAA (Report only)	B767 (340)	MD11 (350)	15 nm	Maintaining FL340 with visible con trail from MD-11 aircraft 15 nm in front at FL350. We experienced light to occasional moderate turbulence. The change from light to moderate occurred rapidly and only for short periods. With wind from west to north-west we decided to fly route offset by 2 nm (L) to remain upwind of con trail.
27/6/97	CAA (Incident Logged)	B767 (350)	B747 (360)	3 min. (c. 25 nm)	Aircraft reported difficulty with wake turbulence from the aircraft above.
27/6/97	CAA (Incident Logged)	B747 (330)	B747 (340)	2 min. (c. 16 nm)	Aircraft requested climb to FL350 due to occasional severe turbulence. Two minutes ahead was the other B747 maintaining FL340 and a similar Mach number. Pilot advised that he suspected the turbulence was caused by the weight (wake?) of the B747 at FL340.
27/6/97	NATS	B767 (340)	MD11 (350)	17 nm	1000ft above we were overtaken by an MD11 at FL350. Flying conditions were smooth until there was a sudden onset of moderate turbulence caused by the MD11 at a range of 17 nm ahead.
7/7/97	CAA (Report only)	B747 (350)	B747 (360)	-	Aircraft reported turbulence from traffic at 1,000 ft separation. Aircraft was offered and accepted descent to FL340.
7/7/97	CAA (Report only)	B767 (330)	B767 (340)	4 min. (c. 32 nm)	Aircraft reports light to moderate chop and requests higher FL. Unable to approve due to B767 4 mins. Ahead at FL340. Could this be the source of the turbulence, bearing in mind previous turbulence reports since RVSM? *(Author's note: Very unlikely to get moderate turbulence from an aircraft 32 nm ahead, and pilot does not suggest wake turbulence.)*

Date	Source	Encounter aircraft & FL	Lead aircraft & FL	Separa-tion	Event description
19/7/97	CAA (Report only)	B767 (340)	B747 (350)	16 nm	Cleared NAT track 'C' at FL340. A B747 was overhead at FL350 also on track 'C'. He gradually pulled ahead but stayed in view throughout. Co-pilot had experienced wake turbulence the previous week so we kept a watchful eye on the B747. He was 16 nm ahead on TCAS and we caught his wake briefly. I turned right and offset 3 nm right and upwind of track.
20/7/97	CAA (Incident Logged) & NATS	B767 (330)	B747 (340)	20 nm	Moderate turbulence encountered suddenly due to preceding B747 1000ft above (RVSM) and 20 nm ahead.
21/7/97	CAA (Report only) & NATS	B767 (350)	B747 (360)	20 nm	Wake turbulence was experienced during cruise at FL350. B747 20 nm ahead at FL360. 1 nm offset to left of track was flown to remain away from wake.
3/9/97	NATS	B767 (370)	B777 Descending	10 nm	A B777 was descended through our level at a distance of 10 nm causing the aircraft to bank about 30 degrees right. The controls were c(g?)rabbed by both pilots and left aileron input. The autopilot did not and was not disconnected. The encounter lasted about 1 or 2 seconds. (see Flight Data Records in Fig. 10)
7/9/97	NATS	DC10 (340)	B767 (350)	15 nm	Aircraft sustained two hard 'jolts' totally unlike atmospheric turbulence. Almost certainly wake turbulence from a B767 1000ft above and 15 nm ahead (Flight data records show 'jolts' of 0.1 'g')
9/9/97	NATS	B747 (330)	B767 (340)	22 nm	Aircraft ahead 22 nm, 1000ft above. Sudden sharp chop - short duration. 1 nm right offset entered. No further encounters.

Comment on the above encounters is reserved for section 4.3 after more details from the two recorded events.

4.2 Examples of encounters

Quantitative examples of encounters with wake vortices may occasionally be obtained from flight recorder data for reported incidents. These records need to be studied carefully to verify that the incidents are probably caused by wake vortices, because some atmospheric disturbances can cause similar patterns of roll or normal acceleration. Three examples are available of wake vortex encounters in Oceanic airspace after the introduction of RVSM. They are events at 1/April/97, 3/Sept/97 and 7/Sept/97 in the above table.

Some previous experience has been reported by Pinsker[xiii] many years ago based on Flight Data Records, and this is used to extend the set of examples. The author of this report has also analysed several examples of cruise encounters, but details of the geographic location or the generating aircraft were not available. These latter examples mainly involve quite small roll excursions (< 5°) although they have been sufficient to generate a report within the airline. There were two encounters with quite large (± 0.6 'g') normal acceleration pulses.

4.2.1 Oceanic encounters

The first event considered in detail, Fig. 10, occurred on 3/Sept/97 when a B767 at FL370 encountering a wake from a B777 descending through the same flight level 10 nm (18 Km) ahead. There is a roll excursion of 17°, which the pilots reported as 30°, but it is common to overestimate moderate bank angles by a factor of 2. There is also a change of normal acceleration of ± 0.25 'g'. The excursion and recovery take about 7 seconds with the main roll excursion lasting about 4 seconds. There appears to be a large control wheel input at a time of 19 seconds, but this is not evident in aileron movement and there is a similar pulse in normal acceleration, which suggests that the roll control pulse is a transient instrumentation error.

The second event, Fig. 11, occurred on 1/April/97 and is a B767 encountering a wake from an unidentified aircraft type that is 10 nm (18 Km) ahead and below. Detailed study of a variety of measured parameters suggest that it probably is an encounter with a wake vortex, and, if this is so, then it is an example of a wake rising. In particular the rapid roll that starts just before

66 sec precedes a corrective roll control input. As described above there are various reasons why a wake may rise, although this is the only example in the 14 events reported or available as Flight Records. The roll excursion is 14° and normal acceleration changes about ± 0.15 'g' and the event lasts about 8 seconds.

The third event was a couple of hard 'jolts' of 0.1 'g' experienced by a DC10 on 9/Sept/97. These were probably the result of encountering vortices that had joined to form 'Crow loops'.

None of these events were hazardous to the aircraft, but they could be a cause of alarm to passengers.

4.2.2 Previous experience

Pinsker[xiii] presents 10 examples of wake vortex encounters in cruise conditions and one immediately following take off. The information is particularly relevant because it is mainly encounters by small jet transport aircraft such as the BAC 1-11 (similar to the Fokker F-100) and the HS Trident (similar to the B727), whereas the Oceanic data is all for B767 or larger aircraft. The events were identified by automatic searches of Flight Data Records for exceptional events, which frequently, but not always, also generated pilot incident reports. The generating aircraft is not always known although the larger civil aircraft operating at that time were the B747-200, Lockheed L 1011 (Tristar), and the Douglas DC10.

The largest roll excursion found was when a BAC 1-11 cruising at FL235 encountered the wake of a B747 descending through the same flight level some 16-20 nm (c. 35 Km) ahead, Fig. 12. The aircraft rolled to 70° of bank and experienced normal acceleration changes of ± 0.6 'g'. The motion is consistent with the BAC 1-11 crossing the wake slowly from left to right while climbing relative to the wake. The wake would follow the descent path of the B747 and the BAC 1-11 in level flight would climb through the wake. To experience this very large disturbance the aircraft must have passed very close to the core of the port vortex.

Another encounter with a B747 wake at 13 nm (24 Km) by a Trident is also noted where the roll excursion was 27°, which is consistent with passing close to a vortex but missing the core.

All the other cruise events in the report are significant pulses of normal acceleration with a maximum increment of about 1.2 'g' and there are only small (c. 5°) changes in roll angle. These will arise when tracks cross nearly at right angles. Two such examples are shown in

Fig. 13.

4.3 Experience in Oceanic airspace following the introduction of RVSM

The table in Section 4.1.1 above lists 11 encounters with the wake of an aircraft between 15 and 25 nm (30 and 45 Km) ahead and at a flight level 1,000 ft above, i.e. operating under RVSM. There is also one example where the following aircraft is above the generating aircraft, and this is the only example relating directly to RVSM where Flight Record Data are available. One of the two remaining examples is an incident where the separation is 32 nm (4 min.) and 1,000 ft, which is not identified by the pilot as a wake vortex encounter and this appears unlikely. The other example is a flight record of an encounter where the leading aircraft descended through the flight level of the following aircraft at a distance of 10 nm (18 Km), which is the type of encounter that could happen under previous separation rules and is not particular to RVSM.

It is difficult to form an objective view of the significance of the 11 encounters directly associated with RVSM. In the example from 4/April/97 in the table, the pilot reported 'severe turbulence' and 'considerable danger to his passengers in the rear of the aircraft' to Air Traffic, which resulted in the report to the CAA. No report was subsequently received through his company, and there is no record of any injuries being sustained. This incident occurred very shortly after the introduction of RVSM and there must be a possibility that it was (slightly?) exaggerated to ensure that it was noted. However, it cannot be ignored.

Other reports indicate that encounters are more of a nuisance than a hazard. The introduction of the offset contingency ruling, which is an easy and effective way of avoiding a sequence of encounters with the same wake in the relatively spacious conditions of Oceanic airspace, minimises the nuisance. The absence of reports in the three months following the formal introduction of offsets, suggests that, although wake vortex encounters will still occur, there is not a major problem that would generate incident reports. Indeed it would appear from many of the reports that they were part of the (appropriate) campaign to introduce offsets.

The limited evidence supports the view that there will be a steady number (very probably more frequent than 1 in 10,000 flights) of wake vortex encounters as a result of reducing vertical separation, but, so far, these have been a nuisance rather than a hazard. The important question is 'What is the probability of encountering a disturbance large enough to be a hazard to aircraft, passengers or crew?'. This cannot be answered directly from this small selection of incidents from a total of about 90,000 flights. However, consideration of the probable forms of hazard and information from more extensive information on wake vortex effects during operations at airports can indicate whether RVSM could be introduced in European airspace with an acceptably low risk. These aspects are considered later in this report.

5. Potentially hazardous encounter scenarios in cruise

Sudden disturbances in roll and/or normal acceleration are not unusual as a result of a range of atmospheric disturbances such as storms, clear air turbulence, etc., or malfunctions of aircraft systems such as an autopilot. It is not necessary to avoid these disturbances unless they are sufficiently large to cause real concern, injury or damage. However it is always desirable to avoid situations where significant disturbances are known to occur frequently, and any significant disturbances should be avoided if they can readily be identified. Wake vortex encounters are rare and should remain infrequent in RVSM. Usually vortices are invisible and their location many miles downstream of an aircraft cannot be reliably predicted. However, when vortices are visible as contrails then pilots should be advised to remain at least 4 wingspans either side of the trail.

The next two sections explore some of the main hazards to aircraft and to passengers that may arise from encountering wake vortices when en-route, and this is followed by a section describing the most likely situations where encounters may occur.

5.1 Aircraft damage or loss of control

5.1.1 Structural damage during an encounter

5.1.1.1 Large roll excursions when tracks are similar or reciprocal

Wake vortices cause roll deviations through a distribution of local up and down draughts on the wing which produce a spanwise lift loading that is different from those generated by gusts or roll control inputs. If the loading results in significant increases in wing root bending moments then there could be structural damage. Pinsker[xiii] expresses this concern and there may be a possible problem that needs to be addressed with induced rolling moments that can reach 4 or 5 times the maximum available roll control moment. However, it should be noted that there is no evidence of such structural damage from major incidents and accidents attributed to wake vortex encounters.

The important factor when considering structural problems is not the ratio of vortex induced roll moments to roll control, because roll control structural limits are usually associated with wing twist rather than wing root bending moments. The factor to consider is the root moment produced on each wing by the limiting load factor and the equivalent rolling moment where the load factor is reversed on the other wing. Simple estimates show that typically this would produce a roll moment about 12 times the maximum roll control moment. Thus, although the vortex induced rolling moments are high, they are unlikely to exceed structural limits unless an aircraft is already applying a large proportion of the limiting normal acceleration. This conclusion is supported by experience with military fighter aircraft in air-to-air combat where it is not unusual to encounter a wake vortex while pulling very high normal acceleration and damage to wing structure has occurred. It is very rare for civil aircraft to manoeuvre near to structural limits except in desperate recovery situations, which are very unlikely to precede a wake vortex encounter.

5.1.1.2 Normal acceleration excursions when tracks are approximately perpendicular

There is also concern about the pulses in normal acceleration experienced by an aircraft crossing a wake nearly perpendicular to their track. In this case the concern is directly associated with the total normal acceleration because the load varies along the wing chord and is almost constant across the span. The result is a normal acceleration doublet and wing twisting moments as the vortex moves along the chord of the wing. Examples of flight data records during such encounters show typical changes of ± 0.9 ‘g’ in normal acceleration and the largest change observed by the author has been 0.7 ‘g’, and the largest in the examples analysed by Pinsker[viii] was 1.2 ‘g’. At these levels the normal acceleration pulse may be structurally important for civil aircraft if the aircraft is manoeuvring hard and already near to structural limits.

It is impossible to estimate dynamic loads, including twisting moments, during a perpendicular encounter because the aircraft modifies the vortex as the encounter proceeds and the dynamics of this interaction are not known. The time taken for the wing to travel through a typical vortex core without modification would be less than 1/20 sec at cruise airspeeds. However, the combination of aerodynamic interactions and the structural response of the aircraft can increase the apparent duration of the effect to nearer a second and the aircraft will have travelled over 100m. In these circumstances the loading on the various parts of the aircraft is a very complex dynamic pattern and the flexibility of the wing will absorb some of the strain induced by the pulse. There are no reports of any damage to civil aircraft from such events. However the problems of military aircraft encountering wakes in air-to-air combat, which include a mixture of both perpendicular crossings and roll disturbances, suggest that structural damage may occur if an aircraft crosses a recently generated wake.

There are practical problems in measuring normal acceleration from such short pulses and assessing the structural implications. Accelerometers are located at a single point in the aircraft and measure accelerations that include structural vibrations as well as the quasi-steady accelerations experienced by the aircraft. In most operational conditions the quasi-steady accelerations are more relevant, but when an aircraft experiences very short pulses of external disturbances then the structural vibration effects can exaggerate or attenuate the response depending on the location of the accelerometer relative to the nodes of the structural modes. Alternatively the signal may be heavily smoothed to ease the visualisation of quasi-steady accelerations and effects of short pulses will be attenuated. Because of the practical difficulties of effectively monitoring the structural effects of perpendicular wake vortex crossings it is important to ensure that adequate separation is maintained in such cases.

It is unlikely that an encounter with a wake vortex will cause any structural damage to a civil aircraft unless tracks cross nearly perpendicular to each other and the age of the vortex is short. A definition of the term ‘short’ requires examination of flight data records and advice from experts in structural flight dynamics, but intuitively there may damage if the wake is less than 1 minute old.

5.1.2 Structural damage during recovery

This situation only arises when recovering from a large roll disturbance, as the normal acceleration disturbances are so transient that there is little affect on flight path or speed and no specific recovery action is needed. Recovery from large roll disturbances is no different from such recovery under any other circumstances as the aircraft is well away from the influence of the vortices when recovery takes place.

Any such recovery requires due care to avoid excessive sideslip which can generate large fin loads, to avoid airspeed increases that may take an aircraft close to the limiting Mach number or losses that could lead to stalling, and to avoid applying too much normal acceleration when recovering any height loss. Following an en-route encounter there are usually no particular pressures of time or potential ground contact and pilots can make an expeditious, but not unduly dramatic recovery. There is not usually any particular concern about exceeding limits, except perhaps speeds when cruising at high altitude where Mach number limits and stalling speeds are close together.

5.1.3 Loss, or incorrect use of controls

Loss of control is important if it lasts long enough to result in exceeding important aircraft limits, and critical if it leads to structural damage that prevents control being regained. Also included in this section is the incorrect use of control that impedes recovery or leads to damage.

Aircraft are naturally driven out of the influence of any vortices they encounter and any loss of control during the vortex encounter will be transient. Once outside the vortex region the aircraft will be recoverable. However in extreme cases the aircraft may be at a large roll angle and the visual horizon may be absent or indistinct, e.g. at night, in flight between cloud levels or flight in cloud. In these circumstances pilots need to be proficient in recovery from unusual attitudes on instruments. This is a skill that is very rarely needed in civil operations and deserves a higher profile in recurrent training schedules.

Thus the main concerns in this section are airspeed/Mach number control in recovery, and recovery skills from unusual attitudes on instruments.

5.2 Injury to passengers or crew

An aircraft may experience any combination of normal acceleration and roll disturbances during an encounter with wake vortices depending on the angle between the vortex (generating aircraft) track and that of the encountering aircraft. In practice a very high proportion of en-route encounters will either be along track, where aircraft are in the same airway, or crossing nearly at right angles where height separation rules require less vertical separation.

An encounter with wake vortices when crossing nearly at right angles will produce a very short pair of opposite pulses of normal acceleration. Although the pulses can be around 1 ‘g’ the duration is so short that passengers or crew who are not restrained by a seat belt will only move up and own by a few inches and are unlikely to hit any part of the cabin, although it may cause them to stumble. Being opposite pulses it is also unlikely that beverages in cups will be spilled, although there could be a minor problem if a beverage is being poured at the moment of encounter because of the pourer’s arm being jolted. Thus normal accelerations during an encounter are not likely to cause problems, other than, perhaps, some short period of alarm for nervous or inexperienced passengers.

Even large roll motion during an encounter does not usually include particularly large lateral accelerations, although there can be modest changes in normal acceleration. Typically, normal acceleration will remain positive and thus unrestrained passengers are not likely to be thrown around violently in the cabin, although it is likely that they could fall or beverages will be spilled. Vortex encounters are totally unpredictable and are another reason why it is always wise to keep a seat belt loosely fastened whenever possible. It is possible that passengers in the rear of large aircraft may be more affected by the motion than those near the front because the centre for the natural roll/yaw and sideslip motion of an aircraft (Dutch roll) is usually just ahead of an aircraft.

However, recovery action from large roll disturbances will usually be energetic and could cause problems to unrestrained passenger and crew. There will also be real concern among all passengers following a large, sudden and unexpected roll disturbance and recovery.

5.3 Summary of conditions that may create significant encounters.

5.3.1 Encounter probability

It is important to realise that there will only be an encounter if an aircraft passes through the ‘wake ribbon’ generated by the other aircraft. The width of this ‘ribbon’ is about twice the wing span of the generating aircraft and it is about one wing span deep, i.e. a B747-400 generates a ‘wake ribbon’ about 120m wide and 60m deep. The ‘ribbon’ descends slowly and is advected in all directions by winds, up/downdraughts and turbulence. The wakes within the ‘ribbon’ gradually decay until it becomes inconsequential about two to three minutes behind the generating aircraft, i.e. about 30 - 45 Km in high altitude cruise conditions. The probability of another aircraft encountering this ‘wake ribbon’ will always be small, although it is very significantly increased if one of a pair of aircraft on similar or reciprocal tracks is climbing or descending relative to the other.

However, despite the low probability of encounter, the ‘ribbon’ is invisible and if persistent down or up draughts are present it can be advected down or up by 1,000 ft or more from the more usual gentle descent to around 400-500 ft below the flight path of the generating aircraft. Thus there will always be some encounters and severe encounters can only be avoided by ensuring adequate time separation, particularly when the probability of encounter is significantly increased, e.g. when one of a pair of aircraft on similar, or reciprocal, tracks is climbing or descending.

5.3.2 Relative flight paths

5.3.2.1 Similar or reciprocal tracks

As already indicated the most frequent cause of an encounter is where one of a pair of aircraft climbs or descends relative to the other. In such cases the encountering aircraft will pass through the same altitude as the ‘wake ribbon’ and will only avoid an encounter if there is sufficient lateral displacement or the wake has decayed to an insignificant strength. There is a much increased probability of encounter if the crosswind component is small because an average crosswind of 5 knots will advect vortices across track by only about 150 m for each minute of separation between aircraft. Climbing or descending relative to another aircraft is a routine occurrence in European airspace.

Flight at 1,000 ft below a leading aircraft less than 3 minutes ahead, or on a reciprocal track, will not often result in encountering a vortex, unless meteorological and/or terrain features result in a persistent local downdraught.

Flight at 1,000 ft above a leading aircraft less than 3 minutes ahead, or on a reciprocal track, can result in an encounter with a vortex but only in conditions with a significant updraught that is sufficient to more than counteract the natural tendency of vortices to descend, which will be rare.

5.3.2.2 Perpendicular tracks

Such encounters will be much less common because there are no navigation or air traffic control procedural biases that tend to generate coincidence between the ‘wake ribbon’ and the track of the crossing aircraft. Again however, any relative climb or descent between a pair of aircraft that ensures that the ‘wake ribbon’ passes through the altitude of the crossing aircraft will significantly increase the low encounter probability.

For a pair of aircraft operating at constant altitudes then, even if the altitudes are close enough for the ‘wake ribbon’ to intersect the altitude of the crossing aircraft, it will only do so at a particular time interval. The only exception would be a ‘ribbon’ that has ceased to descend and is coincidentally at the altitude of the crossing aircraft, but in such conditions the ‘ribbon’ will be nearly completely decayed and insignificant.

5.3.3 Terrain effects

Winds blowing across mountain ranges will deflect the air up and down at heights above the mountains that may be more than twice the height of the range. Occasionally these result in mountain waves and can be seen through associated Lenticular clouds, but often they are invisible and only detectable through small increases or decreases in power to maintain altitude downwind or upwind respectively of the mountain range. These up and down flow components are sufficient to increase the vertical movement of vortices and considerably increase the probability of an encounter.

These affects are not present in Oceanic airspace, but will be present over most land masses including Europe.

5.3.4 Meteorological effects

There are some particular meteorological circumstances that generate up and down flow over areas of many miles. First there is a gentle upflow from areas of high pressure and stronger downflow to the centre of areas of low pressure, next there are the up and down flows associated with weather fronts, and finally there is a residual upflow above Cumulus (and particularly Cumulo-Nimbus) clouds and also generally weaker areas of downflow. There are, of course, strong areas of up and downflow in storm clouds but the associated turbulence will rapidly destroy vortices, and thus encounters with wake vortices in storm clouds are very unlikely.

5.3.5 Speed differences

The ratio of the speed of the generating aircraft to that of the encountering aircraft is a direct factor in the ratio between the wake induced rolling moment and that available from roll control. For many aircraft combinations their cruise speeds are very similar, but there are a few turbo-prop aircraft operating at medium and high altitude, which have significantly lower cruise speeds. These aircraft will be more sensitive to wake vortex encounters, unless they have significantly higher maximum roll control moments in the cruise than pure jet aircraft of similar wing span.

5.4 Summary of potential hazards

The main hazards from wake vortex encounters en-route are all associated with large roll disturbances and they are expected to be:

1. Difficulties with recovery from unusual attitudes on instruments

2. Speed control during recovery at high altitude when the margin between the airspeed corresponding to maximum Mach number and the stalling airspeed is small
3. Potential damage to unrestrained passengers and crew during encounters with large roll disturbance and during the subsequent recovery. This may be more severe for passengers at the rear of an aircraft.
4. Encounter probability is significantly increased when one of a pair of aircraft is climbing or descending relative to the other and the ‘wake ribbon’ passes through the altitude of the encountering aircraft.

These are significantly different from the hazard during approach and take off which is uncontrolled contact with the ground. It should be noted that the author is not aware of any en-route encounter with wake vortices that has resulted in a fatal accident, major damage or personal injury. However increases in traffic density require continual attention to avoid such problems in the future.

6. Indications of acceptable encounter limits

The most important factor determining the acceptability of an encounter with wake vortices is the magnitude of the uncommanded roll angle change, and this is true for all flight phases. However the magnitude of acceptable roll angle change varies from a few degrees when less than 200 ft above the ground to around 30° when there is no imminent danger of striking the ground. Many pilots of civil transport aircraft would consider an uncommanded roll disturbance of 30° as a severe event. The suggested boundary of 30° for potentially hazardous roll events is subjective, although practical experience with civil transport operations suggest that it is likely to be a reasonable value. Unfortunately there is no way of testing this hypothesis without exposing a civil aircraft to vortices that will generate large roll excursions, and this is unlikely to be a practical and safe proposition. Pilots tend to present incident reports for smaller events, which are undesirable but not potentially hazardous, and en-route incidents have been reported where roll angle changes were less than 5°.

Analysis in Ref. i based on the current UK separation requirements for the approach, which have been developed from analysis of pilot incident reports, suggests that the maximum acceptable RollRatio during an approach to land is about unity. This is based on vortex decay proportional to atmospheric turbulence, and the Induced Roll Factor as a function of span ratio that is presented in Fig. 9. The cases for the various combinations of aircraft weight categories converge on a ratio of induced roll moment to control moment of about unity. Unpublished analysis of time histories of 100 reported wake vortex encounters[xiv] shows maximum roll disturbances of 12° for events below 1,000 ft above ground. Results from the encounter analysis method of Ref. xi indicate that for a given pilot control response model the roll disturbance is proportional to the largest RollRatio that is encountered. Thus a maximum RollRatio of 2.5 should result in a maximum roll disturbance of 30° in approach conditions. The aircraft trajectory and roll motion will include a short time where the vortex induced roll moment is much greater than the available roll control moment and the roll motion is scarcely influenced by roll control inputs.

In general the maximum roll angle disturbance will be proportional to the maximum RollRatio and a function of pilot control response lags. It was shown in Sect. 3.2 that the combination of higher indicated airspeeds and reduced maximum roll control moment in high altitude cruise results in only small changes in maximum RollRatio between approach and high altitude cruise for most civil transport aircraft. However, aircraft with lower aspect ratio stiffer wings, which may have higher roll control moments, could have lower maximum RollRatio in the cruise.

Roll responses to control application are usually crisper in cruise and the effects of pilot response lags are greater. This would reduce the maximum RollRatio that corresponds to a roll disturbance of 30°. The full extent of the effects of speed and height could be investigated using the same principles as in Ref. xi. This encounter model is currently configured to look only at approach conditions, but it would be possible to extend the model to study effects of speed and height. In the absence of a method for obtaining quantitative estimates it is possible to use the examples of Figs. 10 & 12 to estimate the likely value of maximum RollRatio that will result in a 30° roll excursion in high altitude cruise, and these events indicate a maximum RollRatio of 0.8. This RollRatio is much lower than the value of 2.5 for approach conditions, which suggests that pilot response has a major influence on the overall roll disturbance.

For practical purposes it is important to derive separation distances between aircraft that relate to this RollRatio so that following aircraft are not likely to experience a potentially hazardous roll disturbance. Vortices decay with increasing downstream distance as shown in the examples of Figs. 3 & 4, and there is a relationship between non-dimensional vorticity and downstream distance for any particular aircraft that does not change much for aircraft of similar weight and wing span. For a fixed RollRatio and a known value of maximum non-dimensional roll control moment, the variation of non-dimensional vorticity with wing span ratio can be determined. A typical separation distance for particular aircraft types can then be determined where the chosen RollRatio would be encountered.

The non-dimensional vorticity has been estimated as functions of wing span ratio, Fig. 14, for Heavy ($\text{MTOW} \geq 136{,}000$ Kg) and Medium ($40{,}000 < \text{MTOW} < 136{,}000$ Kg) aircraft with a maximum non-dimensional roll control moment in cruise of 0.04, and for Small/Light ($\text{MTOW} <= 40{,}000$ Kg) aircraft with a maximum non-dimensional roll control moment of 0.06. Smaller aircraft often have more roll control moment available in cruise because of the greater stiffness of their wings.

The values in Fig. 14 can be compared with the examples in Fig. 10 and Fig. 12. The roll disturbance of 17° in Fig. 10 was caused by a generating aircraft (B777) with a span of 1.3 times that of the encountering aircraft (B767). Using the method of Greene as modified in Ref. i gives a non-dimensional vorticity for 10 nm (18 Km) downstream of a B777 at maximum weight of 0.038, which would be expected to result in a roll excursion of 38° compared with the actual roll of 17°. The incident in Fig. 12 where a BAC1-11 encountered the wake of a B747 about 16-20 nm (c. 35 Km) downstream has a span ratio of 2.3 and the B747 non-dimensional vorticity (Fig. 3) is around 0.035. Thus an excursion of around 48° would be estimated rather than over 70°.

Very large excursions in roll, which last many seconds, are strongly influenced by pilot control actions and it is not surprising to find a significant difference between the estimate and the actual excursion for the BAC 1-11 incident. The smaller incident of Fig. 10 should be more representative and a roll excursion of around half the estimated maximum is shown in Sect. 3.1 and Fig. 8 to be the most common occurrence. The maximum roll disturbance in Fig. 8 only occurs for an encounter starting in the outer 10% or less of the region of influence of the wake, whereas a disturbance of about half the maximum can occur for an encounter anywhere across about 30% or more of the wake. Thus the maximum RollRatio value of 0.8 is a reasonable estimate of the value likely to result in a roll excursion of 30° in high altitude cruise.

The non-dimensional vorticities corresponding to the Maximum RollRatio of 0.8, Fig. 14, can be converted to separation distances for specific aircraft combinations assuming a particular rate of vortex decay from information of the form shown in Figs. 3 & 4. It is suggested that the provisional values of non-dimensional vorticity in Fig. 14 should be used to estimate separation distances below which there may be hazards from wake vortices for particular aircraft combinations. These should be refined as information from pilot incident reports and Flight Data Records become available.

Using the values in Fig. 14 and Fig. 3 indicates that the BAC 1-11 in the above example should be separated from a B747 by at least 30 nm (approx. 4 min.) to avoid the small, but not insignificant, risk of encountering a vortex that would cause more than a 30° roll disturbance. However there is no evidence of vortices persisting more than 3 minutes and the decay rate in Fig. 3 may be slower than it is in practice. Thus a separation of around 24 nm (45 Km) may be more appropriate.

7. Encounter alleviation techniques

7.1 Oceanic airspace

It should be remembered that wake vortex encounters in Oceanic airspace as a result of RVSM are likely to be a nuisance rather than a hazard and may only occur around 1 in 10,000 flights, which is about once in four weeks. However, they are influenced by meteorological conditions and several aircraft may experience problems on particular days. Other encounters due to aircraft climbing and descending are not specifically related to RVSM, although there may be some increase in vertical realignment activity because of any problems that prevent an aircraft continuing with RVSM separation. Encounters due to aircraft climbing or descending may be potentially hazardous.

The nuisance from wake vortex encounters between aircraft that are both cruising in the same direction with RVSM separation of 1000ft can be persistent unless aircraft are allowed to take some evasive action. The simplest operational and effective action, when faced with continuing vortex encounters, is for the following aircraft to move to a parallel track upwind of the generating aircraft. This track could in principle be only a few hundred metres offset, i.e. sufficient to take the encountering aircraft wing tip well outside the nearest vortex. However, in practice the vortices are usually invisible and their across track position will vary with local fluctuations in crosswind. Thus it is prudent to have an offset of at least 1Km.

Such lateral offsets are operationally effective in Oceanic airspace, because

1. There is ample lateral spacing between parallel airways
2. The airways are straight for very long distances
3. All the traffic is travelling in the same direction at similar speeds

Long straight airways are important because crosswinds will change with airway direction and may require a change of offset. Crosswinds may also change with position because of changes in meteorological conditions, but the long straight airways minimise the number of offset changes that may be required.

When encounters are possible, because of appropriate meteorological conditions, then they will be relatively common with traffic travelling in the same direction at similar speeds, but can easily be alleviated with a lateral offset.

In practice the reasonably low air traffic density and differences in cruise speeds mean that aircraft often do not remain at the same range from a generating aircraft for very long. This means that there is little need to review offsets because of changes in crosswind.

It should be noted that offsets need not be cumulative, as aircraft at the same Flight Level will only cause wake vortex encounters in the very rare case where updraughts exactly counteract the natural tendency of vortices to descend.

Another operationally practical and effective way of evading the nuisance is to change the flight level of either aircraft.

Although increasing the longitudinal separation between aircraft would be another way to avoid vortex encounters, it is operationally undesirable because this separation is always slowly changing due to differences in cruise speeds with weight, height and aircraft types.

Collision avoidance equipment (TCAS) has been helpful to pilots in alerting them to nearby aircraft.

7.2 European airspace

European airspace has a multiplicity of airways with widely differing directions, junctions and lengths between junctions of often only a few hundred miles. There are many major airports, with some as close as 200 miles, and there is a wide mix of local and long range traffic and also of aircraft types. Air traffic density is high and increasing. There are significant mountain ranges such as the Alps, Pyrenees and Tyrol, and also a mixture of land and sea which all increase meteorological variety compared with large expanses of ocean.

7.2.1 RVSM related problems with aircraft at constant altitudes

As a consequence of higher traffic density there will be a greater proportion of adjacent traffic in Europe than occurred in Oceanic airspace. These differences, together with the effects of mountain ranges, will significantly increase the occurrence of encounters with wake vortices due to the use of RVSM, although it not possible to predict how much more frequently such encounters will occur.

It is not possible to avoid some contact by aircraft with wakes from an aircraft 1,000ft above (RVSM) in particular meteorological conditions or near mountain ranges, and usually these encounters will occur when separation is between 15 and 25 nm (28 and 46 Km) because of the time taken for vortices to descend. However, some may occur at shorter distances in the lee of mountain ranges where there may be more significant down draughts. These encounters will usually create a nuisance, but they may be more significant for Medium aircraft such as B737, MD-81 and A320 encountering wakes of Heavy aircraft such as B747, B777 & A340. These Medium aircraft have a much lower wing span and may well have lower non-dimensional maximum roll control moments in the cruise than smaller aircraft such as Challenger, Falcon, Learjet, Citation, etc. A detailed classification would require more aerodynamic data on individual aircraft, which may be difficult to obtain, and it will be particularly important to arrange a means for gathering pilot reports from as wide a range of aircraft as possible so that trends may be seen as early as possible.

It will be important to study incident reports, particularly anywhere flight data records are available, so that operating procedures can be adjusted if necessary. Experience in Oceanic airspace suggests that encounters will be rare, but at certain times there will be a group of encounters in a particular region of airspace. Then is the time to deliberately introduce lateral offsets to aircraft on similar or reciprocal tracks that have only 1000 ft vertical separation, and this will dramatically reduce the chances of these largely nuisance encounters. The use of upwind lateral offsets of around 1-2 Km (0.5-1 nm) should be sufficient. These offsets will only apply to specific pairs of aircraft and will not usually be cumulative between successive pairs. In general it would be prudent to continue using offsets until the weather pattern in the region changes.

Particular attention should be given to the severity of incidents and identifying both the aircraft types involved. If a severe incident is reported then it may be prudent to temporarily increase vertical separation in the affected region of airspace, particularly between Heavy and Medium aircraft.

7.2.2 Aircraft climbing or descending

This situation is present already and will not be affected by the introduction of RVSM. Climbing or descending aircraft have been the cause of several major wake vortex encounter incidents over the years and two of the incidents reported in Oceanic airspace. The current incident rate is very low but encounters are occurring.

It is expected that the rate of encounters will increase significantly as the traffic density of both Heavy and Medium aircraft increases, and this type of encounter is more likely to result in a severe incident if the wake age is less than about 2 minutes. Thus it is recommended that studies should be made to find practical ways of ensuring that climbing or descending aircraft have appropriate track offsets to avoid intersecting the track of other aircraft. The alternative is to keep at least 2 minutes away from any other aircraft whose track and altitude will intersect that of the climbing or descending aircraft. Current practice can result in separations of around 1 minute or even less, and, although the probability of an encounter with the ‘wake ribbon’ is low, the consequences of an encounter could be a roll excursion 60° or more such as that experienced by the BAC 1-11, Fig. 12.

If tracks will intersect then ideally all Heavy aircraft (MTOW >= 136,000 Kg) should be at least 16 nm (2 min. or 30 Km) ahead of any aircraft on a similar track when it passes through the flight level of the following aircraft, and 25 nm (3 min. or 46 Km) ahead of a Medium aircraft (MTOW between 40,000 and 136,000 Kg). Smaller aircraft may be less sensitive to encounters than Medium aircraft because of higher roll control moments. Similar separations should be applied if an aircraft climbs or descends through the cruising flight level and behind a Heavy aircraft.

It is probable that the present incident rate is low because lateral offsets are quite common. However, with increasing traffic density and improving navigation precision between waypoints, it is desirable to introduce offsets as a deliberate procedure, otherwise the penalties in terms of separation to ensure that there are no severe encounters are very substantial.

8. Conclusions

The general characteristics of wake vortices, which are shed downstream by all aircraft, have been described together with typical encounter behaviour and are summarised in Section 3.3. Vortices decay with time but may be present for up to about 2-3 minutes in calm conditions, which is equivalent to a distance of around 16-25 nm (30-46 Km) in high altitude cruise conditions. During this time they are driven down by their own characteristics, and they also move vertically under the influence of up and down draughts in the atmosphere, which may be caused by air flowing over mountain ranges or by meteorological conditions. Usually the vortices only descend about 400-500 ft before becoming too weak to be potentially hazardous, but occasionally they will descend further and be encountered by aircraft flying only 1000ft below when Reduced Vertical Separation Minima (RVSM) are in operation. On even fewer occasions vortices may rise above the flight level of the generating aircraft.

Encounters with wake vortices result in roll disturbances if an aircraft is flying approximately the same track, or a reciprocal track, as the vortex core. If an aircraft is crossing the track of the vortices it will experience sharp ‘jolts’ in normal acceleration. Roll disturbances are the most common potential hazard, although the normal acceleration jolts may cause significant structural damage if an aircraft is manoeuvring hard or the wake age is low (say, less than 1 minute).

The maximum potential severity of a roll disturbance from an encounter with wake vortices is proportional to the ratio between the maximum vortex induced roll moment and the maximum available roll control moment (Maximum RollRatio). This ratio depends on four main factors, which are

a) non-dimensional vorticity, which in turn depends on the weight, indicated airspeed and wing geometry of the generating aircraft and the decay of the vortices with time. This parameter is almost independent of altitude.
b) non-dimensional maximum available roll control moment, which depends on aircraft configuration and speed, and is approximately constant with speed and altitude,
c) an Induced Roll Factor which is a function of the ratio between the wing span of the generating aircraft and the encountering aircraft, and various other geometric features of the vortex and the encountering aircraft,
d) the ratio between the speed of the two aircraft.

The actual severity of an encounter will also depend on how close an aircraft passes to the core of a vortex during the encounter, and will be greatest when an aircraft starts outside a pair of vortices and is drawn in to pass through a vortex core. Typical trajectories and roll motion for aircraft passing near wake vortices are described in the report.

It is noted that an aircraft can experience significant roll disturbances even when encountering a wake generated by an aircraft of similar size and weight.

Examination of reports to the UK CAA and NATS during the first nine months of RVSM operations in North Atlantic Oceanic Airspace clearly indicates that wake vortex encounters have been experienced on at least 1 in 10,000 flights. There were 12 reports of encounters with wake turbulence that can be directly attributed to RVSM, and these are all nuisance reports. There were no reports in 3 months following the introduction of lateral track offsets as a contingency measure whenever a pilot reported an encounter.

Consideration of potential hazards from wake vortex encounters at heights well clear of the ground suggests that hazards are primarily associated with recovery from large roll disturbances, and are

a) Difficulties with recovery from unusual attitudes on instruments,
b) Speed control during recovery at high altitudes when the margin between the airspeed corresponding to maximum Mach number and the stalling airspeed is small,
c) Potential damage to unrestrained passengers and crew, which may be more severe in the rear of an aircraft.

Some examples of encounters with wake vortices in cruise are shown from Flight Recorder Data. All the larger roll disturbances occurred when the aircraft in front climbed or descended through the cruising flight level of the following aircraft. Climbing or descending substantially increases the probability of a following aircraft encountering a vortex, and longitudinal separation is sometimes less than that normally maintained between adjacent aircraft in level cruising flight. This encounter possibility is not specific to RVSM. The most dramatic recorded encounter occurred many years ago between a BAC 1-11 (similar to a Fokker 100) and the wake of a B747 that descended through the flight level about 16 nm (30 Km) ahead. The BAC 1-11 rolled 70° before recovering satisfactorily. Most large roll disturbances have been less than 30°, which is dramatic enough, but unlikely to result in serious damage.

It is suggested that roll disturbances greater than 30° may be potentially hazardous, and this is used as a criteria for evaluating possible problems.

An assessment has been made of the expected sensitivity of aircraft in en-route flight conditions to wake vortices based on typical values of the Induced Roll Factor and examples of aircraft from the upper and lower ends of weight and wing span ranges. The weight bands are defined by the UK CAA as Heavy (MTOW >= 136,000 Kg), Medium (MTOW between 40,000 and 136,000 Kg), Small (MTOW between 17,000 and 40,000 Kg) and Light (MTOW < 17,000 Kg) for wake vortex separation on approach to landing. Small/Light aircraft often have stiffer wings and consequently they can have greater available roll control moment in cruise than Medium aircraft. If this is the case then the most critical encounters could be between Medium aircraft and the wake vortices from a Heavy aircraft, which was the case with the encounter between the BAC 1-11 and the wake of a B747. Small aircraft can use their greater roll control to advantage and experience smaller roll disturbances than Medium aircraft.

The only ways to ensure that an aircraft does not have a potentially hazardous encounter are to provide suitable horizontal separation between aircraft either in time or by offsetting tracks upwind for aircraft below. Although vortices will not normally descend more than about 400 – 500 ft they can descend further if there are significant downdraughts, or they may be present because an aircraft has climbed or descended. Thus there will always be the possibility of an encounter if tracks pass very close or intersect. Whenever an aircraft encounters a noticeable and persistent (or potentially persistent) disturbance from a wake vortex the pilot will wish to move away to prevent repeated encounters, even if the disturbances are similar to those experienced in turbulence and only a nuisance rather than a potential hazard. It is important to minimise the chances of an encounter wherever possible, and to provide operationally simple and effective ways of moving away from encounters when they occur. It is not practical, or even operationally desirable, to try and prevent any encounter with wake vortices. The use of lateral track offsets to move away from encounters has proved simple and effective in Oceanic airspace and is equally appropriate in European airspace. Lateral track offsets upwind of about 1 n.m. will usually be sufficient to avoid an encounter.

RVSM is not expected to increase the probability of a hazardous encounter with wake vortices, but pilots and air traffic should be informed that nuisance encounters would increase. Pilots and air traffic controllers should be better informed of the character of wake vortices and typical encounters. Before the introduction of RVSM, there is a need to ensure an effective system for collecting and analysing pilot and air traffic reports of significant encounters. These reports must include information on the leading aircraft and its separation (flight level, and range or time) from the aircraft reporting the event. The use of lateral offsets has been effective in stopping encounters in Oceanic airspace. In European airspace the risks of encounters where aircraft are changing flight level is likely to become more significant with increasing traffic density and improved navigation precision. Thus it seems prudent to introduce a process where an offset, a change of level or tactical heading can be obtained to avoid the possibility of a recurring encounters with wakes less than 2-3 minutes old. Following the introduction of RVSM, a study should be made of the received wake vortex reports and major wake vortex encounters above 5000ft altitude in recent years to establish the important characteristics of these encounters.

9. Recommendations

1. RVSM is not expected to increase the probability of a hazardous encounter with wake vortices, but pilots and air traffic should be informed that nuisance encounters would increase.
2. A change of flight level, a tactical heading or a track offset of 1 n.m. should be made available on request from ATC as a contingency procedure to remove aircraft from persistent nuisance encounters with wake vortices when they occur.
3. Before the introduction of RVSM, an effective system should be established for reporting, collecting and analysing reports from pilots and air traffic of significant wake vortex encounters.
4. After the introduction of RVSM, a study should be made of the received wake vortex reports, together with details of any other major vortex encounters above 5000 ft. in recent years, and this should be included as part of the Monitoring Post Implementation (Safety Case).
5. Pilots and air traffic should be better informed of the character of wake vortices and typical encounters.
6. Confirmation should be sought that recovery from unusual attitudes on instruments as a result of a major upset, such as a wake vortex encounter, is included in pilot simulator training schedules.

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Appendix A: Motion and decay of wake vortices away from the ground.

1. Introduction

Wake vortices are formed as a contra-rotating pair behind any aircraft in flight. These vortices are usually characterised by a total vorticity ($=2\pi$.(Radius).(Tangential velocity)) that is constant at large distances from the centre of the vortex, by a core radius defined as the distance to the peak tangential velocity, and by a formula defining the tangential velocity at any radius as a function of the total vorticity and core radius.

The impulse generated by one vortex on the other moves both vortices downward and they have been observed to descend about 500 ft below the flight path of the aircraft that generated them. In calm air the vortices are sometimes visible as condensation trails and these can last several minutes before dissipating. In turbulent conditions, which are common near the ground, vortices can dissipate in less than a minute.

The processes that lead to decay of vorticity are not well understood. Until very recently all computational fluid dynamics (CFD) methods failed to predict decay of coherent vorticity, although this has always been observed in flight measurements and is the reason why acceptable safe separation requirements could be established. In the last twelve months there have been encouraging signs that Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) CFD methods can predict vortex decay, but the methods have not yet been compared with flight test observations.

In an attempt to provide a semi-empirical basis for estimating vortex behaviour and justifying modifications to safe separation distances for particular aircraft pairs, Greene[10] of NASA, Langley Research Center, developed formulae in 1986 to represent vortex motion and decay. The assumption was made that the vortices are self contained and influenced by buoyancy effects as they descend into regions of increasing air density, and that there is a drag force that also opposes the vertical motion. In addition, vorticity is assumed to decay in proportion to atmospheric turbulence as described by Donaldson & Bilanin in their classic AGARDograph 204 (1975)[6]. The resulting vortex behaviour under light turbulence relates well with current separation criteria, and Greene's method has been a useful way of assessing likely criteria under varying atmospheric stratification, turbulence, etc., and of likely effects of new aircraft.

There is conflicting evidence about vortex behaviour during the first 30 seconds where there is some evidence that vorticity may decay much slower than Greene's method estimates. However, there is much better agreement between Greene's method and flight measurements beyond about 60 seconds which is where all separation requirements are at present. It is in this region that any vertical separation requirement is expected to be found. Thus it is recommended that Greene's method should be used to represent the effects of different altitudes and stratification on vortex motion and decay.

Greene's method does not include or identify changes in vortex state that can occur between about 60 and 120 seconds, where vortices can link to form Crow loops, or one or both of the vortices can burst. Comments on these effects are included in this Appendix in the final section.

2. Initial vorticity, spacing and downward velocity

Greene's method requires estimates of the initial vorticity and the separation between the two vortices as initial conditions, as well as atmospheric parameters. Estimates of these vortex parameters are derived in ref. 3 (Appendices C & D), for the case of a straight tapered wing with zero twist.

The resulting values are

$$\text{Total initial vorticity,} \quad \Gamma_0 = \pm P.\frac{W_g.g}{\rho.V.b_g}$$

$$\text{where } P \approx \frac{1.92}{0.992 + 0.863.tr}$$

$tr =$ taper ratio (tip / root)

$W_g =$ aircraft mass

$g =$ acceleration due to gravity

$\rho =$ air density

$V =$ true airspeed

$b_g =$ wing span

$$\text{vortex separation,} \quad b_{vx} = (0.496 + 0.431.tr).b_g$$

where $b_{vx} =$ separation between vortex cores

$$\text{and, initial descent velocity,} \quad w_{vx} = \frac{\Gamma_0}{2\pi.b_{vx}}$$

3. Atmospheric conditions

In addition to temperature, density and kinematic viscosity for a particular altitude, it is also necessary to calculate the Brunt-Väisälä (B-V) frequency, N, as the buoyancy factor. This B-V frequency is given by

$$N = \sqrt{\left(-\frac{g}{\rho}.\frac{d\rho}{dh} - \frac{g^2}{c^2} \right)}$$

where $h =$ height

$c =$ speed of sound ($= \sqrt{\gamma.R.T}$)

$\gamma =$ ratio of specific heats for air $= 1.4$

$R =$ gas constant for air $= 287.043 \text{ m}^2/\text{s}^2/^\circ\text{K}$

$T =$ absolute air temperature

Now $\frac{1}{\rho}.\frac{d\rho}{dh}$ can be derived as a function of temperature, T,

and temperature lapse rate, La, as follows:

the gas equation gives $\rho = \frac{p}{R.T}$ where $p =$ pressure,

differentiating gives

$$\frac{d\rho}{dh} = \rho.\left(\frac{1}{p}.\frac{dp}{dh} - \frac{1}{T}.\frac{dT}{dh} \right) = \rho.\left(\frac{1}{p}.\frac{dp}{dh} + \frac{La}{T} \right)$$

Now $\frac{dp}{dh} = -K.\frac{p}{T}$ where $K = 0.033672$

Thus $N = \sqrt{\left\{ \frac{g}{T}.(K - La) - \frac{g^2}{c^2} \right\}}$

Lapse rate is 0.0065 °K/m (1.9812 °K/1,000 ft) in the unstable International Standard Atmosphere below the tropopause, and zero (neutrally stable) above the tropopause. In regions of temperature inversions the Lapse rate becomes negative, i.e. temperature rises with height.

Greene uses a value of 2 ft/s (0.6 m/s) as the rms of low turbulence and this has been used in the estimates of this report.

4. Greene's method for estimating Vortex motion and decay

Greene develops a non-dimensional equation of motion where descent is positive (the normal convention for aircraft dynamics). Thus z is a distance positive downwards from the aircraft that generated the vortices, and vortex velocity, w_{vx}, is also positive downwards. The equation of motion is

$$\frac{d^2H}{d\tau^2} + \frac{C_D.L}{4\pi.b_g}\left(\frac{dH}{d\tau}\right)^2 + 0.82.\frac{q}{w_{vx0}}\left(\frac{dH}{d\tau}\right) + \frac{A.N^2}{2\pi.w_{vx0}}.H = 0$$

where $H = {}^{z}\!/_{b_{vx}}$

$\tau = {}^{t.w_{vx0}}\!/_{b_{vx}}$

$t =$ time

$w_{vx0} =$ downward vortex velocity at $t = 0$

$C_D =$ drag coefficient of the oval surrounding the vortex pair $= 0.8$

$L =$ span of the vortex oval $= 2.09.b_{vx}$

$q =$ Root mean square (rms) of turbulence velocity

$A =$ Cross sectional area of the vortex oval $\approx 2.84.b_{vx}^2$

Greene suggests a value of Drag coefficient at vortex Reynolds numbers ($\text{Re}_{vx} = {}^{w_{vx}.L}\!/_{\nu}$) above about 0.6×10^6 of 0.2, where $\nu =$ kinematic viscosity. This is very low and only appropriate if the equivalent shape is well rounded and tapered above the line joining the vortices like a well rounded conical cross section. In practice this is not a good representation because flow is entrained down between the vortices. A bluff equivalent shape will have a much higher Drag coefficient that does not reduce dramatically with increasing Reynolds number. At low Reynolds numbers the Drag coefficient will be about 1.4 because of separation around the bluff shape and this is an upper limit. Typical aircraft wakevortex Reynolds numbers are around 10^7.

The fact that there are no unacceptable wake encounters during military refuelling procedures with a minimum of 500 ft vertical separation, and considering the relatively low roll control moments that can be generated by fighter aircraft (their relative agility in roll comes from low roll inertia and low roll damping rather than high roll control moments), indicates that wake encounters are probably acceptable provided vertical separations exceed around 300 ft. The figure is lower than 500ft because errors in altitude sensing and flying tolerances will inevitably result in closer separation on many occasions. These military procedures suggest that a value of Drag coefficient of around 1.0, or more, would be more appropriate than the value of 0.2 suggested by Greene. If a value around 0.2 were used then the boundary of acceptability would be around 500-600 ft below the tanker, which would have resulted in significant encounters at nominal vertical separations as low as 500ft. The value of 1.0, rather than a larger one, is used because this gives a conservative estimate of acceptable vertical separations.

The equation of motion may be solved numerically to calculate vortex motion and decay.

5. Comments on Greene’s method and other decay processes

Greene’s method works well while there is still significant downward velocity of the vortices, but some of the assumptions become less valid as vortex descent velocity becomes small. Vertical velocities for boundaries of acceptable vortex encounters are significant and should be unaffected by the shortcomings related to low velocities. However, these estimates should not be used to identify the total height lost before the vortices dissipate nor to estimate the total life of the vortices. At time intervals exceeding about 60 seconds (8 - 9 nm) the vortex motion is also likely in many cases to be affected by the development of Crow loops (lozenge shapes often seen in condensation trails, which are formed by vortices linking in a periodic fashion), which will change vortex motion and, from visual observations, appear to accelerate the decay of the vortices. Bisgood (ref. 4) has observed condensation trails at around 30,000 to 35,000 ft and seen crow loops develop behind a B747 at times between 50 and 120 seconds, which is equivalent to along track separations of 7 and 16 nm. Evidence from data analysed by Sarpkaya & Daly (ref. 9) shows that the time at which Crow loops form is dependent on atmospheric turbulence even at very low intensities. The accelerated decay and the shape of the Crow loops will tend to reduce the descent velocity. It will be rare for vortices to descend for 120 seconds without degenerating into Crow loops. Despite this, incidents during landing have been reported at around 120 seconds. Visual observations suggest that the longest persistence of a vortex occurs when one of the pair dissipates, usually through bursting. In these circumstances the remaining vortex can continue for much longer than normal. However, it has lost the main source of impulse to drive it downwards and these single vortices will not descend as far as a pair.

Thus there are several reasons why Greene’s method will overestimate vortex descent beyond about 120 seconds (approx. 16 nm in cruise).

Appendix B: Vortex Induced Rolling Moments

6. Introduction

The tangential velocity, v, of air around a vortex increases rapidly from zero at the centre to reach a maximum at the core radius and then falls more gradually as radius, r, increases further. It is usually assumed that the tangential velocity is inversely proportional to radius at large radii, which means that the total vorticity ($= 2\pi.v.r$) is then constant. The rolling moment induced on a wing that is travelling in the same direction as the axis of a vortex can be calculated from the change in local angle of attack due to the tangential velocity of the vortex. This is discussed in detail in ref. 3.

Maximum induced rolling moment on encountering a single vortex will occur when the centre of the wing is at the vortex core, and even with a pair of vortices the maximum will be very close to this point for following aircraft with a wing span less than about 80% of the span of the generating aircraft. If the span of the following aircraft is greater than 80% of the generating aircraft then both vortex cores can intersect the wing at the same time and peak induced rolling moments will be greatest when the first vortex is some distance from the centre of the wing.

This appendix studies the maximum induced rolling moments and their relationship to the maximum roll control moment that the aircraft can command.

7. Induced rolling moments

In ref. 3 the non-dimensional induced rolling moment on the encountering aircraft from a single anticlockwise vortex is derived as

$$C_{l_{vx}} = \frac{L_{vx}}{\frac{1}{2}.\rho.V^2.S.b} = -\frac{a}{V}.\int_{-\frac{1}{2}}^{\frac{1}{2}} \frac{c}{\bar{c}}.v_r.\frac{y}{b}.d\left(\frac{y}{b}\right)$$

where $L_{vx} =$ Induced rolling moment (positive clockwise)

$\rho =$ air density

$V =$ true airspeed

$S =$ wing area

$b =$ wing span

$a =$ non-dimensional lift curve slope

$y =$ spanwise position (positive to starboard)

$c =$ wing chord at y

$\bar{c} =$ standard mean chord $= S/b$

$v_r =$ tangential vortex velocity at radius r

The induced rolling moment is directly proportional to the wing section lift curve slope and in practice this will be a function of y/b near the wing tips. It will fall to zero at the tip. The form of distribution of tangential velocity with radius from the core is a matter for debate. Iversen (ref. 2) has shown that about 40% of total vorticity is within the core for high vortex Reynolds numbers. A form of velocity distribution derived by Woodfield (ref. 14) from flight measurements of vortices has about 37% of vorticity within the core and has been used in this analysis. This formula is:

Tangential velocity equation: $v_r = \frac{2.\Gamma}{\pi^3.r}.\arctan\left(1.392.\frac{r}{R}\right)^2$

where $\Gamma =$ total vorticity

$R =$ core radius (= radius for maximum tangential velocity)

Substituting in the rolling moment equation

$$C_{l_{vx}} = \frac{a}{V}.\frac{2.\Gamma}{\pi^3.b}.\int_{-\frac{1}{2}}^{\frac{1}{2}} \frac{c}{\bar{c}}.\frac{y}{b}.\frac{\arctan\left(1.392.\frac{r}{R}\right)}{\frac{r}{b}}.d\left(\frac{y}{b}\right)$$

thus the rolling moment is proportional to $\frac{2a}{\pi^3}.\frac{\Gamma}{V_g.b_g}.\frac{b_g}{b}.\frac{V_g}{V}$ and $\frac{\Gamma}{V_g.b_g}$ is the non-dimensionalised vorticity (the suffix g indicates the generating aircraft)

Thus the peak induced rolling moment is

$$C_{l_{vx}} = \frac{V_g}{V}.(\text{non-dimensional vorticity}).(\text{peak induced roll factor})$$

where the 'peak induced roll factor' is $f\left\{\frac{b_g}{b}, \frac{b_g}{R}, \text{taper ratio}\right\}$

Values of the ‘peak induced roll factor’ are plotted in Figure 9 as a function of generating aircraft to encounter aircraft wing span ratio for a ratio of generator span to vortex core radius of 200 and a taper ratio of 0.25. The function is not very sensitive to taper ratio.

8. Maximum control rolling moment

Roll response at low speeds has to meet design requirements and this results in most civil transport aircraft having similar non-dimensional maximum roll control moments (defined in the same way as the non dimensional induced rolling moment) of around 0.07 to 0.09. At high speed the maximum rolling moment is reduced to avoid excessive wing loads or high fin loads through inertial cross coupling. However, it reduces to an almost constant non-dimensional value.

9. Rolling moment ratio

The ratio between the peak vortex induced and maximum control rolling moments (RollRatio) is an important ratio. The peak value will only occur in a limited region of space but it is an indicator of the likely severity of the worst disturbance that an aircraft can experience if it passes through this region during an encounter. An encounter will also pass through areas of lower rolling moment ratio around the peak region, because the trajectory during an encounter will never remain in the region of peak induced rolling moments. Indeed, if the peak ratio approaches or exceeds unity it is not possible to remain in that region.

It is not practical to define a clear analytical relationship between RollRatio and roll disturbances. However, if the RollRatio is significantly less than unity, say < 0.7 then a pilot can deal with an encounter without experiencing much roll disturbance because it is well within the roll control moments at his disposal. As it approaches unity the disturbance will increase, because of the delay in responding to a disturbance. Once it is significantly greater than unity, say > 1.5, then an aircraft passing close to the region of peak rolling moment will experience a very significant roll disturbance and pilot recovery action will not be very effective during the few seconds spent near the peak region, although eventual recovery will always be possible at high altitude. (Unless the pilot overreacts and exceeds some other limit that causes structural damage.)

The separation requirements for landing approach correspond to conditions that are around a peak RollRatio of unity.

The RollRatio is equal to the ratio of the non-dimensional rolling moments and, as non-dimensional maximum control rolling moments are approximately constant, this means that the key parameters are the non-dimensional vorticity, which is a function of the generating aircraft conditions, and the induced rolling moment factor, which is primarily a function of the span ratio between the two aircraft. Thus non-dimensional vorticity is used as the main parameter when studying the motion and decay of vortices in this paper.

[end of Appendix B]