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Chicago Monostatic Acoustic Vortex Sensing System

Volume III: Executive Summary: Decay of B-707 & DC-8 Vortices

D.C. Burnham
J.N. Hallock

Transportation Systems Center
Cambridge MA 02142

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16. Abstract

A Monostatic Acoustic Vortex Sensing System (MAVSS) was installed at Chicago's O'Hare International Airport to measure the strength and decay of aircraft wake vortices from landing aircraft. The MAVSS consists of an array of acoustic antennas which measure the vertical profile up to 60-m altitude of the vertical component of the wind. The decay in wake vortex strength is measured as the vortex passes over successive antennas in the array. Volume I (published in October 1979, 32 pages) described the MAVSS principles of operation, the hardware developed, and the data reduction methods employed. Volume II (published in September 1981, 162 pages) described the analysis of MAVSS data to examine whether landing B-707 and DC-8 aircraft need to remain divided into Heavy and Large categories on the basis of the wake vortex hazard. In this volume, the results of Volume II are summarized in terms of the safety implications of categorizing all landing B-707s and DC-8s as Large aircraft. Volume IV (to be published at a later date) describes the statistical methods used to understand wake vortex decay and presents the data on all common jet transport aircraft.

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PREFACE

Volumes I and II of this report describe a Monostatic Acoustic Vortex Sensing System (MAVSS) which was deployed on two runway ends at the Chicago O'Hare International Airport. The results of the data analysis presented in Volume II indicate that the current wake vortex aircraft categories (of specific interest is the division of B-707s and DC-8s into two categories) might be refined. Since the analysis is inherently complex and lengthy, it was decided that a separate Executive Summary would be useful. In so doing, Volume III referred to in Volume II will now become Volume IV.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

LENGTH

Symbol	When You Know	Multiply by	To Find	Symbol
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km

AREA

Symbol	When You Know	Multiply by	To Find	Symbol
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply by	To Find	Symbol
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t

VOLUME

Symbol	When You Know	Multiply by	To Find	Symbol
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply by	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

LENGTH

Symbol	When You Know	Multiply by	To Find	Symbol
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi

AREA

Symbol	When You Know	Multiply by	To Find	Symbol
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	

MASS (weight)

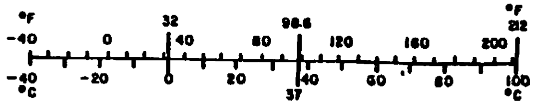
Symbol	When You Know	Multiply by	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	

VOLUME

Symbol	When You Know	Multiply by	To Find	Symbol
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply by	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

This report examines the operational impact of including all landing DC-8 and B-707 aircraft into the "Large" wake-vortex category. The impact is found to be minor. The operational requirements for a wake-vortex categorization system are discussed and the development of the current separation standards is recounted.

The evaluation of the DC-8 and B-707 categories is based on data from three sources. The first, and perhaps most definitive, is the experience of the United Kingdom (UK) where all DC-8 and B-707 aircraft were treated as "Large" for a period of time. The UK has operated a wake-vortex-incident reporting system both during this period and subsequently when the current International Civil Aviation Organization (ICAO) categories were adopted (August 1978). The second source of information is calculations of how vortex strength depends upon aircraft weight and size. The third source of data is measurements of wake-vortex decay for landing aircraft at O'Hare International Airport (July 1976 through September 1977) using the Monostatic Acoustic Vortex Sensing System (MAVSS). The MAVSS measurements of vortex strength were taken in the region just before the runway threshold where a vortex encounter is simultaneously most likely and most dangerous. Volume I of this report (Ref. 1) described in detail the hardware and data processing involved in the measurements. Volume II (Ref. 2) described the analysis of whether landing B-707 and DC-8 aircraft need to be divided into Heavy and Large categories on the basis of their wake-vortex hazard.

The results of this study indicate that all landing DC-8 and B-707 aircraft may be included in the Large wake-vortex category. It should be noted, however, that a number of air traffic problems need to be addressed before implementing the change. The feasibility of operating a system that designates an aircraft as Heavy at takeoff and as Large on landing must be examined. When and by whom is the wake-vortex category changed? Suppose a Heavy B-707 or DC-8 declares an emergency shortly after takeoff. Should this aircraft retain its Heavy status? These and other questions must be resolved.

2. CONCLUSIONS

1. The operational experience in the U.S. prior to 1970 supports the categorization of all DC-8/B-707 aircraft into the Large category. The standard 3-nautical-mile separation was used with no problems noted behind the aircraft types subsequently classified as Heavy.

2. The UK incident reporting statistics prior to August 1978 showed that the incident rate behind Heavy DC-8/B-707 aircraft at Large separations was reasonable, and was in fact similar to the incident rate behind wide-body aircraft at Heavy separations. Such a constant incident rate represents a system that is both fair and efficient.

3. The O'Hare measurements of wake-vortex decay for landing aircraft show that the DC-8/B-707 aircraft classified as Heavy exhibit wake vortex hazards similar to those from DC-8 aircraft classified as Large. The data also indicate similar vortex hazards for jet transport aircraft following Large B-707s, but lower vortex hazards for general aviation aircraft following Large B-707s. The net safety impact of reclassifying the Heavy DC-8/B-707 aircraft as Large is to increase the frequency of exposure of following aircraft to the most persistent vortices currently generated by Large aircraft (i.e., DC-8 vortices). This increased exposure would have the greatest impact on the smallest aircraft now classified as Large. Such aircraft (for example, the Gulfstream II) following the DC-8 now experience the greatest vortex hazard probability of any aircraft pair.

4. The analysis of the weight dependence of the vortex hazard indicated that the heaviest DC-8/B-707 aircraft would have a vortex hazard midway between the average hazard of the Large DC-8 and that of the B-747/L-1011. This effect of actual aircraft weight is not large enough compared to the other variables affecting the vortex hazard to warrant the complexity of using the actual landing weight to determine the aircraft category.

5. The analysis of the wake vortex hazard from DC-8/B-707 aircraft could be used to classify all landing DC-8/B-707 aircraft as Large. The simplest method of accomplishing this change would be to raise the dividing weight between Large and Heavy from 300,000 lbs to perhaps 375,000 lbs, as was used in the former UK categories. This method of effecting the change is not recommended, however, since it would classify as Large, aircraft such as the A-300, IL-62, A-310, and B-767, for which little or no wake vortex data exists. There is some evidence indicating a greater wake-vortex hazard for these aircraft types than for aircraft with four wing-mounted engines. The UK incident reporting system showed abnormally high incident rates behind the A-300. The MAVSS strength measurements indicate enhanced vortex persistence for aircraft with two wing-mounted engines.

3. REQUIREMENTS

The operational requirements for a wake-vortex separation system can be expressed in general terms. The system should be:

1. Safe,
2. Efficient,
3. Fair to all aircraft types, and
4. Simple to use.

The need for these requirements is obvious, but they must be more precisely defined before they can be used to evaluate a system, or as in the present case, to evaluate changes in a system.

The practical definition of "safe" which has been used in wake-vortex studies is that, when the mandated separations are observed, no wake-vortex accidents will occur. Since the current separation system was installed in 1970, this definition implies that the accident rate must be less than one per ten-year period. It is not possible to specify a longer period of accident free operation until the system has been in operation for a longer time. Since it is very difficult to evaluate how safe a system is on the basis of no accidents, an alternative definition of "safe" is that the rate and intensity of wake-vortex encounters be at an acceptable level. The encounter hazard can be based on pilot reports or on measurements of vortex strength and lifetime.

The system must be efficient in its use of airspace. At congested airports increased separations translate into costly delays. Since the construction of additional runways is rarely an option, the spacing of aircraft on existing runways must be the minimum value consistent with safe operation.

The system should be fair in the sense of giving a similar chance of a vortex encounter to all aircraft types. A fair system would not achieve an overall acceptable encounter rate where all the encounters are experienced by a single class of aircraft. A system that is fair is also likely to be efficient since each class of aircraft will use only the minimum amount of airspace required.

The system must be simple enough that it can be used for controlling aircraft operations. This requirement is often in conflict with the requirements of efficiency and fairness which could call for different separations for each pair of aircraft classes.

A satisfactory wake-vortex separation system must minimize the accident/incident rate while maximizing the utilization of airspace. The accident/incident rate is a function of many factors. The total rate is the sum of the accident/incident probability for each pair of aircraft times the frequency of occurance of the pair. The accident/incident probability for a pair is the probability of an encounter times the probability that the vortex remains strong enough to cause an accident/incident at the separation of the encounter. Since the encounter probability is small because of the natural motion of vortices, a safe separation system does not depend solely on having an extremely small probability of the vortex strength being below the accident/incident threshold.

The definition of wake-vortex categories and separations is arbitrary to a considerable extent. The duration of the wake vortex hazard generally increases continuously with the size of the generating aircraft. Likewise, the hazard to a following aircraft increases with decreasing aircraft size. Placing aircraft into categories requires that aircraft lying on either side of a category boundary will be treated differently even though they may have similar wake-vortex characteristics. Because of this arbitrariness in the boundary selection, factors other than wake-vortex characteristics can be used to define the boundary location. The current standards include an example of using another factor, namely, a previously existing aircraft size boundary. Ideally, one would like to locate the boundaries between groups of aircraft which have significantly different wake-vortex characteristics. The practical requirement, however, depends more on the traffic mix at airports than on the wake-vortex characteristics. The categories should be selected to maximize the airport capacity for congested airports while maintaining safe operations.

4. CURRENT SEPARATION STANDARDS

The FAA (and ICAO) categorizes aircraft for separation purposes into three groups according to the maximum certificated gross weight:

Small	Weight $\leq$ 12,500 lbs
Large	12,500 lbs $<$ Weight $<$ 300,000 lbs
Heavy	300,000 lbs $\leq$ Weight

The selection of the boundaries between the categories was determined both by the original intent of the categories and by the aircraft types existing at the time of the selection.

The division between Small and Large categories at 12,500 lbs was formally made in Amendment 10 to CAR 3 in 1953, which limited the applicability of CAR 3 to airplanes having a maximum weight of 12,500 lbs or less. The weight division fell in the middle of the large gap between the few thousand-pound general aviation aircraft and the approximately 28,000 pound DC-3. Subsequent development of aircraft has filled in this gap, so that one of the original selection criteria no longer pertains.

The introduction of jet transports into airline service in 1959 increased the concern about the effects of successively larger aircraft on traffic spacing. With the advent of the jumbo jet in 1969, concern was again expressed over the possibility that the wake vortices generated by these aircraft would be a hazard to other aircraft flying within the terminal area. The division between Large and Heavy aircraft was made in March 1970 to deal with the wake vortex hazard. The introduction of the B-747 more than doubled the maximum certificated gross takeoff weight of jet transport aircraft. Flight tests showed that the B-747 vortices could produce a significant hazard to following aircraft at the 3-nautical-mile IFR separation standard in use at that time. In order to eliminate the apparent hazard, the separation standards were increased behind the newly created category of Heavy aircraft.

At that time the new heavy versions of the DC-8 and B-707 had already been introduced. The dividing line between Large and Heavy was set at 300,000 lbs to include these heavier aircraft with the B-747, in order to minimize the vortex hazard to following aircraft. Subsequently, the weight gap between the DC-8/ B-707 and the B-747 was filled by the L-1011, DC-10, and A-300. At the present time, the original decision to split the DC-8/ B-707 aircraft into two categories appears to be arbitrary and confusing.

By 1973 the IFR landing separation standards behind Heavy aircraft had evolved from 3 nautical miles to 4 nautical miles for following Heavy aircraft and to 5 nautical miles for following Large and Small aircraft. In November 1975 the runway-threshold separation standards for Small aircraft were increased an additional nautical mile to 6 nautical miles behind Heavy aircraft and to 4 nautical miles behind Large aircraft. This increase was based on accident/incident occurrances and measurements of the decay of wake vortex strength.

A most notable feature of the aircraft categories is the very large range of weights (a factor of 24) contained in the Large category. The UK has operated a wake-vortex separation system where this category was divided into two.

5. UK EXPERIENCE

Prior to August 1978, the United Kingdom (UK) included the DC-8H and B-707H in the Large category for the purpose of wake vortex separation on approach. Subsequently, the UK adopted the US/ICAO division of the DC-8/B-707 aircraft into both Heavy and Large categories; the dividing line between Heavy and Large aircraft was lowered by the UK from 375,000 lbs to 300,000 lbs.

The UK has an active and successful program for reporting apparent wake vortex incidents, particularly for operations at Heathrow airport. Prior to the rule change the incident probability behind Heavy aircraft (in this case, more than 375,000 lbs certificated maximum gross takeoff weight) was comparable to the incident probability for Large aircraft behind aircraft with certificated maximum gross takeoff weights between 300,000 and 375,000 lbs. Thus, the separation standard which grouped all DC-8/B-707 aircraft into the same category (Large) gave a well-balanced or fair system in which the incident probability was approximately the same for various aircraft pairs. Subsequent to the rule change, the incident risk to aircraft following a DC-8H or B-707H has been virtually eliminated (the minimum separation was increased from 3 to 6 nautical miles for most following aircraft); however, the incident risk to DC-8H/B-707H aircraft following wide-body aircraft has increased at least fourfold (the minimum separation was decreased from 6 to 4 nautical miles) and now exhibits the highest incident risk of any pairs of categories included in the incident statistics.

In a related issue, the UK have experienced some complications with the categorization of the A-300B. When introduced into service, the A-300B was classed as Large along with the B-707H (recall that the UK dividing line was at 375,000 lbs). However, an unacceptably high vortex incident rate led to reclassifying the A-300B as a Heavy; this special assignment became redundant when the UK accepted the ICAO criteria promulgated in August 1978.

These observations indicate that, perhaps maximum certificated gross takeoff weight may not be the best discriminant of vortex hazard.

Including the DC-8H and B-707H in the Heavy category has brought about a reduction in capacity in the UK without any apparent overall increase in safety. The evidence collected both prior to and since August 1978 through the incident reporting system appears to support the unification of all DC-8/B-707 aircraft into the Large category.

6. CALCULATIONS

The total wake vortex strength (G) can be calculated by a simple equation:

$$G = CW/bVd \tag{1}$$

where the strength depends upon the following parameters:

C = The wing-loading factor, which is approximately unity.
(C = 1.00 for uniform wing loading and
C = 1.27 for elliptic wing loading)

W = Aircraft weight.

b = Aircraft wingspan.

V = Airspeed.

d = Air density.

The wake vortex strength given by this equation is valid after the vortex has rolled up but before any decay has begun. The equation shows that the total strength increases with aircraft weight and decreases with airspeed and wingspan. The Heavy aircraft tend to have larger wingspans as well as weights. Thus, some of the effect of heavier weight is cancelled by the larger wingspan.

In the O'Hare wake-vortex study landing weights were collected for many DC-8 and B-707 aircraft. The airspeed and air density, however, were unknown. It is thus of interest to examine how the vortex strength might depend upon aircraft weight under the assumption of fixed wingspan and fixed air density. If the wing loading (and hence the factor C) is also fixed (i.e., a fixed flap setting), the pilot can respond to changes in weight in two ways. The first is to keep the same airspeed V and change the aircraft pitch angle so as to change the coefficient of lift. This procedure yields a vortex strength G that is proportional to the aircraft weight. The second possible response is to keep the pitch attitude fixed and vary the airspeed to accommodate the weight change. (This method is normally used.) Since the lift is proportional to the square of the airspeed, the latter procedure yields a strength G that is proportional to the square root of the weight. The measurements, described in Section 9, of how the initial vortex strength depended upon aircraft weight were consistent with this square-root dependence.

7. DECAY MODEL

Unfortunately, there is no simple equation to describe the wake-vortex lifetime in the simple way that the initial strength can be specified. In fact, a single vortex lifetime cannot even be defined. The persistence of the wake-vortex hazard depends upon aircraft parameters (wingspan, weight, configuration, engine location, etc.), meteorological parameters (wind velocity, wind shear, turbulence, atmospheric stability, etc.), and decay processes (vortex linking, bursting, and turbulent diffusion). Since the decay processes occur at random even when all the parameters are fixed, the persistence of a vortex can be defined only through a probability.

The current designation of wake vortex separation categories assigns the wake vortex hazard to a single aircraft parameter, the maximum certificated gross takeoff weight. Of necessity, this simplified procedure gives only a rough indication of the wake vortex hazard. The actual hazard persistence for a specified pair of aircraft has a wide spread because of variation in the actual weight (and other parameters) of the leading aircraft, variation in the meteorological conditions, and the probabilistic nature of vortex decay. Because of this spread, the change in the vortex hazard probability will be relatively small for small percentage changes in the maximum certificated gross takeoff weight (e.g., an increase from 300,000 lbs to 375,000 lbs, or a 25 percent change).

The measurements of wake-vortex decay have shown that the vortex decay time depends surprisingly little on the size of the generating aircraft. The faster vortex-hazard decay for smaller aircraft stems more from their weaker initial strength than from a faster decay rate. The result of this effect is that, the vortex-hazard decay for an aircraft can be reasonably described by an effective vortex strength which is close to the initial strength generated by the aircraft. This model for vortex decay can be used to compare the vortex hazard for different aircraft types and to assess how the weight of the generating aircraft affects the vortex hazard. The latter assessment is possible since the weight dependence of the initial vortex strength is known from Equation 1 (Section 6).

8. HAZARD MODEL

A vortex hazard model is required in order to interpret vortex strength measurements in terms of the hazard to a following aircraft. The model adopted assumes that the primary hazard to a following aircraft is the loss of roll control. A vortex is assumed to be benign if its maximum vortex-induced rolling moment on a following aircraft is less than a fraction (f) of the roll control authority of the aircraft. A factor f less than one is used to represent the fact that a pilot cannot immediately use full roll control to oppose the effect of a vortex.

The vortex-induced rolling moment on a following aircraft can be related to an "average" vortex strength which is easily calculated from measured vortex velocity profiles. The "average" vortex strength is simply the average of the vortex circulation up to radius b/2, where b is the wingspan of the following aircraft. This calculation estimates the rolling moment induced when the wing of the following aircraft is centered in the vortex. The vortex hazard model thus predicts that the hazard posed by a vortex is a function only of the wingspan of the vortex-encountering aircraft.

9. MAVSS MEASUREMENTS

The Monostatic Acoustic Vortex Sensing System (MAVSS) measures a vertical profile of the vertical wind velocity above each antenna. It is particularly suited for measuring wake vortices, which have a vertical velocity component directly related to the vortex tangential velocity. The measurement is not corrupted by the ambient wind which is horizontal and hence is not measured. A measurement of the vortex tangential velocity profile requires that the vortex drift past the antenna position. Vortex decay is studied by measuring the vortex as it drifts over a series of antennas. Each antenna where the vortex is detected measures the vortex strength at the time of detection. The MAVSS measurements for aircraft landing at O'Hare Airport covered up to a height of 200 feet with a velocity profile every 0.4 seconds. The antennas were located at 200-foot spacing on baselines 1500 and 2000 feet from the runway threshold.

The MAVSS measurements of vortex strength are subject to a number of limitations. The first is that measurements are possible only for vortices moving at a reasonable speed across the MAVSS antenna array. If the speed is too slow, the vortex decays in transit or may not even reach an antenna. If the speed is too fast, too few data points are collected to adequately characterize the vortex. The most serious consequence of this transport speed limitation is that, the MAVSS cannot measure the stalled vortices which pose a hazard to following aircraft landing on the same runway. A second limitation of the MAVSS measurements is that they have relatively coarse spatial resolution (about 7 feet laterally and 10 feet vertically). Consequently, they tend to smear out the vortex core and thereby underestimate the vortex hazard to small aircraft. A third limitation of the MAVSS is that, the signal is degraded by the ambient noise of aircraft operations. The methods developed for processing and analyzing the MAVSS data were designed to compensate for these limitations. For example, only vortices detected in at least two antennas are analyzed; the transit time between antennas is used to measure the transport speed of the vortices which is needed to convert the measured velocities into vortex tangential velocity profiles.

The useful MAVSS data are collected when there is a crosswind blowing both vortices to one side of the extended runway centerline. Because the vortices separate in ground effect, the first vortex to arrive at an antenna moves more rapidly than the second which tends to stall. The data analysis concentrated on the second vortex which is the one which could pose a hazard to subsequent aircraft landing on the same runway. This emphasis is important since the second vortices are observed to be more persistent.

The limitations of the MAVSS measurements will have little effect on the results of this study since the primary goal is to compare the wake-vortex behavior for the Heavy and Large DC-8/B-707 aircraft. Because the aircraft are almost identical, any systematic errors in the measurements are likely to be the same for both sizes and will therefore not affect the comparison.

9.1 INITIAL VORTEX STRENGTH

The simplest method of analyzing the MAVSS data is to examine the statistics of the individual vortex detections as a function of vortex age. This method is useful for determining the initial vortex strength, but it cannot accurately describe vortex decay. The problem is that vortices can no longer be detected after they have decayed below the MAVSS detection threshold. They are then unavailable for statistical analysis. A method of dealing with the demise of vortices is described in the next section.

Vortex detections at ages between 10 and 20 seconds were used to characterize the initial vortex strength. Earlier measurements are corrupted by aircraft noise and incomplete vortex roll-up. Later measurements are affected by vortex decay. The measured initial strengths showed root-mean-square variations of about 20 percent. The dependence of strength upon actual landing weight (reported by the airlines) was extracted by means of a least-square fit and was found to be consistent with the square-root dependence predicted when a pilot accommodates weight changes by varying airspeed rather than lift coefficient.

9.2 VORTEX DECAY

A satisfactory analysis of vortex decay must deal with the demise of a vortex. The method adopted uses interpolation and extrapolation to determine the strength history of a particular vortex. The MAVSS measurements consist of strength values at times when the vortex passes over the sequence of antennas. The strength is assumed to be constant until the first detection. The strength is assumed to be zero when it is no longer detected at an antenna in the sequence, as long as the detection would not have been obscured by noise from the next aircraft. The strength for times between detections is obtained by interpolation. For more than half of the vortices measured the strength history terminates before vortex demise because the vortex passes the end of the array or lasts into the next aircraft's noise.

The primary use of the vortex strength histories is to determine the persistence of the vortex hazard to a following aircraft. According to the hazard model adopted, the hazard lasts until the "average" strength for the follower's wingspan drops below the level where the vortex-induced rolling moment is equal to a fraction f of the roll control authority. Because the decay of vortices is a random process, all vortices from the same type generating aircraft will not become safe at the same time. The number remaining hazardous will gradually decrease with vortex age. The decay of the vortex hazard is thus described as a probability which depends upon the hazard strength threshold and the vortex age. The hazard probability at a particular age is simply measured as the ratio of the number of vortices with strength above the hazard threshold to the total number of vortices with strength measurements at that age. The hazard probability is observed to decay very rapidly with vortex age once the probability drops below 50 percent. The functional dependence is that, the logarithm of the hazard probability decreases as the square of the vortex age. As would be expected, the vortex hazard lasts longer (i.e., a greater age is needed to reach a given hazard probability) if the hazard threshold is reduced, for example, by selecting a smaller value of f.

The parameters affecting vortex decay can be studied by setting conditions on the vortices to be included in the probability analysis. For example, the vortices first reaching the MAVSS antennas are consistently observed to decay more rapidly than the second vortices. This effect can be explained by the interaction of the vortices with the wind shear near the ground. The vortex decay is also found to be more rapid for larger ambient winds. Thus the proper set of vortices for determining the worst vortex hazard includes second vortices generated under low wind conditions. As discussed above, this set is appropriate for potential vortex encounters in single runway operations. Unfortunately, the set of vortices must be kept large enough to achieve significant statistical accuracy in evaluating the vortex hazard probability. Consequently, the following analyses examined data both for all second vortices and for second vortices with winds below 8 knots. The Heavy/Large comparisons were found to be similar for both wind selections.

9.2.1 Comparisons of Heavy and Large DC-8/B-707 Aircraft

The decay of hazard probability was found to be the same for DC-8, DC-8H, and B-707H aircraft within the statistical accuracy of the measurements. The B-707 hazard decay for following small jet transports (DC-9 size) was also the same. The vortex hazard decayed more rapidly for General Aviation aircraft behind the B-707 than behind the other types. This evaluation was subjected to a number of checks which verified its consistency. Values of f, the ratio of the hazardous induced roll to the roll control, between 0.5 and 1.0 were examined. An apparent discrepancy between the reported weights and the assigned Heavy/Large category was also investigated.

The similarity of the hazard decay for all DC-8/B-707 types is not unexpected since the average landing weights of the Heavy and Large types differ by only 10 percent. The statistical accuracy of the hazard persistence measurements would not allow detection of a 10 percent difference in hazard duration. In fact, the observation of statistically significant differences between the B-707 and the B-707H is somewhat surprising. In any case, the Heavy DC-8/B-707 aircraft show vortex characteristics similar to those of Large DC-8 aircraft, and can therefore be added to the Large category without significantly increasing the vortex hazard behind a Large aircraft. Such a change would, however, increase the number of Large aircraft exhibiting the greatest vortex hazard.

9.2.2 Comparisons to Other Aircraft Types

As expected, the observed persistence of the wake-vortex hazard generally increases with aircraft size. The DC-8/B-707 aircraft show longer hazard duration than smaller aircraft (such as the B-727) and shorter hazard duration than the wide-body aircraft (B-747, L-1011, and DC-10). Although data have not been collected on the re-engined DC-8 (Model 70), there are no reasons to expect any marked change in vortex behavior.

The appropriate assignment of the DC-8/B-707 aircraft to the Large or Heavy category depends, to some extent, upon how different the vortex characteristics are between the Large and Heavy categories of aircraft. A simple relationship was found between the hazard decay for the B-747/L-1011 class, representing the Heavy category, and the hazard decay for the DC-8/DC-8H/B-707H class, representing the upper end of the Large category. If vortex decay times are assumed to be independent of aircraft size, the B-747/L-1011 hazard probabilities correspond to the "effective" initial vortex strength a factor of 1.33 stronger than that of the DC-8/DC-8H/B-707H. This observation shows that there is a significant difference between the two classes of aircraft. (One should note that the DC-10 falls in between.) The form of the observed difference will be used next to evaluate possible effects of aircraft weight on the wake-vortex hazard.

9.2.3 Weight Dependence of Vortex Decay

Since no practical method was found for directly measuring the effect of aircraft weight on the decay of the wake-vortex hazard, the decay model described above was used to evaluate how the vortex hazard might be affected by the actual aircraft weight. The model states that the decay of the hazard probability depends only on an "effective" initial vortex strength. The duration of the hazard is determined by how long it takes for the initial strength to decay below the hazard-threshold strength. The effective initial strength may differ somewhat from the actual initial strength because of a small dependence of the vortex decay times upon aircraft size or engine placement. For aircraft as similar as the DC-8/B-707 types the effective initial strength should be identical to the actual initial strength. The fact that the initial strength depends upon the square root of the weight allows a calculation of the effective strength of the heaviest possible DC-8/B-707. The results of this calculation show that the effective strengths for the heaviest DC-8 and B-707 are 13 and 19 percent, respectively, above the effective strength of the average Large DC-8. These results show that even the heaviest B-707 reaches only about half way across the 33 percent difference in effective strength between the Large and Heavy categories.

The use of actual landing weights to set wake-vortex categories is impractical and probably unnecessary for a number of reasons. First of all, the measured weights at O'Hare fell into a much narrower band than the full range of certificated landing weights. Similar weights were found in checks at other airports. Secondly, the random variations in wake-vortex decay are so great that the variations introduced by differing weights are insignificant. Thirdly, in the specific case of DC-8/B-707 aircraft, the maximum landing weight of a Large DC-8 is higher than the observed average weight of a Heavy DC-8/B-707. Consequently, an average Heavy DC-8/B-707 has a lower vortex hazard than the heaviest Large DC-8. Thus, a consideration of weight effects on the wake-vortex hazard supports the assignment of all DC-8/B-707 aircraft to a single category.

10. REFERENCES

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