CHARACTERIZING THE HAZARD OF A WAKE VORTEX ENCOUNTER

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Abstract

The National Aeronautics and Space Administration (NASA) is conducting research with the goal of enabling safe improvements in the capacity of the nation's air transportation system. The wake vortex upset hazard is an important factor in establishing the minimum safe spacing between aircraft during landing and take-off operations, thus impacting airport capacity. Static and free-flight wind tunnel tests and flight tests have provided an extensive data set for improved understanding of vortex encounter dynamics and simulation. Piloted and batch simulation studies are also ongoing to establish a first-order hazard metric and determine the limits of an operationally acceptable wake induced upset. This paper outlines NASA's research in these areas.

Introduction

Many of today's major airports are capacity limited, leading to increased airport congestion and delays. The ability to relieve the congestion through airport expansion or new airport construction is limited and increasingly difficult. NASA, the Federal Aviation Administration (FAA), airport operators, and the airline industry are all interested in methods to improve airport capacity. NASA is conducting a Terminal Area Productivity (TAP) Program to provide the necessary research to support the FAA and industry in safely achieving clear-weather (visual flight rules) airport capacity in instrument meteorological conditions (IMC). The TAP Program consists of four elements: Air Traffic Management, Aircraft/Air Traffic Control Systems Integration, Low-Visibility Landing and Surface Operations, and Reduced Spacing Operations.

The wake vortex research described in this paper is a part of the Reduced Spacing Operations element of the TAP Program. Improvements in landing frequency through reduced in-trail spacing have the potential to improve system capacity by 10-15%.[1] This potential capacity improvement has renewed interest in wake vortex research. The spacing required to avoid the wake turbulence of the preceding airplane is one of the limiting factors in safely reducing in-trail spacing.

A wake vortex upset is most hazardous for aircraft near the ground during landing and takeoff.[2] The degree of upset mainly depends on the relative size of the vortex generating and vortex encountering airplanes, and the extent of wake decay. The initial energy or strength of the vortex and the response of the encountering airplane are directly related to aircraft size and weight. The rate of wake decay is highly dependent on the atmospheric state.

One of two conditions must be met to safely reduce the spacing between aircraft. The wake of the preceding aircraft must have either moved out of the intended flight path of the following airplane or it must have sufficiently decayed such that the encountering airplane can safely land. The research outlined in this paper should provide the tools required to determine what constitutes sufficient wake decay. However, the establishment of acceptable wake decay boundaries will require a strong government/industry interaction and consensus and is outside the scope of this research.

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The results of this research will be integrated into an advanced Aircraft Vortex Spacing System (AVOSS) concept under development at NASA Langley.[3] AVOSS will provide dynamic, weather dependent wake vortex spacing requirements for an advanced automated air traffic control system.

Approach

The approach used to characterize the wake encounter hazard is divided into three objectives:

a) Validation of wake encounter simulation models.

b) Establishing the metric used to quantify the upset potential of a wake vortex encounter.

c) Application of hazard metric and simulation models to commercial fleet for development of candidate acceptable encounter limits.

This paper will outline the research being conducted in these three areas. This partition of the research by objective is also chronological. Consequently, more work has been completed in the area of simulation validation than in the other two.

Simulation Validation

The wake encounter simulation is the primary tool used to assess the wake upset potential and establish acceptable wake encounter boundaries. Therefore, the limitations and errors associated with the encounter models must be well understood. Various methods have been used to model the effect of the wake on an encountering airplane, from simple one-degree-of-freedom roll upset models to multi-degree-of-freedom vortex-lattice and Navier-Stokes solutions [4-13]. Many of these methods were developed during the 1970s and 1980s to study the wake hazard potential of the new B-747, L-1011, and DC-10 size airplanes to smaller aircraft. However, very little flight test or wind tunnel data existed upon which to validate these methods. Most of the simulation validation was provided through pilot subjective evaluation. This may have been sufficient for studying the wake upsets associated with "hazardous" encounters, however, the upset potential associated with "acceptable" wake encounters is expected to be much smaller and thus more sensitive to modeling errors. For small airplanes following much larger airplanes the wake upset may occur so quickly that the pilot input has little consequence. However, for airplanes of similar size and weight the flight controls can affect the resultant upset. In order to provide an accurate simulation tool these effects must be carefully modeled and validated.

Wind Tunnel Tests

Two NASA wind tunnel facilities have been used in the past three years to study the wake-vortex encounter. These facilities used three different test techniques. In the 80-by 120-Foot Tunnel at the NASA Ames Research Center the wake characteristics of a 0.03 scale B-747 and DC-10 model were measured at one-half mile scale distance downstream.[14-17] The data obtained during the test included the lift and rolling moment induced on various size wing planforms mounted on a downstream survey carriage. The velocity distribution in the wake flow field was also measured using a hot-film anemometer probe on the survey carriage. The accuracy of vortex-lattice methods to compute the loads induced on a following wing were also studied. The carriage was located 81 feet downstream of the generating wing which corresponds to a full-scale distance of one-half mile. A photograph of the test setup is shown in figure 1. The results of the test showed that the span ratio of the leader/follower airplane pair has a significant affect on the wake-induced rolling moment.

Two different test techniques were used to study wake-vortex encounters in the 30-by 60-Foot Tunnel at the Langley Research Center. The first was a free-flight model technique in which the airplane model was flown in the test section through the wake of a wing mounted upstream, as shown in figure 2. Smoke was injected into the wake of the upstream wing to mark the trailing vortices. Rather than attempting to scale realistic separation distances via the geometry of the test setup, the vortex strength was controlled via the angle of attack of the generating wing. Both dynamic and steady

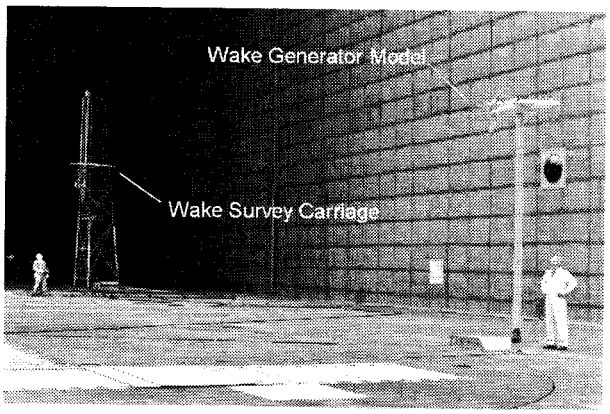

Figure 1. - Photograph of experimental setup in 80x120 Foot Wind Tunnel.

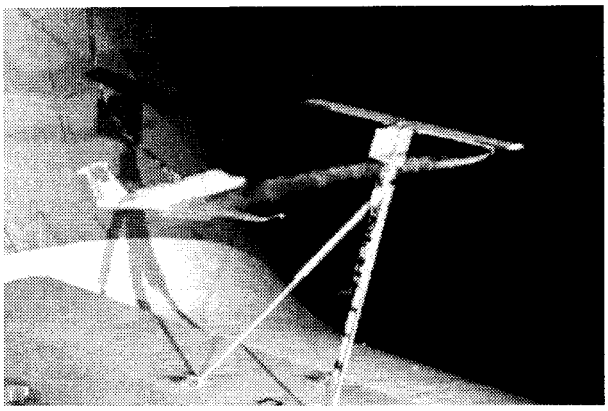

Figure 2. - Free-flight wake-vortex encounter test with generic business jet model.

encounter maneuvers were flown to examine the response of the airplane to the wake and to measure the amount of control power required to counteract the wake, respectively.

The airplane model was propelled by high-pressure air and piloted via signals passed through an umbilical to movable control surfaces. The states of the model were measured from on-board accelerometers and gyros and from a photogrammetric camera system mounted along the perimeter of the test section.

The third test technique, shown in figure 3, used a sting mounted model to measure the static forces and moments induced by the vortex. The wake generator wing was mounted on a movable tunnel survey carriage upstream of the airplane model. The wake was positioned at a variety of locations relative to the airplane to map the wake effect. Wake velocity data was also collected using a five-hole-probe to enable accurate modeling of the vortex flow field.

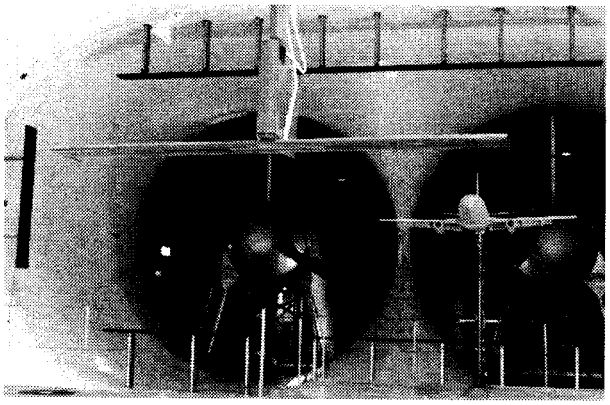

Figure 3. - B-737-100 static vortex encounter test.

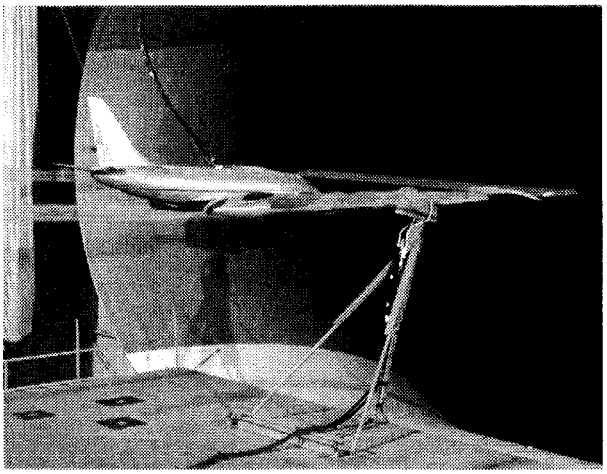

Figure 4. - B-737-100 free-flight wake-vortex encounter test.

Two airplane configurations have been tested using the free-flight and static test techniques in the 30x60 tunnel. The first was a generic business-jet configuration shown in figure 2. This model was used to explore the feasibility of the test technique. The second configuration, shown in figures 3 and 4, was a model of the NASA Langley B-737-100 research airplane. This configuration was selected as the "nominal" case for all model validation efforts since high fidelity simulation models and flight test data were readily available for comparative evaluation studies. The results of the 30x60 tests are currently being analyzed and documented and should be published within the year. An example of the analysis is presented in figure 5 which shows a comparison of the measured and computed vortex induced rolling moment from the generic business jet static test.

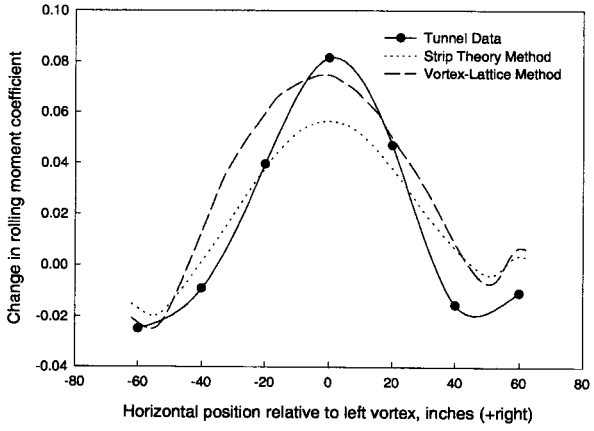

Figure 5. - Comparison of predicted and measured vortex induced rolling moment for a generic business jet model.

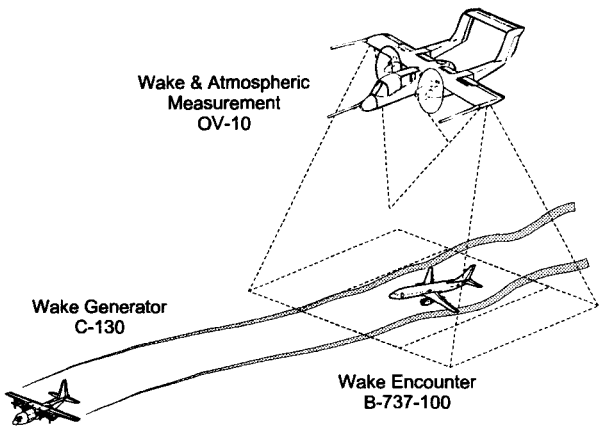

Figure 6. - Wake encounter flight test setup.

Flight Tests

In addition to wind tunnel experiments, a series of flight experiments were also conducted to provide full-scale validation data for wake encounter and wake decay models. These flight tests involved three NASA airplanes as illustrated in figure 6.

The NASA Wallops Flight Facility's C-130, shown in figure 7, was the wake generator. It was outfitted with wing tip smokers to mark the wake. It weighed between 105,000 and 95,000 pounds during the test and has a wing span of 132 feet 7 inches. The NASA Langley B-737 flew both dynamic and steady wake encounter maneuvers through the vortex wake. The maneuvers are very similar to those flown in the wind tunnel free-flight tests for purposes of comparative analysis. The wake induced forces and moments were recorded onboard. The B-737 was approximately the same weight as the C-130. A photograph of a vortex encounter, taken from a camera mounted on top of the B-737 vertical tail, is shown in figure 8.

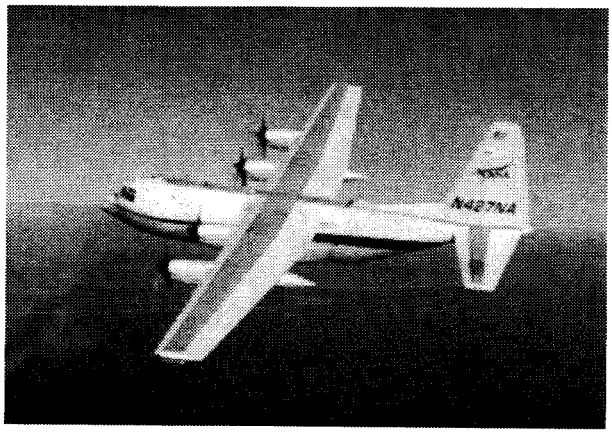

Figure 7. - C-130 wake generator airplane.

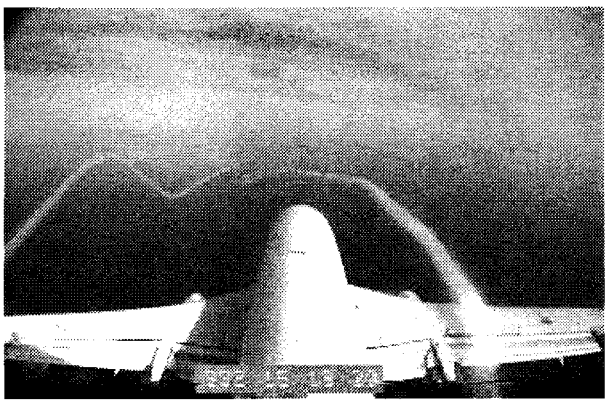

Figure 8. - Tail video of B-737 wake encounter.

The wake position relative to the B-737 was recorded using an experimental wing-mounted stereoscopic video system on-board a specially instrumented OV-10A airplane, shown in figure 9. The OV-10 flew above the B-737 to video record the wake encounter, as illustrated in figure 6. Figure 10 shows a picture taken with this video system of the B-737 encountering a wake. The position of the vortices relative to the B-737 was computed post-flight from the stereoscopic shift of the images between the left and right wing tip cameras.

The OV-10 was also used to measure the flow field characteristics of the wake using a three-boom, flow-sensor arrangement on the aircraft. After the B-737 completed a series of wake encounter maneuvers at a fixed distance from the C-130, the OV-10 would descend and fly through the wake, measuring its velocities and position. An example of a wake vertical velocity measurement from the three booms is shown in figure 11. During this particular wake measurement the OV-10 was flying through the wake from left to right. The airplane flew through the left vortex but passed below the right vortex. This is reflected in the measured velocities. Theoretical vortex models are fit

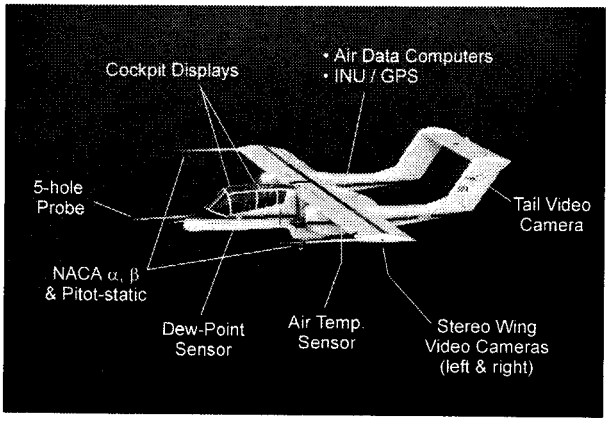

Figure 9. - OV-10 major instrumentation systems

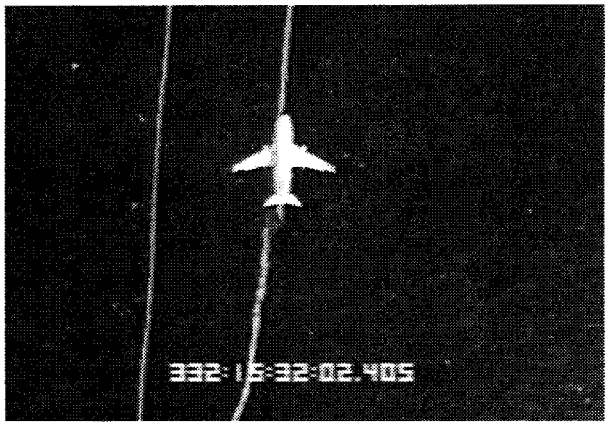

Figure 10. - OV-10 left wing video image of B-737 wake encounter.

to the measured wake velocities to estimate the vortex characteristics such as circulation strength, core location, and core radius.

The OV-10 was also equipped to measure the ambient weather conditions for correlation with the wake transport and decay characteristics. This information is critical to understanding the variation in wake characteristics. As an example, figure 12 shows the descent of a wake measured by the OV-10 as a function of time. During the first 60 seconds the wake descends in a predictable manner. However, during the next 60 seconds the wake descent is considerably different. This may be due to local variations in the vertical wind, temperature, or turbulence. The OV-10 atmospheric measurements will be correlated with such anomalies to better understand their influence on wake transport and decay. An extensive overview of the research systems and measurement capabilities of the OV-10 is presented in reference 18.

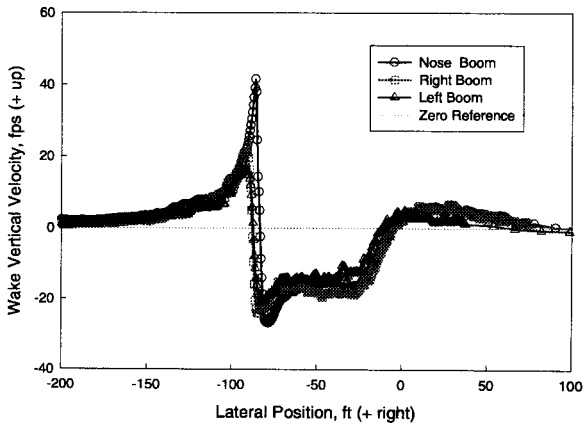

Figure 11. - Example of a wake vertical velocity profile measured by the OV-10 research airplane.

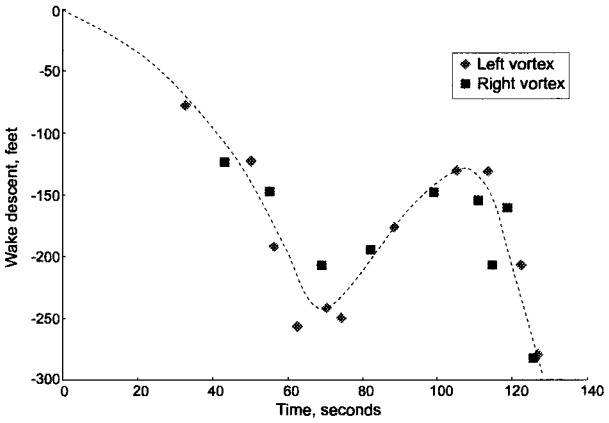

Figure 12. - OV-10 measured wake descent of a C-130.

Hazard Metric

The second major objective of this research is to establish a metric to quantify the upset potential of a wake vortex encounter. This metric will be used to establish the boundary between acceptable and unacceptable wake encounters. In the 1970s and 1980s, several key piloted simulation studies were conducted to obtain an estimate of the magnitude of vortex-induced motions considered hazardous near the ground.[7,8,9,11,19] An excellent summary of the results of these studies is provided by Rossow and Tinling.[20] These simulation studies provided some preliminary insight into suitable hazard metrics. For example, maximum bank angle, encounter altitude, vortex strength, and the encounter angle, were found to correlate with the boundary between the encounters judged to be hazardous and non-hazardous[7,8]. Similar correlation was not found for roll rate or roll acceleration. The parameter that yielded the best defined hazard boundary was maximum bank angle. Figure 13 reproduced from reference 8 shows the data (collected under simulated instrument flight conditions) used to produce a candidate hazard boundary for a B-707 as a function of maximum bank angle and encounter altitude. Note that although a boundary can be drawn, there is considerable scatter in the data, and limited results below 200 feet.

Although these previous studies have provided excellent insight there is not sufficient data to establish a definitive hazard metric. These studies tried to define the limit of what would be considered hazardous, which may not be quite the same as the limit of what is considered acceptable. The limits of an acceptable non-hazardous encounter may include consideration of such factors as flight-path deviations, control required to maintain attitude, touchdown requirements, and ride

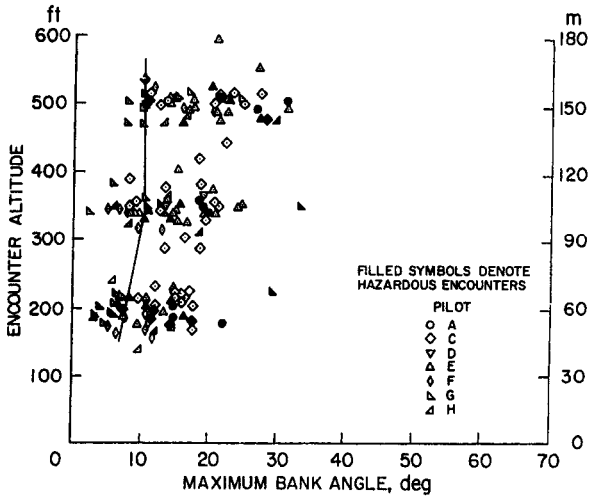

Figure 13. - Maximum bank angle data from simulated wake encounters (Figure 10 of Reference 8).

quality. An example of this was obtained from the flight data recorder of a commercial airliner which executed a missed approach after encountering wake turbulence. The data showed that the pilot elected to execute a missed approach without having experienced any appreciable bank angle upset. However, considerable wheel input was required by the pilot to maintain the wings level condition. Based on the required control input and the fact that the condition was not improving, the pilot executed a missed approach. In this example the maximum bank angle metric would not have been sufficient. Any wake encounter which requires the pilot to execute a missed approach would be counterproductive to airport capacity and would therefore be considered unacceptable.

Currently, piloted and batch simulation studies are being conducted to expand on the results of the previous work and gather the additional information needed to define a first-order hazard metric. The batch simulation is used to assess the sensitivity of various encounter metrics to encounter geometry and modeling errors.[13] The guidance and control inputs for the simulation are provided through an auto-land system. The piloted simulation studies will be used to expand the subjective assessment of an acceptable encounter metric. The combined results of this work can then be used to establish a metric for development of acceptable operational limits. A strong government/industry interaction will be required to establish a consensus on these boundaries and may require additional studies to refine and augment the first-order estimates.

Fleet Analysis

The final objective of the wake encounter research is to apply the simulation tools and hazard metric to the commercial fleet and establish acceptable wake encounter limits. Preliminary fleet-wide hazard assessments conducted by Stuever [21] et al., and Tatnell [22] are indicative of how a hazard metric and model may be applied. The detailed airplane configuration information required for a high fidelity wake encounter simulation is not practical for fleet-wide analysis. Simple encounter models that only require limited airplane configuration information are best suited for this application. However, the errors associated with the simple models must be understood and documented from the simulation validation studies.

An airplane database that is accurate and representative of the airplane mix at the major airports must be established and verified by a government/industry team. A candidate database of some 65 aircraft was compiled at NASA Langley for preliminary analysis.[21] The database includes geometric, mass-property and limited aerodynamic data. The minimum set of data required will depend on the encounter analysis method selected.

Concluding Remarks

Current NASA wake vortex research is focused on increasing airport capacity by safely reducing wake-hazard-imposed aircraft separations through advances in a number of technologies including vortex motion and decay prediction, vortex encounter modeling, and wake-vortex detection. This work is being integrated into an Aircraft Vortex Spacing System (AVOSS) concept which will provide dynamic, weather dependent wake vortex spacing requirements for an advanced automated air-traffic control system.

Static and free-flight wind-tunnel tests and flight tests have provided an extensive data set for improved understanding of vortex encounter dynamics and simulation. This data is currently under analysis and is expected to be published within the next year. This data will be used to validate and understand the limitations of various wake encounter modeling methods.

Piloted simulation studies are currently being conducted to establish a first-order hazard metric and determine the limits of a pilot acceptable wake induced upset. This information will be used in future analytical studies applied to a representative database of the commercial fleet to assess the potential impact on airport capacity. A strong government/industry interaction will be required to establish a consensus on

these boundaries and may require additional studies to refine and augment the first-order estimates.

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