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NASA WAKE VORTEX RESEARCH

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Abstract

The National Aeronautics and Space Administration (NASA) is conducting research that will enable safe improvements in the capacity of the nation's air transportation system. The wake-vortex hazard is a factor in establishing the minimum safe spacing between aircraft during landing and take-off operations, thus impacting airport capacity. The ability to accurately model the wake hazard and determine safe separation distances for a wide range of aircraft, weather, and operational scenarios may provide the basis for significant increases in airport capacity. This paper describes the current and planned NASA research which 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.

Nomenclature

b	airplane wing span, ft
U	forward speed of airplane, ft/sec
W	airplane weight, lb
Γ	initial vortex circulation strength, ft^2/sec
ρ	air density, slug/ft^3

Introduction

Many of today's major airports are capacity limited, leading to increased airport congestion and delays, especially during adverse weather conditions. With air-traffic continuing to increase and very few new airports, this trend is expected to continue. The National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), airport operators, and the airline industry are all interested in methods to improve airport capacity. One way to improve capacity is to reduce the in-trail spacing of airplanes. Improvements in landing frequency through reduced in-trail spacing have the potential to improve system capacity by 10-15%.(1) The spacing required to avoid the wake turbulence of the preceding airplane is a limiting factor in reduced spacing. This potential capacity improvement has renewed interest in wake vortex research.(2)

The NASA is conducting research with the goal of enabling safe improvements in the capacity of the nation's air transportation system. One part of this research, the Terminal Area Productivity (TAP) Program, is providing the necessary research to support the FAA and industry in safely achieving fair-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 falls under the last element, Reduced Spacing Operations.

Reduced Spacing Operations will depend upon improved flight precision capability for reduced arrival-time variance; however, the minimum separation between arriving aircraft is limited by the wake-vortex hazard. The wake-vortex hazard is a factor in spacing aircraft landing and taking off on a single runway, closely-spaced parallel runways, and intersecting runways. The need for aircraft spacing to avoid upset by a vortex encounter is deemed most important for aircraft following each other while landing and taking off on a single runway.(3)

The knowledge base on which current wake-vortex-imposed separation standards are based evolved during the late 1960's and the 1970's. In the U.S., aircraft are

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Following Aircraft	Leading Aircraft		
	Heavy	Large	Small
Heavy	4	3	3
Large	5	3	3
Small	6	4	3

Table 1. - U.S. wake vortex separation standards, distances in nautical miles.

classified as "Heavy" (300,000 lb or greater), "Large" (between 12,500 and 300,000 lb), and "Small " (less than 12,500 lb) based on maximum gross takeoff weight.(3,4) Separation distances in the U.S. are based only on the weight classifications of the leading airplane and the following airplane (Table 1). No account is made for factors such as airplane configuration or actual weight, atmospheric turbulence and winds, or local terrain effects. Therefore, the ability to accurately model the wake hazard and determine safe separation distances for a wide range of aircraft, weather, and operational scenarios may provide the basis for significant increases in airport capacity.

Airport capacity and the establishment of minimum safe spacing standards are international problems; however, as aircraft operate across international borders, they may be subject to significantly different wake-vortex-imposed spacing. In the U.S., there are two different operational modes, depending on the meteorological conditions. In visual meteorological conditions (VMC), there is no required minimum spacing and the pilot is responsible for maintaining a safe distance behind another aircraft. In instrument meteorological conditions (IMC), the air traffic controller is responsible for maintaining safe separations. Safe separation is determined by a number of factors in IMC. The minimum spacing, however, is vortex-imposed and is significantly greater than at busy airports during VMC operations. Fortunately, visual meteorological conditions occur about 80% of the time (on average) in the U.S.

Class	ICAO	UK	US
Heavy	≥ 300,000	≥ 300,000	≥ 300,000
Large	-	-	< 300,000 > 12,500
Medium	< 300,000 > 15,000	< 300,000 > 90,000	-
Small	-	≤ 90,000 > 37,500	≤ 12,500
Light	≤15,000	≤37,500	-

Table 2. - Comparison of aircraft weight classes for wake vortex separation, weights in pounds.

The system which has evolved in the United Kingdom (U.K.) is significantly different. All operations are treated as IMC operations and minimum vortex-imposed separations are applied. Since vortex-imposed separations apply all of the time, there has been a greater incentive to conduct research to better define the minimum safe spacing. As a result of a vortex encounter incident reporting system, a different set of weight categories and spacing has evolved. Table 2 shows a comparison of the U.S., U.K., and International Civil Aviation Organization (ICAO) weight classifications, and Table 3 shows the required spacing. The U.S. and the ICAO have three fairly similar weight classes and equivalent spacing standards except for "Large-Small"/"Medium-Light" leader-follower pairs. The U.K., however, has markedly different standards with four weight classes with significantly greater spacing (as much as a factor of two more) given to smaller aircraft. However, the most significant fact is that there is so much difference in the international system.

Wake vortex research conducted by the NASA in the 1970's emphasized reduction of the wake hazard through changes to the aerodynamic characteristics of the aircraft.(5-7) Significant technical progress was made but no practical solutions were obtained. Current NASA 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, wake-vortex hazard characterization, and vortex detection. Wake-vortex-related research for Terminal Area Productivity is being performed at both the Ames and Langley Research Centers, with the majority of the research being conducted at the Langley Research Center. The research at Langley is divided into two main

Lead Aircraft	Following Aircraft	Minimum Separation Distance, nm		
		ICAO	UK	US
Heavy	Heavy	4	4	4
Heavy	Large	-	-	5
Heavy	Medium	5	5	-
Heavy	Small	-	6	6
Heavy	Light	6	8	-
Large	Large	-	-	3
Large	Small	-	-	4
Medium	Medium	3	3	-
Medium	Small	-	4	-
Medium	Light	5	6	-
Small	Light	-	4	-
otherwise either 3 nm or no vortex spacing requirement				

Table 3. - Comparison of aircraft separation distances for wake vortex avoidance.

areas: wake-vortex hazard characterization and wake vortex sensing. This paper reviews prior work and presents an overview of the wake-vortex hazard characterization research planned and being conducted at the NASA Langley Research Center.

Previous Research

Wake vortex research has been conducted in the U.S. for over thirty years by a diverse group including the FAA, NASA, the Air Force, the Army, the Navy, aircraft manufacturers, airlines, airport operators, and many university groups. In addition, there has been extensive research by a number of other countries. Of this research, the best known has been the joint research programs sponsored in the U.S. during the 1970's by the FAA and NASA. The NASA program focused on reducing the wake hazard at the source through aerodynamic changes to the aircraft. The FAA program focused on developing measurement techniques and an extensive data base which could be used to develop an operational system for advising air traffic controllers when conditions were appropriate for reducing aircraft spacing. The research in both areas was extensive.(8-23)

In 1970, the wake vortex problem was one of safety. Flight tests, conducted by NASA and the FAA, found significant vortex-imposed rolling motions 10 nautical miles behind "Heavy" jets at altitude. It was not known how long the vortex hazard would persist when aircraft were near the ground during approach, landing, and departure operations. Most of the vortex-induced accidents occurred to "Small" aircraft on final approach; therefore, the early efforts were primarily concerned with vortex phenomena during landing operations and with reducing the hazard to "Small" aircraft.

In early 1973, the FAA Air Traffic Service requested that the separation standards be reviewed because the British had promulgated standards which included a 10-nautical-mile separation for a "Small" aircraft behind a "Heavy". By late 1973, enough data had been collected to demonstrate that the standards for landing commercial aircraft were adequate for preventing hazardous vortex encounters. In 1975, at the instigation of the FAA Systems Engineering and Development Service, the landing separation standards for "Small" aircraft were revised by adding an extra nautical mile of separation at the runway threshold. At about this time, the emphasis of the wake vortex program shifted from safety to increasing capacity without reducing safety.

The pre-1970 theories describing wake vortex characteristics were very simplistic. It was generally known that

1) the vortex strength depended on the size, weight, and speed of the generating aircraft,
2) the vortices generally descended and separated when they approached the ground, and
3) the vortex motion was strongly influenced by the ambient wind and ground.

However, the lack of field measurements prior to 1970, particularly of vortices near the ground, precluded an in-depth understanding of vortex behavior, especially decay.

Vortex Advisory System

The initial efforts of the FAA-sponsored wake vortex program focused on the development of sensor systems for detecting and tracking vortices near the ground. Various sensing techniques were investigated including acoustic, electromagnetic, passive ground wind, pressure, and laser Doppler. Large-scale data collection activities began with the installation of several sensor systems at New York's John F. Kennedy International Airport in June 1973 to measure vortices from landing aircraft. Other data collection sites were established at Stapleton International Airport, Heathrow International Airport, and O'Hare International Airport. Data on vortex behavior between the middle marker and runway threshold were obtained on a combined total of over 70,000 landings. Extensive analysis of the landing data led to the concept of the Vortex Advisory System (VAS). The basic concept of VAS is to adjust aircraft separations for IMC operations on a single runway according to wind measured near the middle marker. Measurements showed that, when the wind vector was outside an ellipse with the minor axis (crosswind) of 5.5 knots and major axis (headwind) of 12.5 knots, no wake vortices remained on the runway more than 80 seconds and it was safe to reduce separations to 3 nautical miles. The VAS was installed at Chicago's O'Hare International Airport in 1977 for a field demonstration. Meteorological towers were installed around the airport to measure the ambient wind near the middle markers of all landing runways. The wind data were fed to a microprocessor which drove a display giving controllers either a red or green light for reducing separations to a uniform 3 nautical miles.

During the field demonstration of VAS, a number of problems and constraints were encountered which had not been anticipated.(2) These include the fact that:

1) VAS was based on data recorded in the middle-marker-to-threshold region and provided no guidance for reduced spacing near the outer marker or beyond,
2) increased complexity resulted for missed approach procedures for a following aircraft when the lead aircraft was a "Heavy",

3) the requirement for use of VAS in visual as well as instrument meteorological conditions produced a possible loss of capacity in visual meteorological conditions, and

4) VAS was a predictive system with no real-time ground truth measurements.

Perhaps the strongest argument against VAS resulted from two vortex encounters experienced by an FAA aircraft which was intentionally flown close behind a "Heavy" aircraft during the VAS demonstration. Even though the FAA aircraft was not obeying VAS guidelines when the encounters occurred, the severity of the encounters was a strong warning of the potential hazards which could exist with VAS when occasional operational errors occur.

Even though VAS was termed a failure as an operational system, it was clearly a success in other ways. The data collection program supporting the development of VAS and supporting theoretical work has provided most of our understanding of wake vortex motion and decay under realistic airport conditions. The data have revised our thinking about vortex decay by showing that vortices decay from the outside while maintaining high velocities near the core, just the reverse of conventional vortex theory. The data also showed that atmospheric stability, turbulence, ground effects and winds are as important as aircraft size (class) for determining how long a wake hazard lasts.

Flight Tests

One of the first objectives of the flight tests conducted during the early part of the wake-vortex program of the 1970's was the determination of a minimum distance at which it is safe for aircraft of various sizes to enter the wakes of other aircraft. It soon became apparent that neither lift changes nor yawing and pitching moments induced by a vortex wake are perceived as hazardous, even though they may at times be objectionable. The vortex-induced characteristic that is perceived as being most hazardous is the rolling moment that is imposed by the coherent rotary motion of the vortex. For this reason, the research program of the 1970's concentrated its efforts on this problem.

In the early flight test programs, the criterion used for controllability was the roll control ratio, the ratio of roll acceleration due to the vortex-induced rolling moment to the roll acceleration possible with maximum roll-control deflection. When the roll control ratio is equal to one, the encountering aircraft is able to just hold its own against the vortex-induced rolling moment if the controls are applied and changed instantaneously as needed. How much under one the ratio should be to allow for the reaction time of the pilot and flight path corrections is not obvious. Because the trajectory of the aircraft is not usually aligned with the vortex axis for large distances, and because the aircraft is often thrown out of the wake vortex by the vortex flow field, the forces and moments are usually temporary or intermittent, thereby causing scatter in the flight test data. Control inputs by the pilot also add scatter to the data as those inputs may alleviate or augment the vortex-induced motions of the aircraft.

Flight test results for various combinations of aircraft sizes were used along with other available information to determine initial separation guidelines at airports. At the time of the initial tests, it was felt that it was adequate to simply have the vortex-induced rolling moment less than the roll control available on any size following aircraft. It was recognized, however, that although the roll excursions experienced at altitude are perceived to be non-hazardous, they would probably be unacceptable near the ground during landing or takeoff.

Simulation Studies

In order to obtain a better estimate of the magnitude of vortex-induced motions that would be acceptable near the ground, a series of piloted simulation tests were conducted.(24-27) These simulations provided data on the wake-vortex hazard perceived by pilots with repeatable encounter conditions. The tests included not only the vortex encounters but also atmospheric turbulence and the usual piloting duties associated with the airport environment. The pilots were given no indication as to whether a vortex was present in the flight corridor or how or when it would be encountered. The piloting task was to fly a 3-degree glide slope toward a landing with an abort capability if desired. The pilots that had flight experience with wake-vortex encounters before experiencing those on the simulator reported that qualitatively the simulations seemed realistic.

After a number of simulated encounters had been flown under both visual and instrument meteorological conditions, the separation of occurrences into hazardous and non-hazardous categories was found to correlate best with maximum roll or bank angle. It was concluded from the simulations that, under IFR conditions, a maximum roll angle of more than 7 degrees is perceived as hazardous at altitudes of 200 feet or less. The primary reason given by the pilots for rating an encounter as hazardous was proximity of the ground and subsequent altitude loss caused by the encounter. A similarly well-defined boundary between hazardous and non-hazardous conditions was not found for either roll rate or roll acceleration.

The finding that a vortex encounter is considered non-hazardous if the maximum roll excursion is less than a certain value prompted studies of the feasibility and effectiveness of an automatic control system for minimum roll angle. It was observed that since the simulator experiments were designed to make the vortex encounter unexpected, the pilot response during a typical encounter first consisted of a time delay of about 0.4 sec. It was then reasoned that a considerable reduction in roll excursion could be achieved if an automatic system were used to command immediate action. Numerical analysis showed that when the full amount of roll control is used with an automatic system and when the roll control ratio is less than one, the angle of roll can be kept within acceptable limits.(28)

The simulator research provided guidance on what a pilot would view as a hazardous encounter. There is no similar consensus on the level of vortex strength which would result in a safe encounter. Therefore, the current spacing standards were intended to be conservative. With the current emphasis on increasing capacity, it is appropriate to ask how conservative the spacing standards really are, and if any can be safely reduced. This is especially pertinent since, in VFR operations, pilots routinely reduce spacing to levels below the IMC standards.

Current Research Activities

The wake-vortex research currently being conducted at NASA is part of an integrated NASA/FAA Wake Vortex Systems Research Program. This program is one element of the larger Terminal Area Productivity (TAP) Program within NASA. As previously noted, the goal of the TAP program is to achieve clear weather airport capacities in instrument weather conditions. The primary objective of the NASA/FAA Wake Vortex Program is to improve airport capacity by safely reducing wake vortex imposed separation standards. The FAA is responsible for developing system requirements and coordinating with other advanced air traffic management efforts. NASA is responsible for vortex hazard characterization, development of vortex detection technology, and system concept development. The objective of the hazard characterization research is to relate the hazard posed by a potential vortex encounter to sensor observable quantities. This requires modeling of the vortex generation, transport, decay, and the vortex encounter dynamics. Static and free-flight wind-tunnel model tests and flight tests using a specially instrumented OV-10A airplane will provide data for improved understanding of vortex encounter dynamics and simulation. The objective of the vortex detection research is to develop the sensor technology which will allow for the detection, tracking, and quantifying of the wake vortices. The system concept research will be focused on the development and demonstration of a specific concept designated as the Aircraft Vortex Spacing System (AVOSS), shown in Figure 1. The AVOSS concept will provide predictive and adaptive wake vortex separation requirements to an advanced automated air traffic control environment.

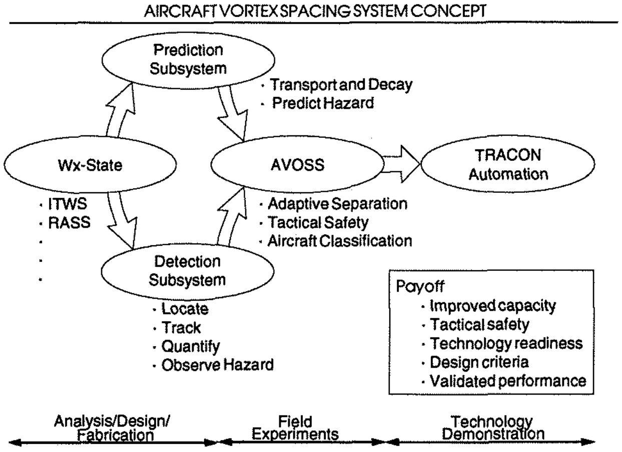

Figure 1. - Aircraft vortex spacing system concept.

Vortex Modeling and Sensitivity Studies

Wake vortex motion and strength forecasting will evolve from the vortex modeling studies currently being conducted. Ultimately, this capability can be used both as a forecasting capability for AVOSS and as a tool for determining the impact of supersonic and very large commercial aircraft on spacing guidelines.

Current wake spacing is based only on the maximum takeoff gross weight of the leading and following aircraft. The actual wake hazard depends on a number of factors such as the operating weights and spans of the aircraft, meteorological conditions, and altitude. There have been significant changes in the commercial aircraft fleet since the current U.S. spacing was set in the 1970's. This has occurred due to:

1) evolutionary growth in weight of existing aircraft types,
2) retirement of some older aircraft types, and
3) introduction into service of newer, more efficient aircraft types.

A logical question is whether or not the current spacing adequately reflects the dual requirements of safety and airport capacity.

As a first step in making a preliminary assessment of this question, the initial wake strength (Γ) of a representative sample of the current fleet was calculated from

$$\Gamma = \frac{W}{\rho U \frac{\pi}{4} b}$$

where ρ is the standard atmospheric density, U is assumed to be 135 knots (landing approach speed), and the $(\pi/4)b$ term represents the vortex spacing for an elliptical wing loading. Figure 2 shows the calculations performed at two weights, maximum landing and empty, for each aircraft to represent the extremes in vortex strength which

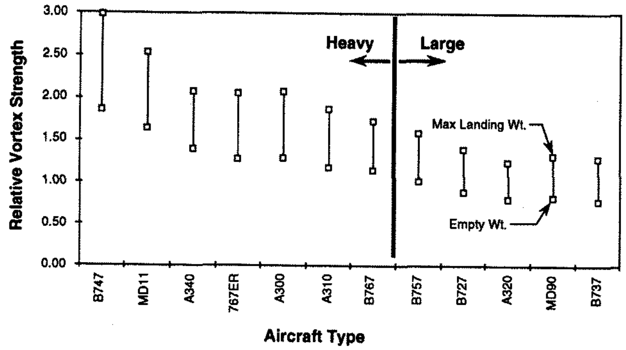

Figure 2. - Calculated initial wake strengths for landing approach.

might occur during landing. The calculated strengths have been normalized since we do not know at this time what vortex strength represents a hazard. The boundary between the "Heavy" and "Large" categories is indicated. As can be seen, there is an almost continuous distribution of initial vortex strength due to the possible range of operating weights for a given aircraft and the wide range of sizes in the current fleet. For a "Large" follower, the current standards increase the spacing by 2 nautical miles when the lead aircraft is a "Heavy". Based on this chart, it is difficult to quantify a rationale for determining where the boundary between "Heavy" and "Large" should be.

As a first step toward understanding the potential impact of meteorological conditions on the wake hazard, wake decay characteristics out of ground effect are being assessed for typical transports using an existing decay model.(29) This model includes the effects of density stratification (or nonadiabatic lapse rate) and atmospheric turbulence, but does not include any effects of the ground or winds. Figure 3 shows how these effects are predicted to influence the wake decay of a Heavy aircraft. The solid curves show the effect of density stratification in the absence of atmospheric turbulence and the dashed curves show the effect of increasing levels of turbulence with a standard-atmosphere lapse rate. Both effects can be very strong; however, near the ground it is expected that turbulence effects will be more important.

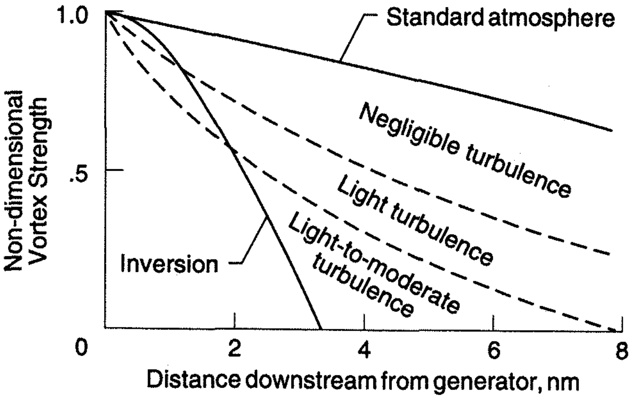

Figure 3. - Predicted wake decay for a Heavy aircraft for different atmospheric conditions.

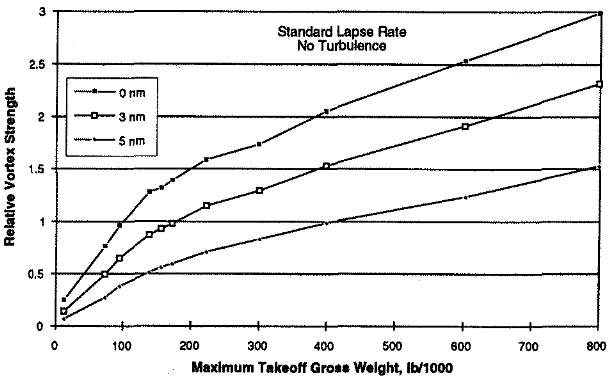

Figure 4. - Calculated wake decay in a calm atmosphere.

Current and proposed transport aircraft are being studied for a range of atmospheric conditions representing both "worst case" and typical VFR and IFR weather conditions. Typical calculations are shown in figures 4 and 5 for a calm atmosphere and a low level of atmospheric turbulence (1.5 ft/sec rms). Relative wake strength is shown as a function of aircraft weight at 0, 3 and 5 nm behind the aircraft. For the low level of turbulence, figure 5 , it can be seen that vortices are predicted to decay significantly (to about one fourth of the initial strength for a 200,000 lb aircraft) in 3 nm. A similar calculation without any turbulence, figure 4, predicts that a 200,000 lb aircraft wake would still have three fourths of its initial strength at 3 nm. Figure 6 shows the effect of increasing the turbulence level to a "typical" value (3 ft/sec rms) found in the atmosphere. Wakes are predicted to decay extremely rapidly for these conditions which is consistent with the observed safety of the reduced spacing used routinely in VFR conditions. Turbulence, therefore, appears to be a key parameter in wake decay.

To incorporate vortex decay in ground effect, numerical simulations of the behavior of a wake vortex pair near the ground are being developed.(30-32) Using the full Navier-

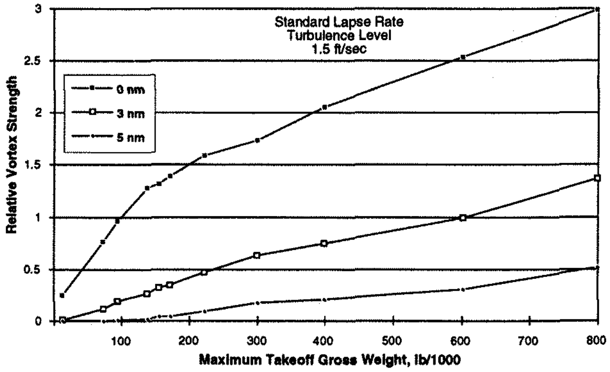

Figure 5. - Calculated wake decay in light turbulence.

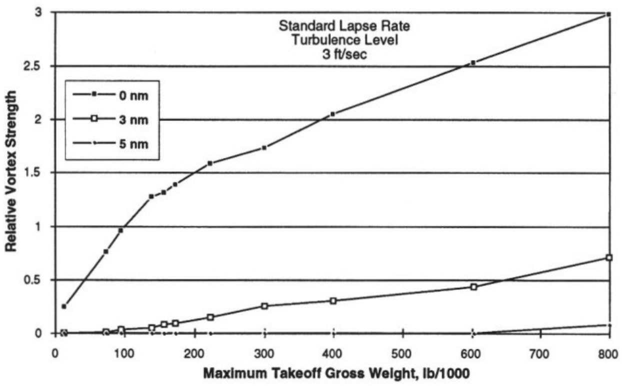

Figure 6. - Calculated wake decay with "typical" turbulence.

Stokes equations in two dimensions and a Reynolds stress transport model, vortex strengths and trajectories are being predicted for various circulation Reynolds numbers. The influences of stratification and cross wind are being studied, along with extending the upper limit on circulation Reynolds number. Simulation of the wake vortex system is started after the near-wake flow has consolidated into its characteristic trailing-axial-vortex pair. This approach enables both laminar and turbulent predictions of the two-dimensional approximation for the vortex system and can include stratification and cross wind effects. A parametric study of the swirl Reynolds number, the cross wind velocity profile (varying the magnitude of the mean cross wind and the thickness of the atmospheric boundary layer), and the stratification level (lapse rate) will establish ranges over which each parameter influences the vortex-ground encounter and will determine the upper limits on parameter levels which can be simulated using existing computer resources.

The upper Reynolds number limits allowed by the two-dimensional, unsteady simulations will be increased by refining the grid. A moving grid which adapts to the local flow field will be implemented to properly model the influence of crossflow over a wider parametric range. Attempts will be made to model vortex jets and wakes (in the third coordinate direction) to determine the influence of three-dimensional effects on the flow. A separate three-dimensional code is also being developed using a modified version of the Terminal Area Simulation System (TASS) model which was used extensively to simulate microbursts for the NASA/FAA wind shear program.

After validating wake-vortex models at Reynolds numbers which are more consistent with typical aircraft wake vortex systems, effort will be devoted to simplifying the models to enable implementation of a real-time forecasting capability. Efforts are being directed toward establishing realistic approximations of atmospheric conditions relating to airport operations and toward establishing the levels of atmospheric temperature and velocity fluctuations above which vortex effects can be considered to be minor disturbances.

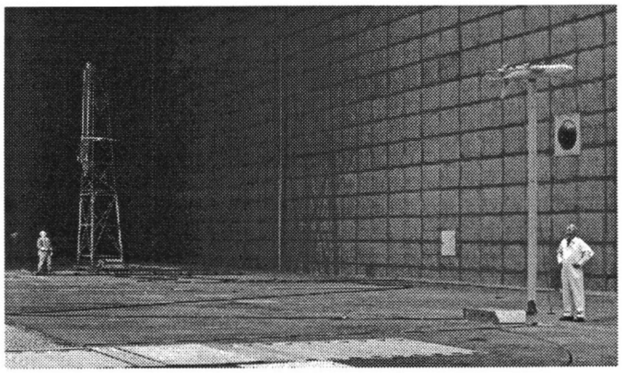

Figure 7 - Photograph of experimental setup in 80x120 Foot Wind Tunnel.

Wind tunnel tests

Two different wind tunnel test techniques are being used to study the upset due to a wake-vortex encounter. In the 80x120-Foot Wind Tunnel at the NASA Ames Research Center the wake characteristics of a B-747 and DC-10 model are being measured and the accuracy of vortex-lattice methods to compute the loads induced on a following aircraft are being studied.(33-35) The data obtained during the test include the lift and rolling moment induced on a wing mounted on a survey carriage located 81 feet downsream of the generating wing. This corresponds to a full-scale distance of one-half mile. A photograph of the test setup is shown in figure 7. The velocity distribution in the flow field of the vortex wake is measured with a hot-film anemometer probe.

The use of the free-flight model technique for experimentally studying wake-vortex encounters is being explored in the 30x60-Foot Wind Tunnel at the Langley Research Center, as shown in figure 8. Vortices are generated by a 12 ft span wing mounted at the upstream

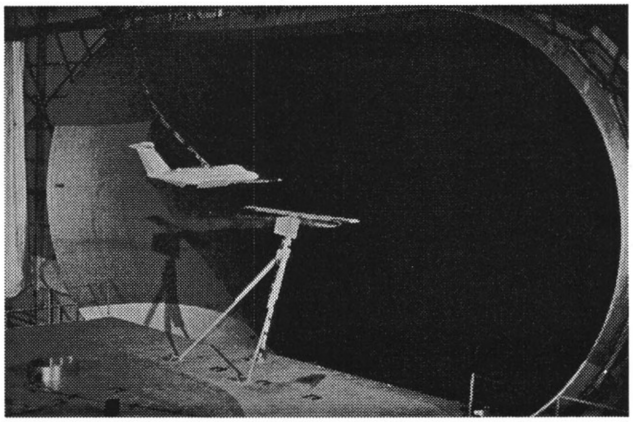

Figure 8. - Free-flight model vortex encounter test.

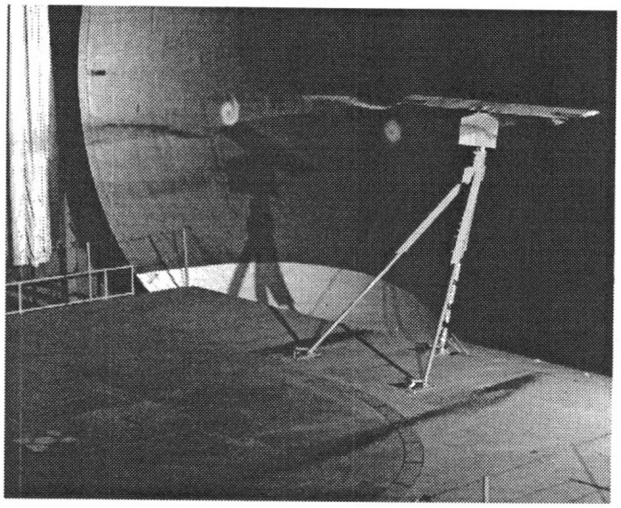

Figure 9. - Vortex-generator wing in the Langley 30x60-Foot Wind Tunnel.

end of the test section. Smoke is injected into the flow to make the trailing vortices visible (figure 9). A generic business-class airplane model propelled by high-pressure air and piloted via signals passed through an umbilical to movable control surfaces is flown into the wake of the upstream wing. This technique is not intended to scale realistic separation distances; rather, the vortex strength is controlled by varying the angle of attack of the generating wing. Vortex strength can be calculated from the lift generated by the wing; these calculations will be verified via flowfield surveys. The response of the airplane during the vortex encounters has been recorded and is currently being analyzed. These data plus additional flowfield data and static model force and moment measurements will be used to compare with the experimental and simulated encounter trajectories and evaluate the utility of scaled upset measurements.

The static forces and moments induced by the vortex will be measured with the model sting-mounted on the small model support system in the tunnel. The vortex generator wing will be mounted on the tunnel survey carriage. Force and moment data will be obained on the model for a wide variation of vortex generator wing positions in front of the model to represent many possible vortex encounter geometries. These tests also provide an opportunity to study the interaction of the vortex and the model, i.e. both the effects of the vortex on the model and the model on the vortex will be observed. The results will be compared to theoretical predictions.

OV-10 flight tests

Currently, an OV-10A is being instrumented by the Langley Research Center as a wake-vortex research airplane. The OV-10A, shown in figure 10, is a twin-engine, two-place, high wing, propeller-driven airplane with a gross weight range of 9,900 to 14,000 lb It has a 40 ft span rectangular wing with an area of 291 sq ft. Operating speeds range from 60 to 230 knots. It was selected for the vortex-encounter mission because it has a rugged airframe and sufficient internal volume and payload carrying capability for the extensive instrumentation required and for a flight-test engineer to operate the experimental systems. The OV-10A will be used to gather in-flight data on vortex-decay, atmospheric parameters, and vortex-encounter dynamics. It will be flown into and in the vicinity of the wake of a C-130 airplane operated by NASA's Wallops Flight Facility.

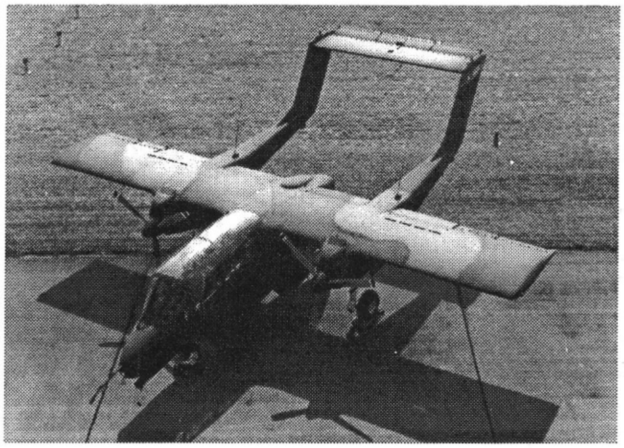

Figure 10. - OV-10A wake vortex research airplane.

The C-130, a four-engine, high-wing, propeller-driven transport, will be equipped with smoke generators to mark the vortices in its wake. It will be operated at a weight of about 130,000 lb and a speed of about 160 knots at an altitude of 5000 ft for the vortex encounter tests. Measurements will include mass and geometric properties of each airplane, atmospheric parameters, relative position of each airplane, relative position of the OV-10A with respect to the vortex pair, accelerations, angular rates, attitudes, and flow angles in the vicinity of the OV-10A. Stereo video cameras will be used to record descent of wake vortices (marked with smoke) and vortex strength will be inferred from the rate of descent. Flow sensors will measure local flow angles and atmospheric turbulence. Lapse rate and relative humidity of the air will also be recorded. The airplane will fly through the vortices and measure strength (velocities) directly to compare with strengths inferred from descent rates. Vortex-strength data will be used to validate vortex-decay prediction models. Vortex-encounter data will be used to validate wake encounter models.

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. Static and free-flight wind-tunnel model tests and flight tests using a specially instrumented OV-10A airplane will provide data for improved understanding of vortex encounter dynamics and simulation. Methods will be developed and validated for the prediction of vortex decay near the ground with variable atmospheric conditions and winds. Ground-based field measurements will be used to validate and refine the vortex propagation and decay models. An Aircraft Vortex Spacing System concept will be developed which integrates the predictive and detection technologies to provide adaptive wake vortex separation requirements for an advanced automated air traffic control environment.

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