WAKE VORTEX TECHNOLOGY

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INTRODUCTION

Aircraft trailing vortices are one of the principal factors affecting aircraft arrival and departure rates at airports. Minimization of the trailed vortex strength would allow reduction of the present spacing requirements. Such reductions would allow full utilization of advances in automatically aided landing systems as described in reference 1, while maintaining or improving safety within the terminal area. For several years, NASA has been conducting an intensive in-house and contractual research effort involving theoretical and experimental studies of various wake vortex minimization techniques, the results of which were reported in reference 2. NASA's work was done in conjunction with the Federal Aviation Administration investigation of various sensing devices for detecting the presence of vortices within the terminal area. The FAA's investigation is aimed at developing, for installation at major airports, a vortex avoidance system that would increase runway capacity by varying the separation distances to conform to the conditions present. A complete ground-based detecting system would involve the detection and prediction of the presence and strength of the vortices present at a given time. Both the NASA effort for vortex reduction and the FAA effort for detection aid the overall national air transportation goal to alleviate aircraft trailing vortices as an operational constraint. The purpose of this paper is to review the NASA effort.

EXPERIMENTAL METHODS

Shown in figure 1 are the experimental facilities that have been used to evaluate the various vortex minimization concepts. Pictured are the four primary model test facilities that have been used along with flight tests. For all tests, the basic operational problem of one airplane flying in trail behind another and encountering the vortex wake is recreated. The primary model test facilites employ the experimental method illustrated in figure 2. The vortex upset potential on the trailing aircraft is determined by measuring the vortex-induced rolling moment on a trailing airplane. For the vortex minimization tests, the vortex generator aircraft has generally been representative of a wide-body jet while the vortex penetrator has been either a small jet transport (DC-9) or a business jet size airplane (Learjet or T-37). The vortex minimization concepts are implemented on the transport airplane while measurements are made to assess the performance degradation attributable to the vortex minimization scheme. Measurement of the vortex induced rolling moment on the trailing airplane provides a direct measurement of the effectiveness of the vortex minimization concept.

The wind tunnels used for the model tests are the 40- by 80-foot tunnel at Ames Research Center and the V/STOL tunnel at Langley Research Center. In addition to these two wind tunnels, two model towing facilities were used. In these facilities, both the vortex generator model and the trailing rolling moment model are towed through a quiescent fluid medium. In one of these facilities (vortex flow facility) located at Langley Research Center, the models are towed through the air, and in the other facility, the models are towed in a water basin. Tests in the water towing basin were conducted under contract to Hydronautics, Inc. The model facilities provide for downstream measurements of the vortex wake from very near field to as much as 2 scale miles behind the vortex generator aircraft. Additional details concerning these facilities can be found in reference 3.

EXPERIMENTAL RESULTS

Wake vortex minimization experiments have shown that significant reduction in the vortex-induced rolling moment on a trailing airplane can be achieved primarily by increasing the normal dissipation rate by using turbulence to rapidly diffuse the vorticity. The experiments have indicated several methods of increasing turbulent diffusion either directly by turbulence injection or indirectly through vortex interaction. The following sections briefly describe these methods.

Turbulence Injection

Shown in figure 3 is a device which was flight tested on a C-54 airplane to investigate the effect of turbulence injection on the vortex wake. The device, as illustrated, consisted of considerable flat-plate area normal to the free stream to produce turbulence near the wingtip. The device did not alter the wing lift characteristics but added an increment of drag. The device increased the basic airplane drag coefficient by about 0.05. The flight-test results of the device are reported in reference 4 and shown in figure 4. The flight test consisted of flying a PA-28 Cherokee airplane in the C-54 airplane vortex wake at various separation distances with and without the turbulence device on the C-54. As shown in figure 4, without the turbulence device on the C-54 airplane, the PA-28 airplane could penetrate no closer than 8 km before the roll-control capability of the PA-28 airplane was exceeded. However, the turbulence injection device caused a visible alteration of the vortex pattern which was marked with smoke (reference 4) and significantly reduced the vortex-induced rolling moment. As shown in figure 4, the vortex-induced roll was always lower than the roll-control capability of the PA-28 airplane. These flight tests were the first quantitative indication that wake vortex effects could be significantly reduced. It is recognized that the implementation of such a concept has considerable operational penalties; however, the turbulence produced by equipment on airplanes, such as landing gear, engines, and engine pods, can be used to provide reduction in trailed vortex strength. Details concerning the development and tests of the turbulence device are given in references 4 to 6.

Vortex Interaction

Vortex interaction and control is a term used to describe the turbulence and shear stress produced during coalescence of several vortices into a single vortex. Some of the work described in reference 7 has shown that two vortices of the same sense considerably strain and distort each other during the merging process. The production of turbulence during the merging process is discussed in more detail in the analytical studies in references 8 and 9. The vortex wake behind a large jet transport is dominated by several vortices coming from the wingtip, flap end, wing-body junction, and other places where large changes in spanwise load distribution occur. Downstream, the vortices from one-half the airplane coalesce into a single vortex leaving behind the classical vortex pattern of a pair of aircraft trailing vortices. Numerous methods have been attempted to control the early wake development, two of which are described in this section.

The simple inviscid analytical techniques discussed in reference 10 indicated that the vortex wake development of a wide-body transport aircraft could be considerably altered by introducing an additional vortex pair into the wake. Model tests of such a method were conducted and described in reference 11. To produce an additional vortex pair in the wake of a wide-body jet model, fins were placed on the upper surface of the wing as shown in figure 5. The fins were canted with respect to the local free-stream so as to produce a vortex of the same sense as the wingtip vortex. The spanwise postion of the fin on a 747 model airplane was varied during tests in the 40- by 80-foot wind tunnel. The effect of the fin vortex on the model wake was measured 15 spans behind the 747 model using a Learjet size wing for rolling-moment measurement. The results of these tests are shown in figure 6. For these tests, the ratio of the fin height to wing span of the 747 model was about 0.08 and the fin cord was about 0.04 of the span. As indicated in figure 6, the vortex-induced rolling moment was reduced by about a factor of 4 with the fin at about the 50-percent-semispan position. The effect of fin spanwise location on the vortex-induced rolling moment is significant. The work on the fin concept is relatively new and, at this time, little has been done to address the operational problems that may be incurred with the implementation of this method.

Another method of controlling vortex interaction is to vary the spanwise position of the flap vortex and relative strengths of the flap and wingtip vortices. This is done by altering the spanwise load distribution. Analytical studies of such a method are discussed in reference 8. The results of reference 8 indicated that, if the wingtip and flap vortices were of nearly equal strength and the flap vortex was located at about the 40-percent-semispan position, the effect of vortex interaction was maximized. Numerous model tests and flight tests were conducted employing span load alteration for vortex interaction. A 747 airplane was used in which only the inboard flap section was deployed for the landing approach. Details concerning the model tests of this method are described in reference 7. Flight-test results of this configuration are indicated in figure 7 and 8.

In figure 7, the vortex pattern behind a 747 airplane in the normal landing approach flap configuration is made visible by smoke devices mounted under the wing. The wake is seen to develop quickly into a pair of trailing vortices. Flights with the 747 were conducted at a lift coefficient of 1.2. Vortex penetrations were conducted with Learjet and T-37 airplanes. During these tests, roll upsets greater than the control capability of the Learjet and T-37 airplanes were experienced at distances of from 6 to 8 n. mi. behind the 747 airplane (reference 12).

Figure 8 illustrates the vortex pattern behind the 747 airplane at a lift coefficient of 1.2 with only the inboard flap segment deployed. This configuration is seen to inhibit the merging of the wingtip and flap vortex into single vortex. The enhanced vortex interaction produces a significantly diffuse vortex wake. Model tests (reference 7) indicated that this configuration would reduce the vortex-induced rolling moment about 50 percent. Flight tests indicated that the T-37 airplane could approach as close as 3 n. mi. behind the 747 airplane before experiencing large roll upsets. This wake vortex minimization method has considerable performance penalties which prohibit its operational use; however, the method does illustrate the importance of vortex interaction for future aircraft design consideration.

Flight Spoilers

A concept was developed which employs both the principle of turbulence injection and vortex interaction through span load alteration. The method consists of deploying selected flight spoilers on the airplane. Considerable details concerning the development and implementation of this concept are described in references 13 to 17. Evaluation of the flight spoilers have been conducted on DC-10, L-1011, and 747 airplane models. Flight tests have also been conducted using the spoiler concept on 747 and L-1011 airplanes. Flight tests and model tests with the 747 airplane have shown that the use of the two outboard spoiler sections can reduce the vortex-induced rolling moment on a Learjet size airplane by about 50 percent.

Photographs of flight tests using the spoiler concept on a L-1011 airplane are shown in figures 9 and 10. The vortex pattern for the normal landing approach configuration of the L-1011 is shown in figure 9. Tests indicated that for a T-37 airplane, roll upsets exceeding the roll control power of the T-37 were experienced at about 6 n. mi. The use of the three outboard spoiler sections on the L-1011 airplane for vortex minimization and their effect on the vortex pattern is seen in figure 10. Comparison of smoke-marked vortex wake with and without the spoilers deployed (figs. 9 and 10) indicates that the vortex wake is quickly diffused. The spoiler both sheds turbulence into the wake and alters the span load distribution. The relative importance of turbulence and span load alteration on the spoilers ability to diffuse the vortex is unknown. Tests showed that a T-37 airplane could approach as close as 2 n. mi. without an uncontrollable upset.

Details concerning the performance decrement caused by the use of the spoilers are covered in references 13 to 17. The spoilers do appear to offer several advantages for vortex minimization use on existing airplanes, since they are effective and available for use. Certain operational problems, such as possible buffet and associated structural problems, approach speed increases, and climb requirements, are still unanswered. By comparison with the other methods discussed for vortex minimization, the spoilers offer the greatest chance for operational use on existing aircraft. The other vortex minimization techniques described can only be implemented in future aircraft design.

ANALYTICAL STUDIES

Under an NASA contract, a computer code was developed to solve the vortex equations of fluid motion including convection and turbulent diffusion. The objective of the theoretical work is to describe in detail the vortex wake for a given aircraft configuration. The computer code is capable of calculating the wake history including the effect of atmospheric conditions such as winds, wind shear, atmospheric turbulence, atmospheric stability, and the influence of the ground plane. The computer code is a two-dimensional, time marching, finite difference approximation to the Reynold's stress equation. Details concerning the computer code are reported in references 8 and 9. All of the vortex minimization methods described in the previous experimental sections have been investigated using the computer code. The analytical results generally agree with the experimental results.

Shown in figure 11 are the calculated results of a pair of vortices descending into a wind shear. These results of the computer code are taken from reference 18. Shown in the figure are vorticity contours in the cross-flow plane at increasing nondimensional time increments. Over the time steps shown, the left vortex is seen to decrease in maximum vorticity from five nondimensional units to two units. The right vortex is seen to completely vanish because of its interaction with the opposite sensed vorticity in the wind shear.

A flight-test result of one vortex vanishing while the other vortex remains for a considerable time was reported in reference 19. For these tests a small single-engine airplane was flown over El Mirage dry lake bed under various atmospheric stability and turbulence conditions while the vortices were made visible by smoke and photographed. Although the exact wind conditions for which one vortex was seen to disappear and the other remain were not documented, it does appear that some wind shear was present. The calculations shown in figure 11 serve to illustrate the capability of computer code while offering an explanation of the solitary vortex observed during the tests of reference 19.

FUTURE EFFORT

Although the basic methods of vortex minimization have been identified, considerable effort is required to provide a comprehensive technology base for understanding the intricate interrelationship of direct turbulence effects and indirect turbulence effects through vortex interaction. To aid in achieving this understanding, extensive model tests are being conducted using the model shown in figure 12. This model has an aspect ratio of 7, an NACA 0012 airfoil, and a rectangular planform of 248.9 cm span, with 72 movable airfoil sections. The local angle of attack of each section can be independently set, thus allowing a wide range in span load variation. Detailed near-field and far-field flow measurements along with the measured wing load pressure distribution will be obtained to aid in validation of the analytical techniques presently developed. Work on the analytical techniques is continuing for improvement in the existing computer code. Flight tests and model tests are being continued to provide a better assessment of the operational feasibility of implementing wake vortex minimization concepts on existing aircraft.

CONCLUDING REMARKS

This paper has provided a brief overview of the highlights of NASA's wake vortex minimization program. The significant results of this program can be summarized as follows:

1. Tests have shown that it is technically feasible to reduce significantly the rolling upset created on a trailing aircraft. Prior to NASA's effort, there was considerable doubt as to the possibility of achieving a measurable reduction in the trailing vortex strength.

2. The basic principles or methods by which reduction in the trailing vortex strength can be achieved have been identified. At least one of these methods may have application to existing airplanes while all of the principles are suitable for implementation in future aircraft wing designs.

3. An analytical capability for investigating aircraft vortex wakes has been developed. The analytical techniques have been shown to agree generally with previous experimental test results. The analytical techniques will be useful in future aircraft designs.

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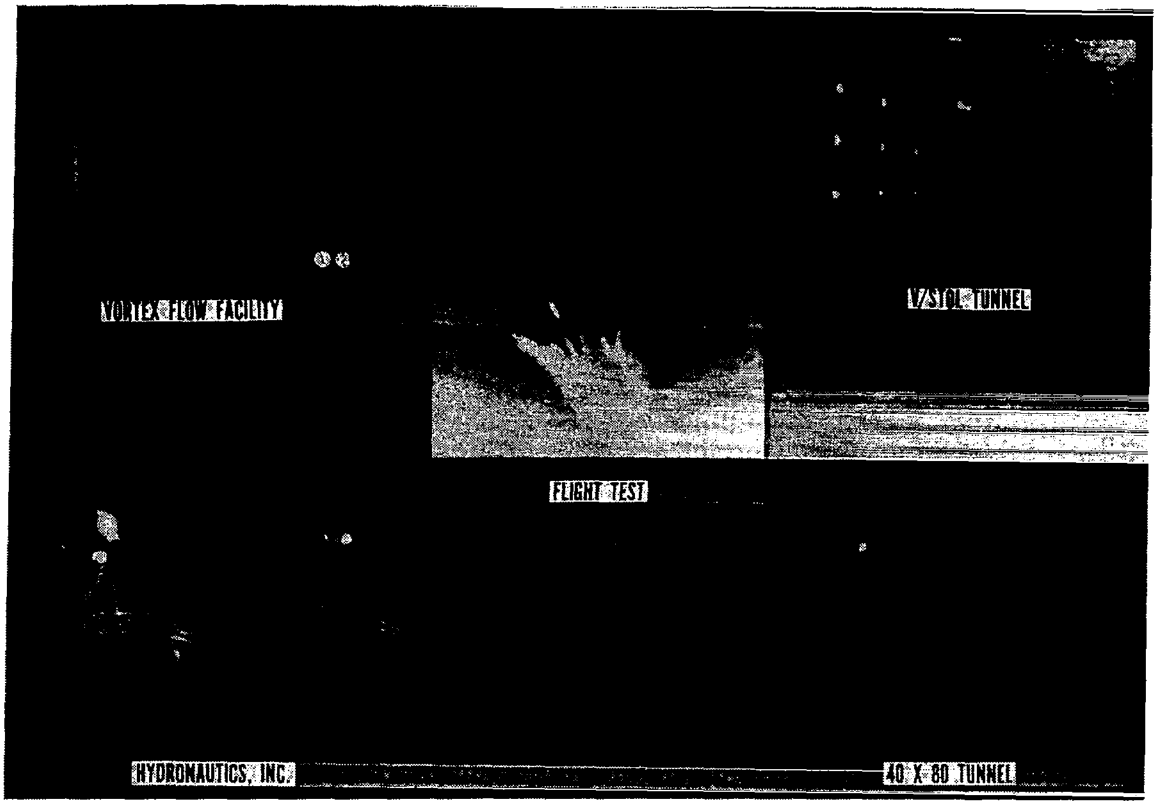

Figure 1.- Experimental facilities.

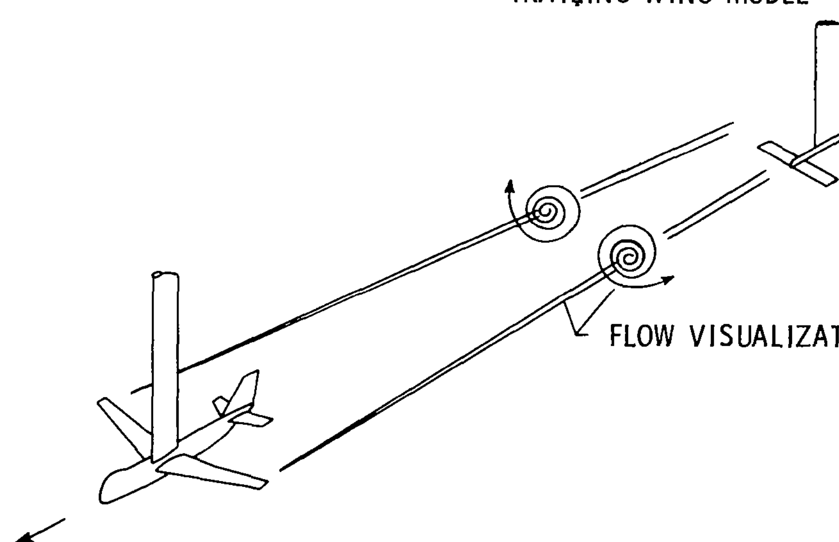

Figure 2.- Experimental test technique.

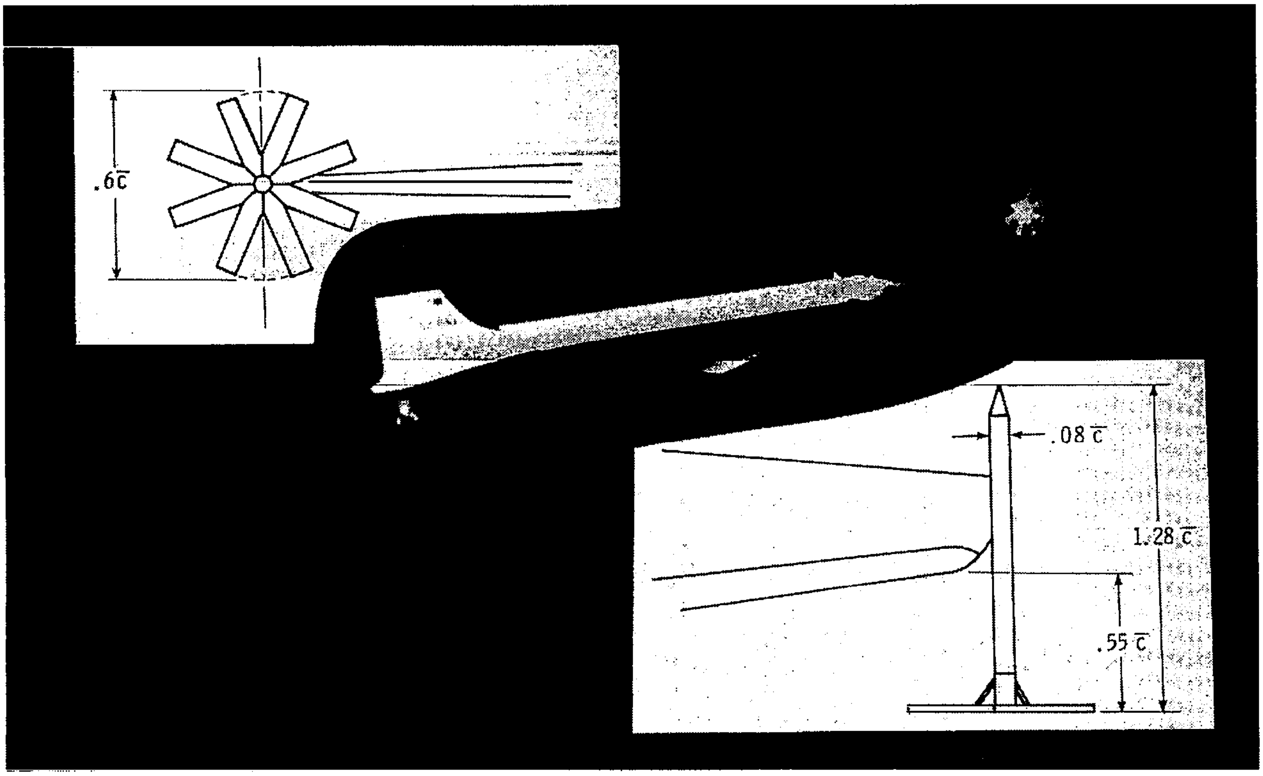

Figure 3.- Turbulence device installed on C-54 airplane for flight tests. ($\bar{c}$ is wing mean aerodynamic chord.)

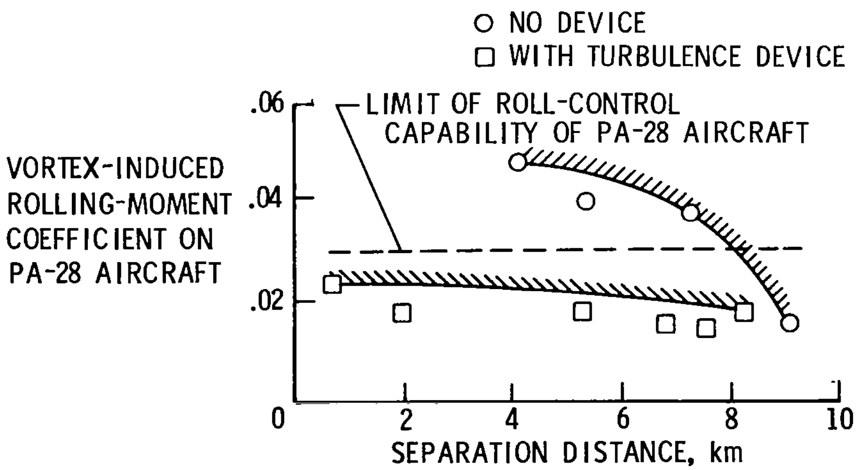

Figure 4.- Flight-test results of the turbulence device.

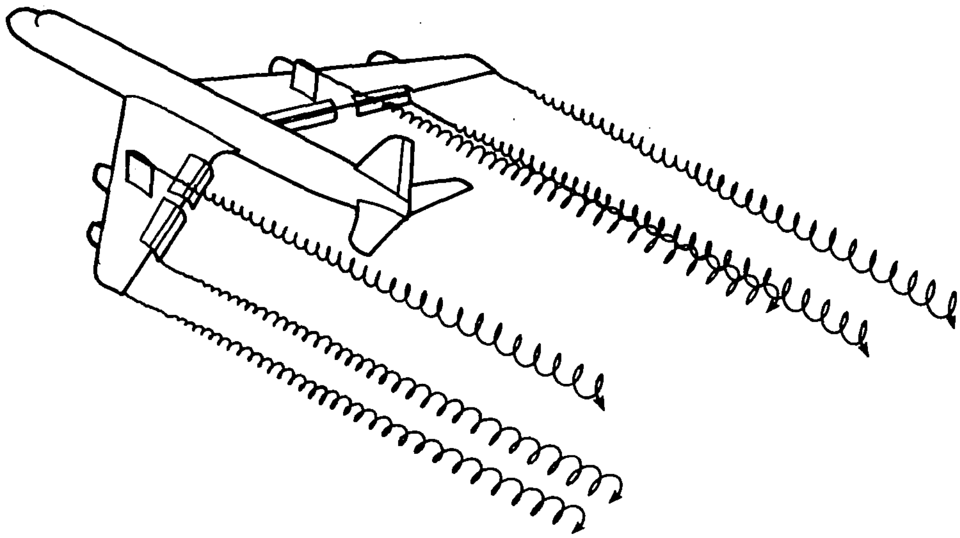

Figure 5.- Wing fins for vortex attenuation.

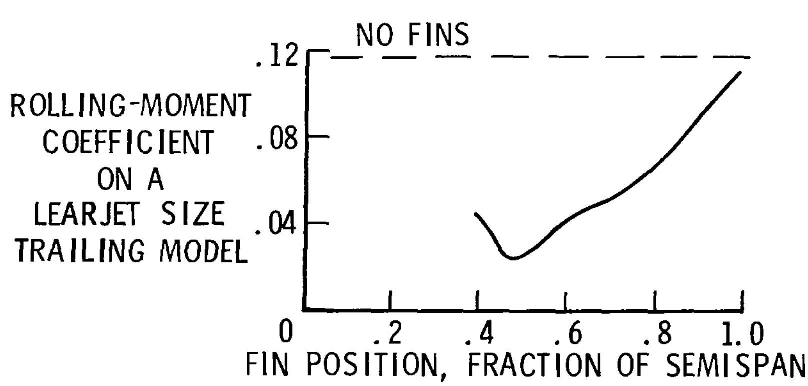

Figure 6.- Model-test results of wing fin.

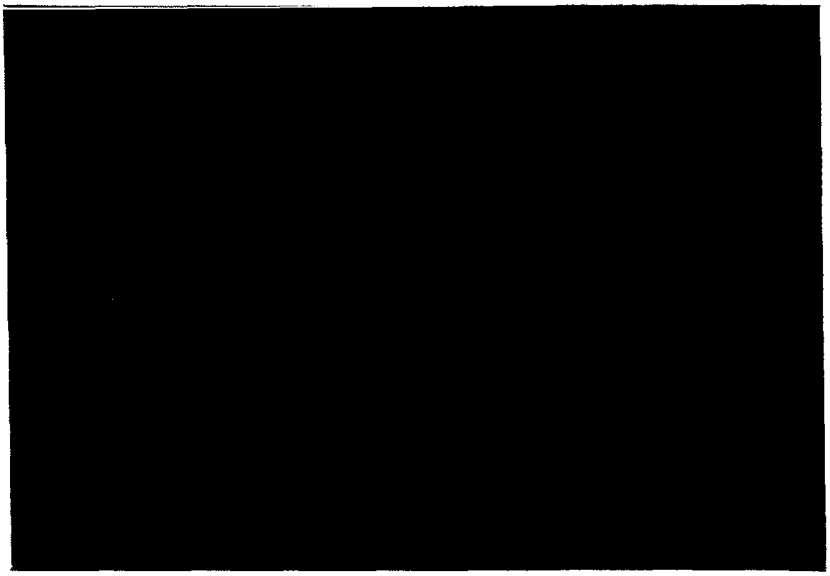

Figure 7.- 747 airplane with all flaps extended.

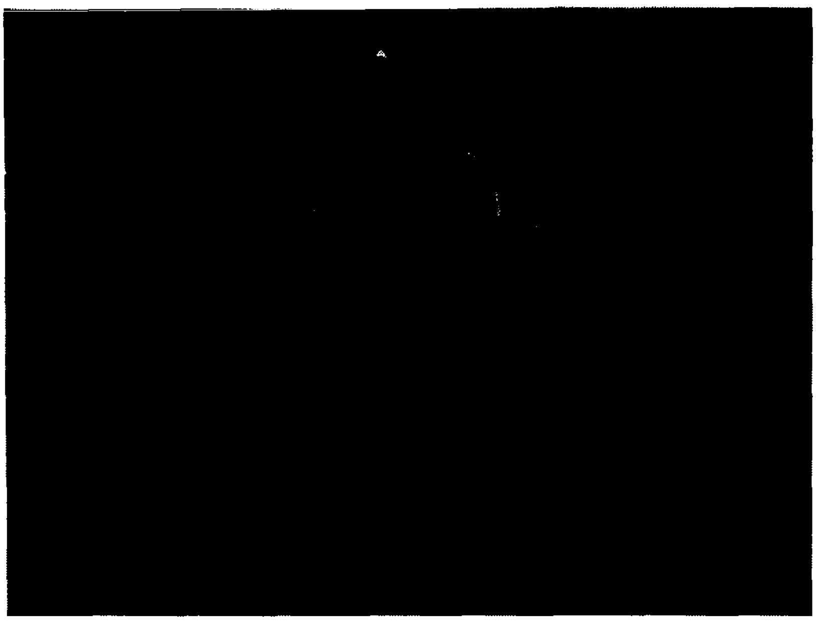

Figure 8.- 747 airplane with only inboard flap extended.

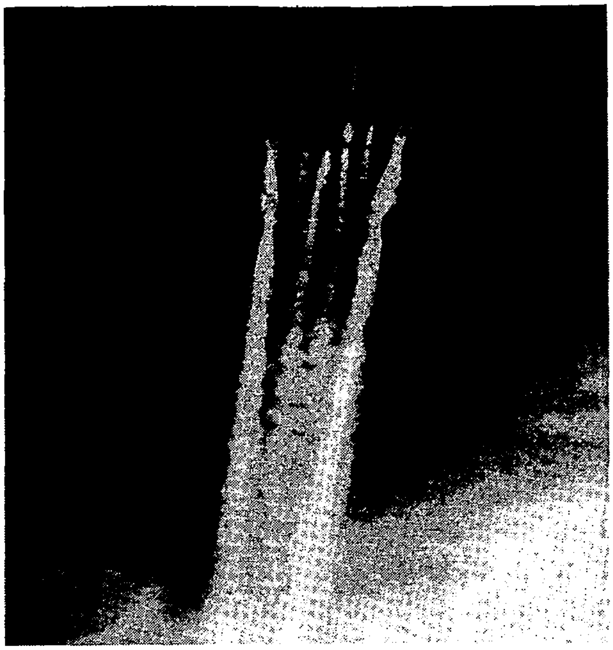

Figure 9.- L-1011 in normal landing approach configuration.

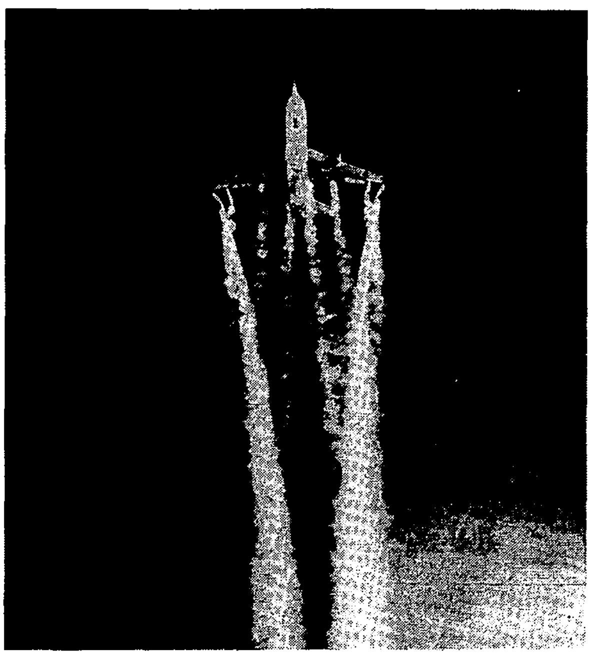

Figure 10.- L-1011 with spoilers deployed for vortex minimization.

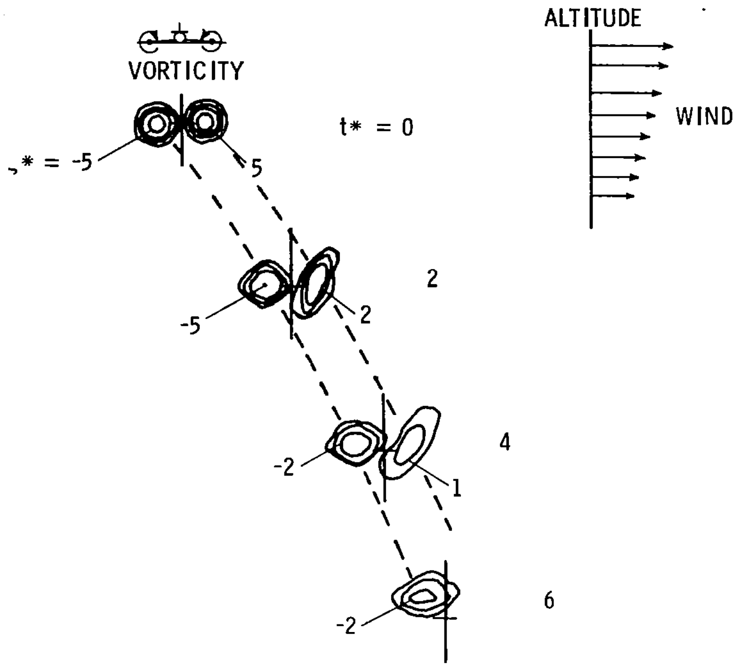

Figure 11.- Analytical results of pair of vortices descending into a wind shear. (t* is nondimensional time; ζ* is nondimensional vorticity.)

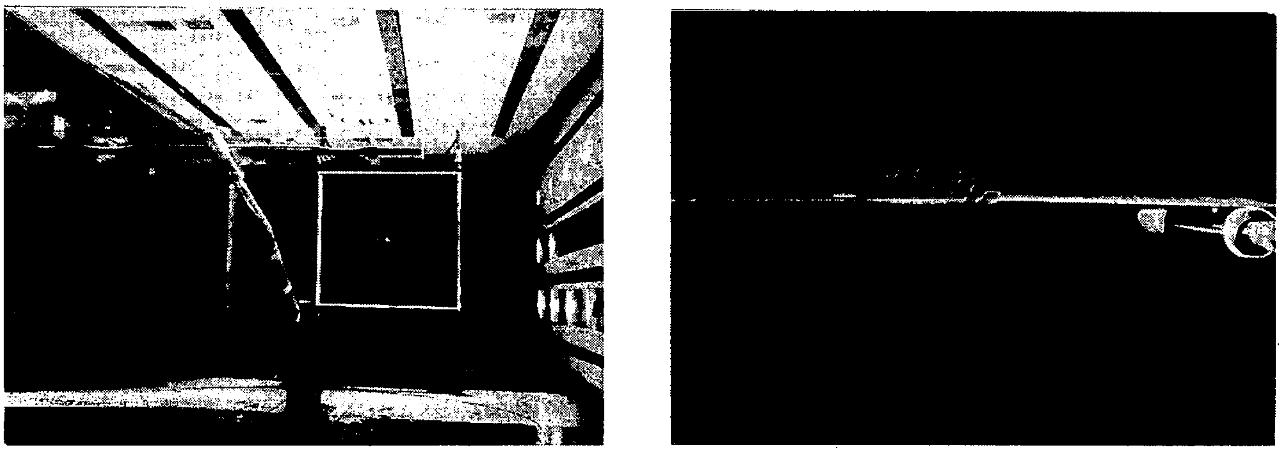

Figure 12.- Model used for variable span load investigation.