N77-18097

SUMMARY OF NASA WAKE-VORTEX MINIMIZATION RESEARCH

R. Earl Dunham, Jr.
NASA Langley Research Center

SUMMARY

This paper is a review of the NASA effort in the area of wake-vortex minimization and summarizes the results presented at the NASA Symposium on Wake Vortex Minimization, February 25 and 26, 1976, Washington, DC. Some additional results obtained since the symposium are also included. Theoretical and experimental techniques for assessing the effectiveness of various wake-vortex minimization techniques are described. Three methods of reducing the effect of aircraft trailing vortices and a preliminary assessment of the operational suitability of employing wake-vortex minimization techniques are discussed.

INTRODUCTION

Aircraft trailing vortices are one of the principal factors affecting aircraft acceptance and departure rates at airports. Minimization of the hazard posed by the vortex would allow reduction of the present spacing requirements. Such reductions would allow full utilization of advances in automatically aided landing systems (ref. 1) while maintaining or improving safety within the terminal area. For several years NASA has been conducting an intensive in-house and contractural research effort involving theoretical and experimental studies of various wake-vortex minimization techniques. This work was done in conjunction with the Federal Aviation Administration's investigation of various sensing devices for detecting the presence of vortices within the terminal area.

This paper is a brief review of NASA's effort in the area of wake-vortex minimization and summarizes the results presented at an NASA symposium on wake-vortex minimization (ref. 2). Additionally, some results, obtained since the symposium, of the application of one wake-vortex minimization technique to DC-10 and L-1011 aircraft are presented.

17

SYMBOLS

$b/2$	aircraft semispan, m
C_L	lift coefficient
$\bar{c}$	aircraft average wing chord, m
d	separation distance between vortices, m

t time

U_∞ free-stream velocity, m/sec

X,Y,Z orthogonal coordinate axis system with origin at wing center

Γ vortex circulation, m^2/sec

Subscripts:

1 vortex one

2 vortex two

THEORETICAL STUDIES

Inviscid Analysis

A theoretical method used to describe the rolled-up vortex system of a lifting surface is the technique of Betz (ref. 3) which was recently reassessed and described in reference 4. The theory, based on the conservation equation for inviscid two-dimensional vortices, relates the circulation in the fully rolled-up vortex to the span loading on the lifting wing. Because of the simplicity of the method, the details of the rollup process are not described; however, the technique has been shown to be useful in predicting gross vortex characteristics behind lifting surfaces (ref. 5) and often has been found to be more accurate than more complex methods.

The rollup process of the vortex sheet from a lifting surface has been determined by calculations of the two-dimensional time-dependent motion of point vortices. This type of rollup calculation for an elliptically loaded wing is illustrated in figure 1. Point vortex computerized-rollup calculations are subject to unrealistic numerical instabilities because of the singular point at a radius of zero from the point vortex. Reference 6 discusses techniques for minimizing these errors and describes a technique for monitoring the numerical stability of these calculations. As shown in figure 1, the application of the principles described in reference 6 provides an accurate point-vortex calculation description of the rollup of an elliptically loaded wing.

The Betz modeling and the two-dimensional time-dependent point-vortex calculation techniques have been used to study a variety of span-load distributions for wake-vortex minimization. Analysis has indicated that span-load alterations, in order to produce large vortex core sizes with related reductions in circumferential velocities, are limited in the achievable amount of vortex minimization. (See refs. 4 and 6.)

The two-dimensional time-dependent calculations have shown the possibility of achieving wake-vortex minimization through the production of a chaotic wake structure to enhance the dissipation of shed vorticity. In figure 2, the numerical calculations for a stepped or sawtooth span-load distribution are shown to have chaotic wake rollup. Model tests (ref. 7) of a wing having a sawtooth span loading showed that the shed vortices did undergo the large-scale excursions shown in figure 2; however, several spans downstream, when vortex linking was completed, a vortex pair still remained. The model results indicate that the interaction of multiple vortex pairs in a wake brings about large disturbances to the vortex sheet. It is necessary to include viscous effects in the theoretical calculations to understand the significance of this process.

Viscous Studies

Under an NASA contract, a computer program has been developed to solve the vortex equations of fluid motion including convection and turbulent diffusion. The computer code uses a second-order closure for the velocity correlation and an invariant turbulent model. Details of the turbulent model and the second-order closure technique may be found in references 4, 8, and 9. The computer code was used to calculate the merging of two equal-strength like-sign vortices. Figure 3 indicates the pressure-intensity field during the merging process of two equal-strength like-sign vortices where minimums in pressure are designated by the darkened regions. During the merging process, considerable turbulent kinetic energy is generated and is plotted in figure 4 for the merging of two equal-strength like-sign vortices. The process of turbulence generation during vortex merging is significant because it will aid the dissipation process of the merged vortex. The merging of the vortices illustrated in figures 3 and 4 is representative of the merging which normally takes place between the wing-tip and outboard flap vortex of an aircraft in the landing configuration. The results of the viscous vortex analysis have shown that by altering the span-load distribution of a large transport aircraft so that the wing-tip and flap vortices are of nearly equal strengths with the flap vortex at the 40-percent semispan station, the turbulence produced during the merging process is maximized. Such a configuration leads to an enhanced diffusion of the trailed vorticity. Experimental results of this configuration are discussed later.

EXPERIMENTAL STUDIES

Experimental studies have been conducted to evaluate various wake-vortex minimization techniques. Primarily, the vortex minimization techniques were evaluated for the vortex-generating aircraft in the landing configuration. Vortex effects on a trailing aircraft for an in-trail type penetration (that is, one aircraft behind another) are used to infer the vortex hazard in the terminal area, since this type of encounter is most likely to occur during landing approaches. Experimental studies consisted of both flight tests and model tests of vortex minimization techniques.

Model Tests

Model tests have been conducted utilizing the test procedure illustrated in figure 5. For most of the tests, a B-747 aircraft model was used as a vortex generator, since it is representative of current wide-body jet transports. As will be discussed later, a limited number of tests were conducted by using DC-10 and L-1011 vortex-generating aircraft. The effectiveness of various vortex minimization techniques was determined by measuring the vortex-induced rolling moment on a smaller wing model positioned downstream of the vortex-generating aircraft. This technique has been used in wind tunnels and towing facilities in which both the vortex generator and the trailing wing are translated through a fluid medium. Facilities which have been used to obtain a rolling-moment assessment of vortex minimization concepts are the Ames 40- by 80-foot wind tunnel, the Langley V/STOL wind tunnel and vortex flow facility, and, under contract, a water towing tank at Hydronautics, Inc. Details concerning these facilities and the test technique can be found in reference 10. Additionally, laser-Doppler velocimeters (ref. 11) and hot-wire anemometers have been used during some tests to measure vortex velocity components. Flow-visualization studies in several facilities have proven to be a useful qualitative indication of the vortex.

Flight Tests

Flight tests have been conducted at the Dryden Flight Research Center using NASA's B-747 aircraft as a vortex generator while using a T-37B and the Ames Research Center Learjet as vortex probe or trailing aircraft. Also, the Wallops Flight Center C-54 aircraft and Langley's PA-28 aircraft have been used to evaluate one wake-vortex minimization technique. The test technique has involved the determination of the vortex-induced rolling moment from the measurements obtained during the probe aircraft while making in-trail vortex penetrations. A discussion of the flight-test procedures and examples of the data obtained are provided in references 12 and 13. In addition to rolling moments, some measurements of the vortex velocity distributions have been obtained by hot-wire probes on the Learjet (ref. 12).

Flight-test measurements of the vortex-induced rolling moment have been found to correlate qualitatively with results obtained in the model-test facilities. Techniques which have been identified by model tests to minimize the vortex upset on a trailing model have been shown to provide similar reductions in flight tests. The results do not correlate directly in magnitude because of differences in the level and scale of ambient turbulence and Reynold's number between model tests and flight tests.

WAKE-VORTEX MINIMIZATION TECHNIQUES

During the course of NASA's experimental program, numerous wake-vortex minimization concepts or ideas were investigated. Several concepts or methods were found to provide some alteration in the detailed vortex structure without significantly reducing the rolling moment on a trailing aircraft wing model. These unsuccessful concepts are discussed in reference 14. For the purpose of the following discussion, the concepts which have been found to meet the primary program objective of a significant reduction in the vortex-induced rolling moment on a trailing aircraft have been divided into three categories. The first is the use of turbulence generation or injection to rapidly diffuse the vorticity. The second is the use of vortex interaction which has been identified in the preceding theoretical section. The third area for discussion is to combine the effects of vortex interaction and turbulence injection.

Turbulence

Figure 6 illustrates a turbulence device as it was installed on a C-54 aircraft for a flight-test evaluation. The device generates considerable turbulence without affecting the wing-lift characteristics. Details concerning the development of this device can be found in reference 15. The turbulence device was found to rapidly diffuse and dissipate the vortex system from the C-54 aircraft. A flight-test evaluation using a PA-28 aircraft to probe the C-54 vortex system indicated that significant reductions in the vortex-induced rolling moment were obtained when the turbulence device was installed on the C-54 aircraft. (See fig. 7.) Model tests on a B-747 of a similar turbulence device have shown that by proper spanwise placement of the device, the vortex-induced rolling moment on a following aircraft can be reduced considerably. However, as would be expected, the operational penalties associated with the drag of such a device are significant.

The turbulence within a jet engine exhaust has been shown to provide some dissipation of the aircraft's trailing vortices. However, as shown in reference 16, the levels of thrust required to achieve a significant reduction in the vortex-induced rolling moment on a following aircraft are large. As indicated in reference 16, the thrust for significant vortex dissipation during the landing approach of a B-747 would require full power on the outboard engines and some reverse thrust on the inboard engines for flight-path control.

Vortex Interaction

Theoretical studies have indicated that turbulence is produced during the merging process of a wing-tip and flap vortex. Additional analyses have shown that the interaction phenomena produce a maximum amount of turbulence dissipation when the wing-tip and flap vortices are of nearly equal strength and the flap vortex originates at the 40-percent semispan station. This concept was implemented on a B-747 aircraft by deploying only the inboard flap segment during landing approach to achieve the desired location of the flap vortex. Details concerning the development of this concept are given in reference 17.

Figure 8 illustrates the differences in the character of the vortex interaction and merging for a B-747 aircraft in a normal landing configuration with all the flaps deployed and in a wake-vortex minimization configuration with only the inboard flaps deployed. Model-test and flight-test results of this concept indicate reductions of approximately 50 percent on the vortex-induced rolling moment on a trailing aircraft.

As indicated in reference 17, the implementation of this concept on a B-747 aircraft, in the manner described, imposed severe penalties on the pitching-moment characteristics and maximum lift-coefficient capability of the aircraft during landing approach. Additionally, the deployment of the landing gear adversely affected the vortex merging phenomena, which could only be reestablished by using a large vortex generator just aft of the wing and on either side of the fuselage. (See ref. 17.)

Combined Effects

The deployment of certain flight-spoiler combinations alters the span-load characteristics, sheds significant turbulence, and can be used to combine the effects of vortex merging and turbulence injection. References 18 and 19 cover the development and implementation of the spoiler concept for wake-vortex minimization. As shown in references 18 and 19, the maximum reduction in trailing-wing rolling moment behind a B-747 aircraft is achieved by deploying the two outboard spoilers (numbered 1 and 2 in fig. 9) during landing approach. Model-test results using this spoiler configuration indicate significant reductions in the vortex-induced rolling moment on a Learjet-size aircraft behind a B-747 (fig. 10). The results of reference 18 show that symmetric deployment of the two outboard spoiler panels on a B-747 aircraft increases the landing configuration drag about 20 percent while reducing the maximum lift-coefficient capability about 5 percent. Additionally, it was found during flight tests that the spoiler concept produced significant aerodynamic buffet which seriously detracts from the ride quality and may have structural implications with regard to the flap and flap-bracket fatigue life.

Model-test results of applying the spoiler concept to DC-10 and L-1011 aircraft for vortex minimization are shown in figure 11. The data show that the deployment of the proper spoiler combination on these aircraft provides a significant reduction in the vortex-induced rolling moment for a Learjet-size aircraft. The spoilers to be used on the DC-10 and L-1011 aircraft are the two most inboard flight spoilers (comparable to spoilers 3 and 4 in fig. 9). The results of the DC-10 and L-1011 aircraft have shown that the vortex-minimization techniques developed during B-747 aircraft tests are applicable to other vortex-generating aircraft. The implementation of any concept must include consideration of the differences in span loading, engine, and spoiler placement along with other configuration differences.

OPERATIONAL CONSIDERATIONS

A preliminary analysis of the operational considerations of implementing the turbulence concept by use of drag devices or engine thrust, the vortex-interaction concept by extension of only the inboard flap, and the combination of these concepts by deployment of the flight spoilers for wake-vortex minimization on a B-747 aircraft has been performed under contract. All the concepts have certain performance penalties which would preclude their use during take-off operations; consequently, they were only considered to be used during the approach and landing.

The analysis indicated that any form of turbulence injection through the use of high thrust settings on selected engines with partial reverse thrust on the other engines was operationally unsuitable. Considerable hardware would be required to implement a retractable turbulence device similar to that shown in figure 6 on a B-747 aircraft. The analysis indicated that such a device could not meet the approach-climb requirements (one engine out), but could be used during landing. Additionally, some penalties were incurred during the cruise configuration because of the hardware employed to stow the drag devices.

Because of cost and the performance penalties associated with their use, the turbulence concepts would probably be considered unsuitable for operational use.

The implementation of the vortex-interaction concept by deployment of only the inboard flap considerably reduced the static margin and restricted the center-of-gravity range severely. This technique was considered unsuitable for operational use.

The use of the spoiler concept was found to be operationally the most promising concept analyzed. The spoiler concept appears to meet most certification requirements, with the possible exception of the approach-climb requirement. An assessment of the structural penalties associated with the flight spoiler-induced buffet or possible solutions to this problem have not been conducted. As is seen in figure 10, the vortex-induced rolling moment on a trailing aircraft can be significantly reduced by using the flight spoiler but not totally eliminated. Such reductions are characteristic of all the vortex-minimization concepts evaluated. As indicated in reference 13, vortex-minimization concepts, such as the flight spoilers, can reduce the distance at which a probe aircraft can controllably fly behind a B-747 aircraft. An analysis has not been conducted to determine whether the economic gains of a reduction in separation criteria are offset by the economic penalties associated with implementing wake-vortex minimization techniques, such as would be incurred with structural changes, to withstand or reduce any flight spoiler-induced buffet.

CONCLUDING REMARKS

Considerable advances have been made in the area of theoretical analysis of wake-vortex minimization techniques. Experimental model-test and flight-test procedures have been developed for evaluating various wake-vortex minimization techniques and the model tests and flight tests have been shown to qualitatively agree. Tests have indicated that turbulence injection and vortex interaction brought about by a suitable span-load alteration can considerably reduce the trailing-vortex intensity. The use of the existing flight spoilers on a wide-body airplane utilizes both the turbulence injection and the vortex-interaction technique to bring about wake-vortex minimization. A cursory analysis of the operational feasibility of employing wake-vortex minimization techniques has been conducted. All the vortex-minimization techniques incur severe performance penalties which would preclude their use during take-off. The flight-spoiler concept was considered the most feasible candidate; however, a solution to the spoiler-induced buffet was not analyzed. Additionally, the economic penalties associated with implementing any wake-vortex minimization concept must be balanced by any economic gain in reduced separations.

REFERENCES

1. Walsh, Thomas M.; Morello, Samuel A.; and Reeder, John P.: Review of Operational Aspects of Initial Experiments Utilizing the U.S. MLS. Aircraft Safety and Operating Problems, NASA SP-416, 1976. (Paper No. 2 of this compilation.)

2. Wake-Vortex Minimization. NASA SP-409, 1976.

3. Betz, A.: Behavior of Vortex Systems. NACA TM 713, 1933.

4. Donaldson, Coleman duP.; and Bilanin, Alan J.: Vortex Wakes of Conventional Aircraft. AGARD-AG-204, May 1975.

5. Bilanin, Alan J.; and Donaldson, Coleman duP.: Estimation of Velocities and Roll-Up in Aircraft Vortex Wakes. J. Aircraft, vol. 12, no. 7, July 1975, pp. 578-585.

6. Rossow, Vernon J.: Inviscid Modeling of Aircraft Trailing Vortices. Wake-Vortex Minimization, NASA SP-409, 1976.

7. Ciffone, D. L.; and Orloff, K. L.: Far-Field Wake-Vortex Characteristics of Wings. J. Aircraft, vol. 12, no. 5, May 1975, pp. 464-470.

8. Bilanin, Alan J.; Teske, Milton E.; Donaldson, Coleman duP.; and Snedeker, Richard S.: Viscous Effects in Aircraft Trailing Vortices. Wake-Vortex Minimization, NASA SP-409, 1976.

9. Lewellen, W. S.; and Teske, M.: Turbulence Modeling and its Application to Atmospheric Diffusion. Part II Critical Review of the Use of Invariant Modeling. Rep. No. EPA/600/4-75/016b, U.S. Environ. Prot. Agency, Dec. 1975. (Available from NTIS as PB-253 451/9GA.)

10. Stickle, Joseph W.; and Kelly, Mark W.: Ground-Based Facilities for Evaluating Vortex Minimization Concepts. Wake-Vortex Minimization, NASA SP-409, 1976.

11. Ciffone, Donald L.; and Orloff, Kenneth L.: Application of Laser Velocimetry to Aircraft Wake-Vortex Measurement. Wake-Vortex Minimization, NASA SP-409, 1976.

12. Jacobsen, Robert A.; and Barber, M. R.: Flight-Test Techniques for Wake-Vortex Minimization Studies. Wake-Vortex Minimization, NASA SP-409, 1976.

13. Barber, Marvin R.; Hastings, Earl C., Jr.; Champine, Robert A.; and Tymczyszyn, Joseph J.: Vortex Attenuation Flight Experiments. Wake-Vortex Minimization, NASA SP-409, 1976.

14. Dunham, R. Earl, Jr.: Unsuccessful Concepts for Aircraft Wake-Vortex Minimization. Wake-Vortex Minimization, NASA SP-409, 1976.

15. Patterson, James C., Jr.; Hastings, Earl C., Jr.; and Jordan, Frank L., Jr.: Ground Development and Flight Correlation of the Vortex Attenuating Spline Device. Wake-Vortex Minimization, NASA SP-409, 1976.

16. Patterson, James C., Jr.; and Jordan, Frank L., Jr.: Thrust-Augmented Vortex Attenuation. Wake-Vortex Minimization, NASA SP-409, 1976.

17. Corsiglia, Victor R.; and Dunham, R. Earl, Jr.: Aircraft Wake-Vortex Minimization by Use of Flaps. Wake-Vortex Minimization, NASA SP-409, 1976.

18. Croom, Delwin R.: The Development and Use of Spoilers as Vortex Attenuators. Wake-Vortex Minimization, NASA SP-409, 1976.

19. Croom, Delwin R.: Low-Speed Wind-Tunnel Investigation of Various Segments of Flight Spoilers as Trailing-Vortex-Alleviation Devices on a Transport Aircraft Model. NASA TN D-8162, 1976.

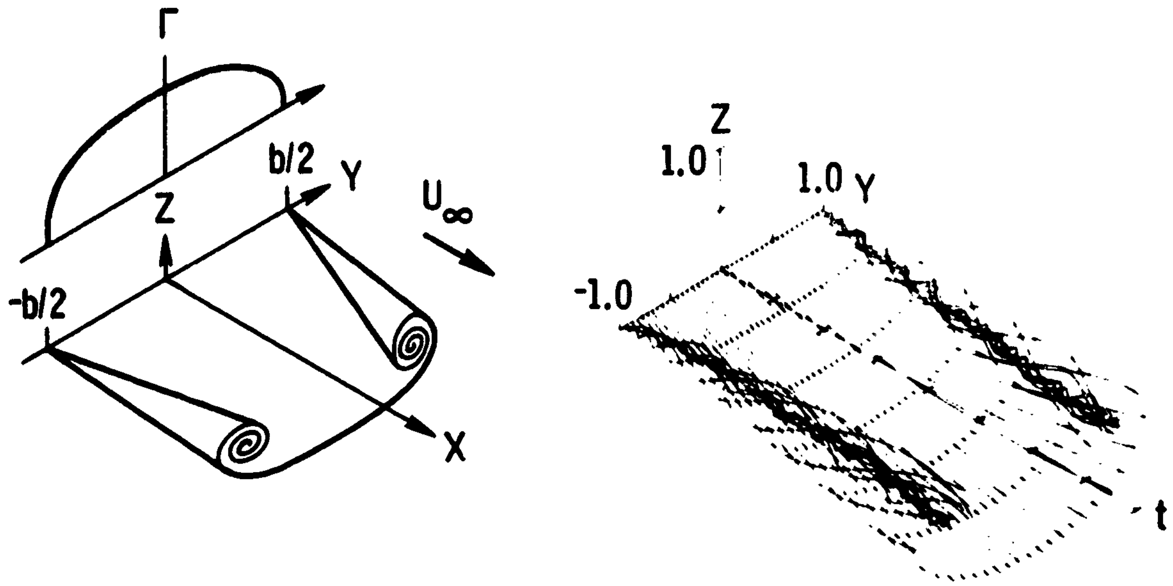


Figure 1.- Results of point-vortex calculations of the vortex-sheet rollup from an elliptically loaded wing. (Data from ref. 6.)

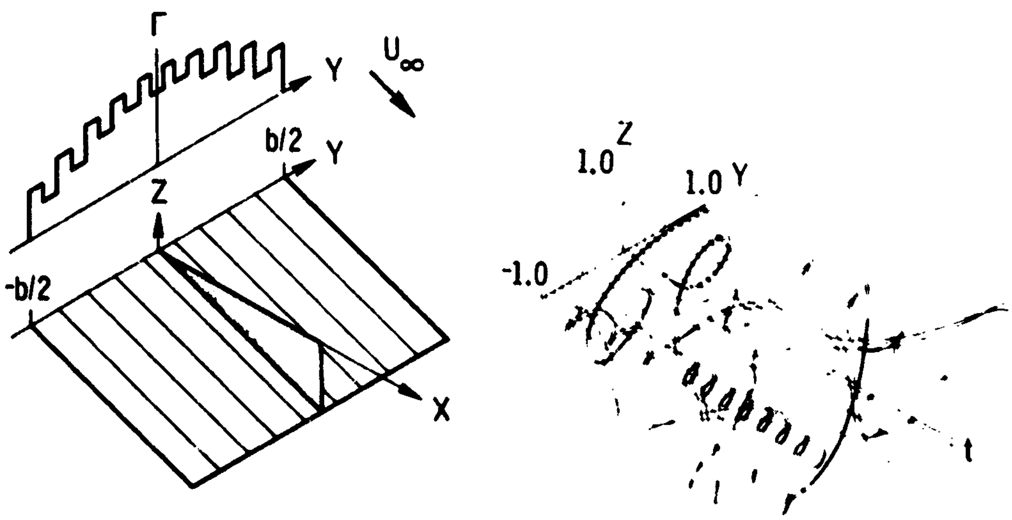
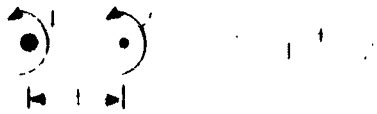
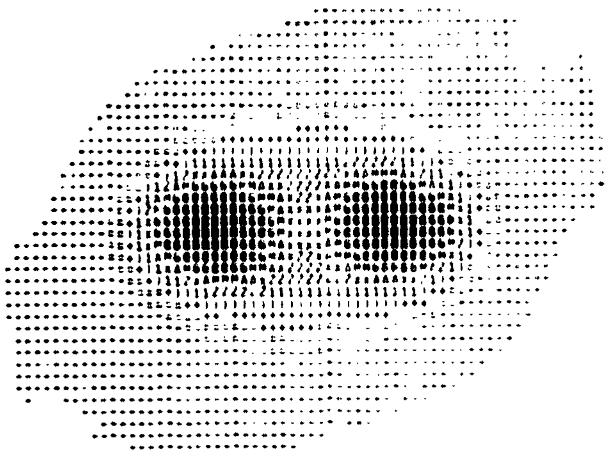


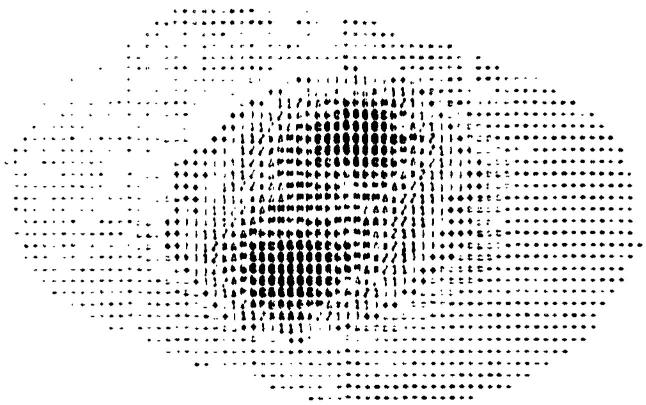
Figure 2.- Results of point-vortex calculations of the vortex-sheet rollup from a sawtooth-load distribution. (Data from ref. 6.)



(a) Initial setup for start of calculations.

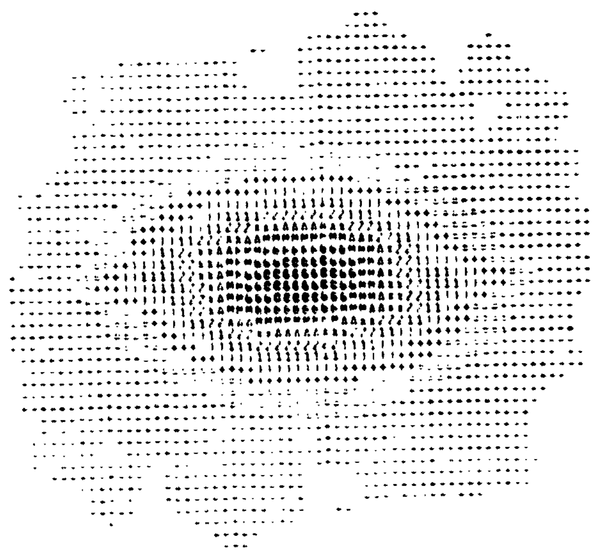


(b) Pressure-intensity plot at a nondimensional time ($t\nu/d^2$) of 0.0.



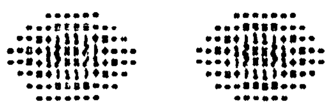
(c) Pressure-intensity plot at a nondimensional time ($t\nu/d^2$) of 1.33.

(d) Pressure-intensity plot at a nondimensional time ($t\nu/d^2$) of 2.67.



(e) Pressure-intensity plot at a nondimensional time ($t\nu/d^2$) of 4.0.

Figure 3.- Illustration of merging and interaction of two equal-strength like-sign vortices. (From ref. .)



(a) Turbulent kinetic energy at a nondimensional time ($t\Gamma/\pi d^2$) of 0.0.

(b) Turbulent kinetic energy at a nondimensional time ($t\Gamma/\pi d^2$) of 1.33.

(c) Turbulent kinetic energy at a nondimensional time ($t\Gamma/\pi d^2$) of 2.67.

(d) Turbulent kinetic energy at a nondimensional time ($t\Gamma/\pi d^2$) of 4.0.

Figure 4.- Turbulent kinetic energy intensity plots for the merging of two equal-strength like-sign vortices. (From ref. 8.)

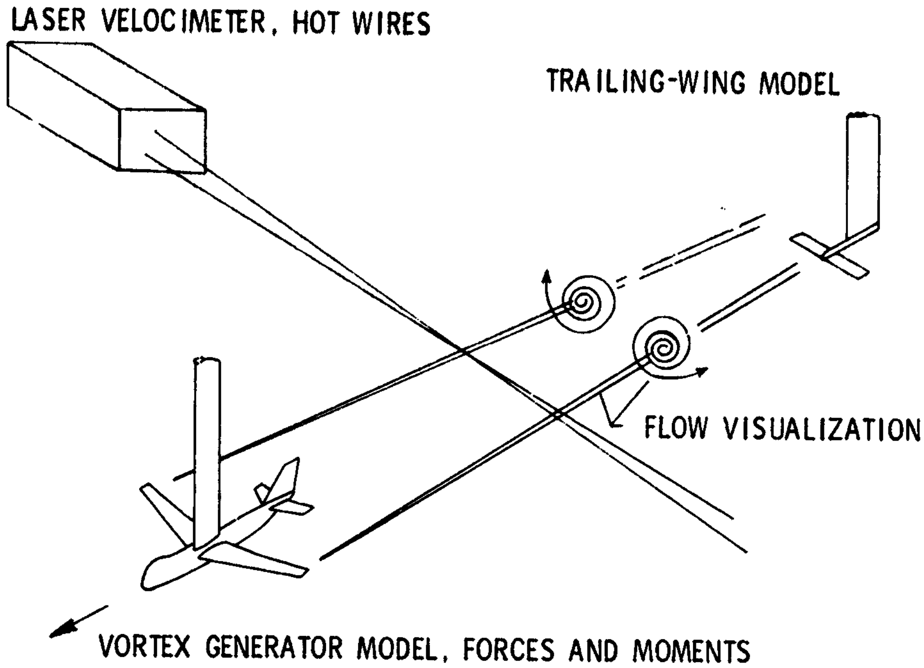


Figure 5.- Illustration of model-test procedure.

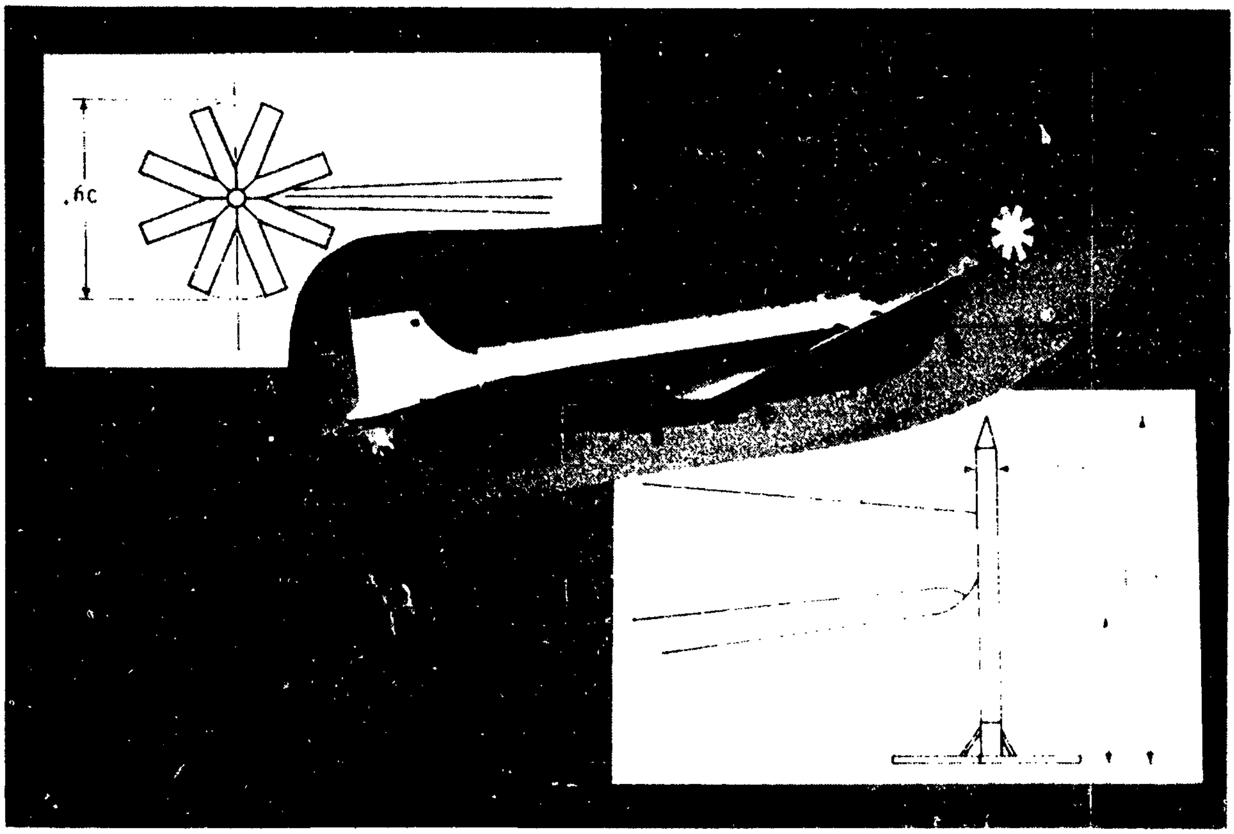


Figure 6.- Turbulence device installed on C-54 airplane for flight tests.

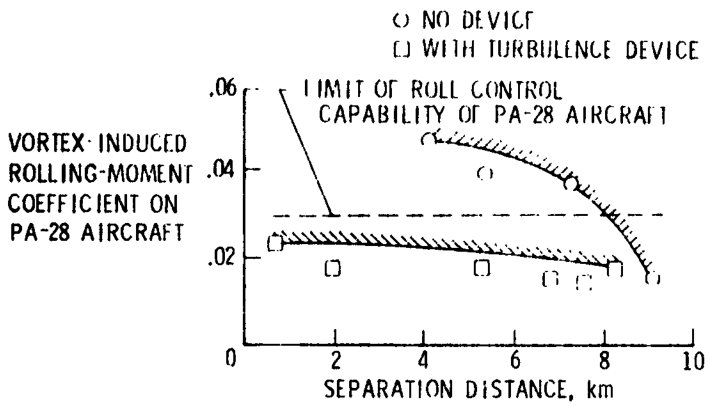
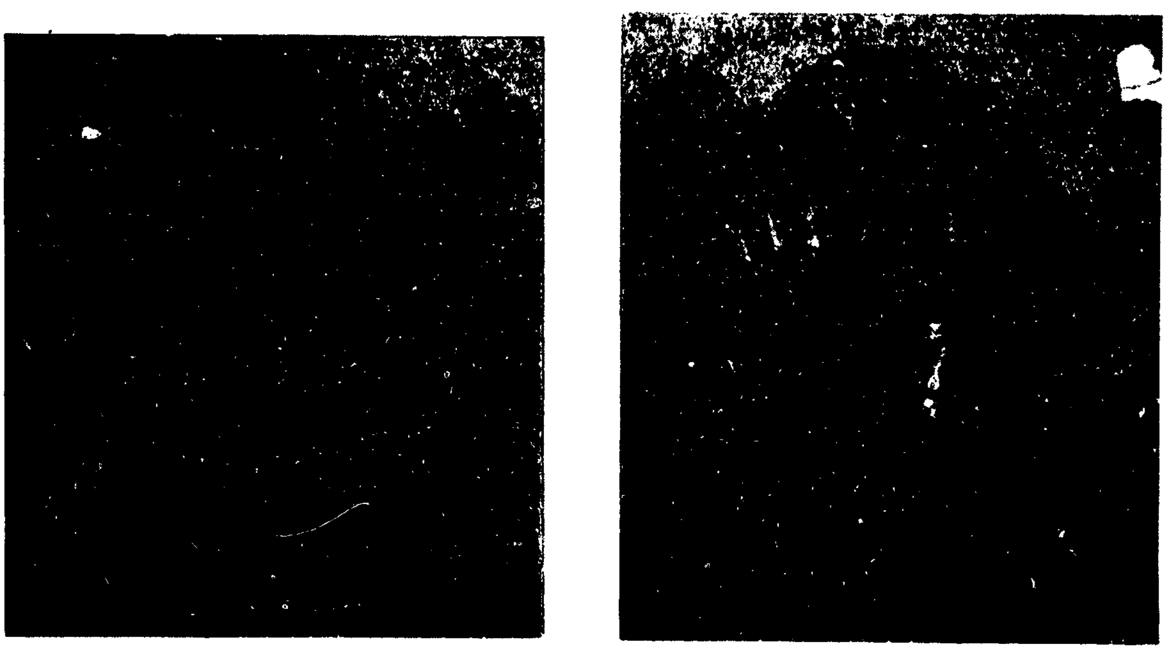


Figure 7.- Flight-test results of the turbulence device.



(a) All flaps extended. (b) Only the inboard flap extended.

Figure 8.- Photographs illustrating vortex interaction.

ORIGINAL PAGE IS
OF POOR QUALITY

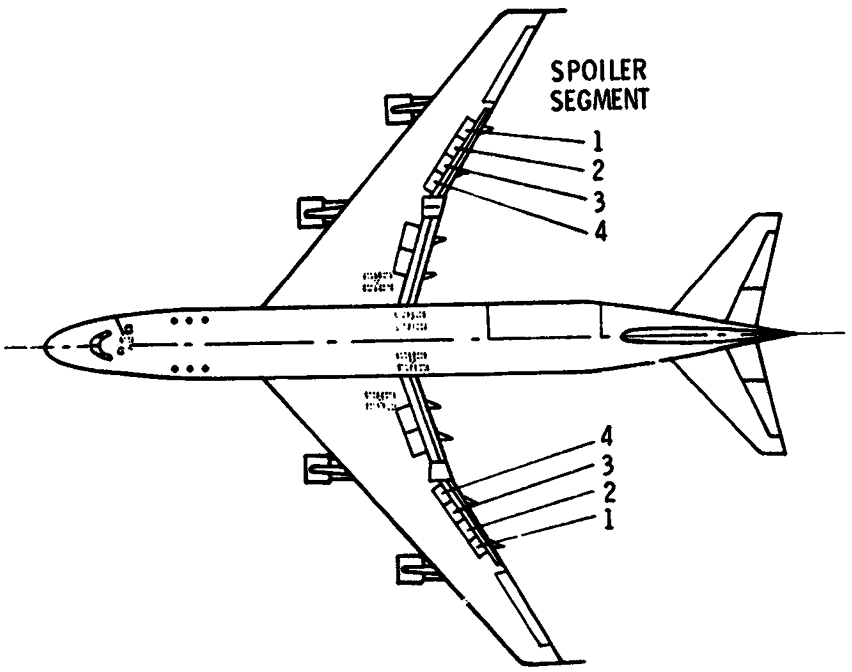


Figure 9.- Location of flight spoilers on a B-747 aircraft.

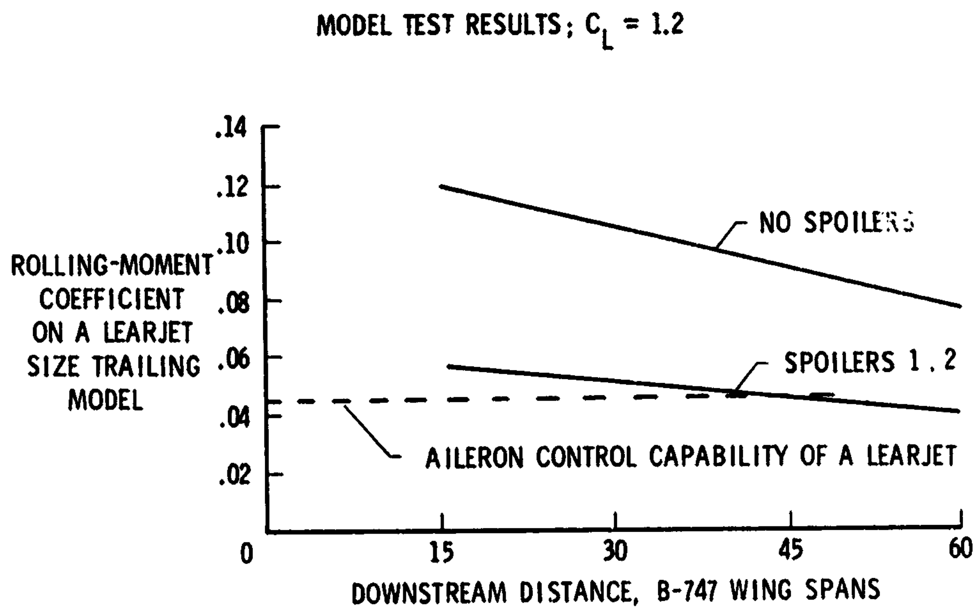


Figure 10.- Model-test results of the effect of using the flight spoilers on B-747 for vortex minimization.

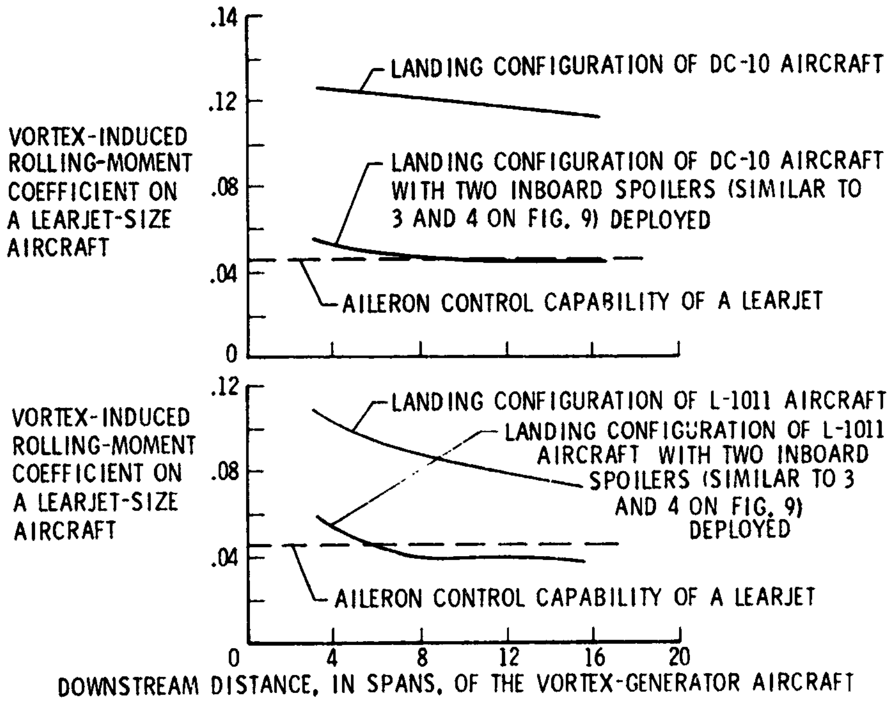


Figure 11.- Model-test results of using flight spoilers for wake-vortex minimization on DC-10 and L-1011 airplanes.