WAKE VORTEX ATTENUATION FLIGHT TESTS: A STATUS REPORT

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SUMMARY

Flight tests have been conducted to evaluate the magnitude of aerodynamic attenuation of the wake vortices of large transport aircraft that can be achieved through the use of static spoiler deflection and lateral control oscillation. These methods of attenuation were tested on Boeing B-747 and Lockheed L-1011 commercial transport aircraft. Evaluations were made using probe aircraft, photographic and visual observations, and ground-based measurements of the vortex velocity profiles.

The magnitude of attenuation resulting from static spoiler deflection was evaluated both in and out of ground effect. A remotely piloted QF-86 drone aircraft was used to probe the attenuated vortices in flight in and out of ground effect, and to make landings behind an attenuated B-747 airplane at reduced separation distances.

INTRODUCTION

The National Aeronautics and Space Administration has conducted extensive research and testing to determine the feasibility of aerodynamically attenuating the wake vortices of large transport aircraft. This program has been underway since 1974, and it has resulted in numerous flight and ground facility tests. Much of the early work conducted under this program was reported in the Wake Vortex Minimization Symposium held in 1976 (ref. 1). This paper reviews all of the flight work that has been conducted during the program, with an emphasis on the results of the work done after the symposium.

Table I summarizes the flight experiments that were reported at the 1976 symposium. All of the methods shown in the table were successful in attenuating the vortices to some degree. However, each method had some attendant characteristic that resulted in its not being practical for actual airline usage. The means of attenuation for all of these tests were defined in various ground facilities that were developed to support the minimization research. The capabilities of the ground facilities are reported extensively in reference 1, and are not mentioned here except in passing.

Two series of flight tests have been conducted since the Wake Vortex Minimization Symposium (table II). The objectives of these tests can be categorized as follows:

(1) An evaluation of the effectiveness of altered spoiler deflections on the L-1011 aircraft to attenuate wake vortices.

(2) An evaluation of the effectiveness of altered spoiler deflections on the B-747 aircraft to attenuate wake vortices. These tests included an evaluation of ground effects, which involved flying a remotely controlled drone into the spoiler-attenuated vortices at low altitudes. The tests also included landings behind an attenuated B-747 aircraft at reduced separation distances.

(3) An evaluation of the attenuation that resulted from the excitation of dynamic vortex instabilities. This series of tests used the L-1011 airplane as the vortex-generating aircraft. However, the tests were inspired by the results of the tests conducted with the B-747 airplane in the first series of tests, which showed that significant attenuation resulted from oscillating the spoilers and ailerons.

As shown by the number of test flights made with altered spoiler deflections, an emphasis was placed on that concept for vortex attenuation. This concept was emphasized because spoiler deflection alterations would probably be easier to incorporate in an existing fleet of aircraft than any of the other concepts. In addition, the number of possible combinations of altered spoiler deflections results in a rather large test matrix.

SYMBOLS

AGL	above ground level
b	wingspan, m
C_L	lift coefficient
C_l	rolling-moment coefficient
DME	separation distance, n. mi.
I_x	rolling moment of inertia, kg-m^2
p	roll rate, deg/sec
$\dot{p}$	roll acceleration, deg/sec^2
p_{s_b}	boom-mounted static pressure, N/m^2
q	dynamic pressure, N/m^2
S	wing area, m^2

V_t	true airspeed, m/sec
δ_a	aileron position, deg
φ	bank angle, deg

Subscripts:

max	maximum
tw	trailing wing
v	vortex

FLIGHT TEST METHODS

Figure 1 shows the L-1011 vortex-generating test aircraft equipped with the smoke generators that are used to mark the vortices so that a probe aircraft can fly into them. Four smoke generators are installed on each wing of the test aircraft. Each smoke generator marks one of the points of aerodynamic discontinuity on the wing (the wingtip, the outboard edge of the outboard flap, the outboard edge of the inboard flap, and the wing root). Smoke-marked vortices are shown in figure 2. A depiction of a light aircraft probing the vortices is presented in figure 3; as indicated by the figure, this study is concerned primarily with the probe aircraft's roll response.

During the tests, vortices were probed at distances as great as 12 nautical miles and as small as 2 nautical miles. The objective of the vortex attenuation effort, however, was to make it possible for light aircraft to fly as close as 3 nautical miles behind aircraft classed as heavy on landing approach, in contrast to the present requirement for a separation distance of 6, 5, 4, or 3 nautical miles, depending on the class of the following aircraft. Therefore, the major effort of this program has been concentrated on the 3-nautical-mile separation distance, as depicted in figure 3. The distance between the two airplanes was measured with an onboard distance-measuring radio and recorded in the probe airplane.

The probe airplanes were equipped with response-measuring instrumentation that enabled real time calculations to be made of the rolling moment induced on the probe airplane by the vortex. Figure 4 shows time histories of the variables that are used to compute the vortex-induced rolling-moment coefficient, which is calculated as follows:

$$C_{l_v} = \frac{\dot{p} I_x}{qSb} = \left(C_{l_{\delta_a}} \delta_a + C_{l_p} \frac{pb}{2V_t} \right)$$

Roll acceleration, $\dot{p}$, is obtained by differentiating the roll rate measurement. A calculation of the vortex-induced rolling-moment coefficient is desirable because it is difficult to evaluate the severity of a vortex encounter in terms of bank angle, roll rate, or roll acceleration. The difficulty arises from the fact that the pilot of the probe aircraft must constantly maneuver the airplane to attempt to stay in the vortex wake. The calculation of the rolling-moment coefficient enables the masking effects of the ailerons and of roll damping to be subtracted from the airplane's total response, leaving a direct measurement of the airplane's response to the vortex. Reference 2 describes the derivation of the vortex-induced rolling-moment coefficient and discusses its use as a measure of aircraft response to a vortex encounter.

In addition to using a probe airplane to determine the upset potential of attenuated and unattenuated vortices, measurements of the vortex velocities were made by using a laser-Doppler velocimeter (LDV) and a monostatic acoustic sensing system (MAVSS). These devices, which are described in detail in reference 3, belonged to the Department of Transportation's Transportation Systems Center (TSC). Their use in the wake vortex minimization program reflected the desire on the part of both agencies to minimize the difficulties that result from the wake vortices of large aircraft. Figure 5 shows the LDV in use during one of the flight tests.

The general approach for the most recent flight tests, which were made with the L-1011 airplane, was to evaluate the effectiveness of the vortex attenuation of each static or dynamic configuration visually and photographically and to explore only the most promising configurations with in-flight probes and measurement with the LDV and MAVSS.

RESULTS AND DISCUSSION

Selected Static Spoiler Deflection

Figure 6 presents the vortex-induced rolling-moment coefficients on a T-37B probe aircraft that resulted from a conventionally configured B-747 aircraft, and from the same aircraft using the best spoiler attenuation configuration that was defined at the time of the Wake Vortex Minimization Symposium. The figure shows that the spoilers did attenuate the vortices, but that the vortices were still significantly more powerful than T-37B roll control capability. To see whether vortex attenuation resulted when selected spoilers were deflected on other heavy transports, wind tunnel and tow tank facility tests were made on L-1011 and DC-10 models (refs. 4 and 5, respectively). The results of these tests were encouraging and led to subsequent flight tests with an L-1011 airplane, which yielded the results shown in figure 7. The spoilers again provided attenuation, but not to a level that the T-37B controls could overpower. An interesting finding of this test series was that the deflection of three spoiler panels provided more attenuation than the two spoilers that were deflected on the B-747 airplane. This prompted additional wind tunnel tests with a B-747 model to determine the magnitude of attenuation that the deflection of three spoiler panels would produce on that airplane (ref. 6). The results of those wind tunnel tests are presented in figure 8. The figure shows that more attenuation would be achieved. Another surprising result was that a spoiler deflection on the three panels of 15° yielded more attenuation than a larger deflection. Since deflecting the spoilers induces buffet and performance penalties on the airplane, the greater attenuation with less deflection was particularly attractive.

Because the wind tunnel tests were so promising, flight tests were initiated to evaluate the effectiveness of deflecting the three spoiler panels on the B-747 airplane. The results of those tests are presented in figure 9. The three spoiler panels did yield more attenuation than the two panels previously tested. However, unlike the wind tunnel prediction, 15° of spoiler deflection yielded less attenuation than the 30° deflection.

The attenuation achieved by deflecting the three B-747 spoiler panels was greater than any that had been achieved by using spoilers on either the B-747 or L-1011 aircraft. Figures 10(a) and 10(b) present time histories of T-37B roll response to typical vortex encounters resulting from the conventional B-747 landing configuration and the B-747 configuration with three spoilers deflected. The conventionally configured B-747 (fig. 10(a)) caused several bank angle excursions that exceeded 90° and one upset that completely inverted the T-37B airplane. The static pressure measurement in the time history comes from a nose-boom-mounted static pressure orifice. The static pressure transducer is sensitive and has a washout to compensate for altitude changes and a pilot reset to null it. Its function is to identify the sharp drops in pressure that occur when the airplane encounters a vortex core. The time history for the spoiler-attenuated vortex encounter (fig. 10(b)) shows much smaller roll and bank angle responses, and the variations in the nose boom static pressure are much smaller. The figure shows that the pilot is able to keep the airplane's bank angle variation within approximately 30°, with one excursion as great as 60°. The time history also shows that the roll and bank angle excursions have a slower onset rate, which is very important to an unsuspecting pilot. The slowing of the excursions would be expected from the data presented in figure 9, since that figure shows that the upset potential of the vortex is only slightly greater than the roll control power of the airplane.

Low Altitude Tests

The upsets resulting from the vortices of the attenuated configuration were small enough and slow enough so the pilots felt they could cope with vortex encounters at separation distances of 3 nautical miles at altitudes as low as 70 meters. This permitted the evaluation of a previously untested hypothesis: that if the ground effects provided some additional vortex attenuation, landings might be possible at the desired 3-nautical-mile separation distance. Therefore, an effort was made to evaluate the vortices in and out of ground effect, with a remotely controlled QF-86 drone used as a probe.

Before low altitude probes were made in flight, a piloted simulation was developed to help determine the problems associated with vortex encounters at low altitude. The simulation utilized the vortex velocities measured by the LDV during the previous flight tests. Unfortunately, the LDV has not yet been refined to the point where it can measure attenuated vortices in ground effect. Therefore, the simulation did not contribute to an understanding of the effects of ground effect on attenuated vortices, although it indicated that ground effect did reduce the severity of unattenuated vortices.

The results of flying the remotely controlled aircraft probe at low altitudes 3 nautical miles behind the attenuated B-747 configuration are presented in figure 11. The data show that bank angle excursions as large as 60° were produced at altitudes as low as 20 meters, well within the ground effect of the B-747 airplane. The remotely controlled probe aircraft was also landed seven times 4 nautical miles behind the attenuated B-747 configuration. The pilot was able to maintain maximum exposure to the visible wake vortex during the entire approach until it became necessary to concentrate on lining up with the runway for the landing itself. Slight wind variations made it difficult to place the vortex trail precisely over the center of the runway, so it could not be positively determined that the drone was in the vortex wake during the most critical portion of the landing approach and flare.

Oscillating Spoiler and Aileron Tests

During the remotely controlled aircraft probe tests, a test was run to evaluate the effects on the vortices of oscillating the lateral controls of the B-747 in the attenuated configuration. It was theorized that the interplay of the ailerons and the spoilers during such oscillation and the resulting changes in lift distribution might produce hard spots in the wake. Therefore, a test was made wherein the B-747 pilot was asked to oscillate the lateral control wheel at a frequency of about 6 seconds per cycle. The resulting wake was probed by the T-37B airplane to see if hard spots did in fact result. Unexpectedly, however, the T-37B pilot reported that the wake was completely devoid of coherent rotary motion at the 3-nautical-mile separation distance. Because of this result, additional tests were conducted, first to verify the finding, and then to try to determine whether the attenuation was due to spoiler and aileron control motion or if B-747 wing rocking was causing the effect. Table III lists the tests conducted and gives a qualitative assessment of the results.

For the first tests shown in table III, the spoilers and ailerons were oscillated simultaneously through the pilot's roll control wheel. For these oscillations, spoilers 2, 3, and 4 were preset in the 30° position used in the attenuated configuration and then allowed to oscillate with the roll control inputs. This caused the three spoilers on the rising wing to retract and the affected spoilers on the falling wing to become further extended. A test was then made with aileron deflection only, that is, the ailerons oscillated with the pilot's roll control wheel and the spoilers were locked in the retracted position. For all of the above tests, the pilot oscillated the roll control wheel nearly its full deflection at the 6 second per cycle frequency, and the resulting bank angle oscillations were approximately ±7°. The spoiler-alone oscillation shown in table III was performed by having the pilot modulate the speed brake lever between 15° and 30°. The speed brakes were modulated symmetrically, so no aircraft roll motion resulted from their deflection.

Figure 12 presents a time history of T-37B response to a wake produced with both the spoilers and ailerons oscillating. The figure shows bank angle variations so small that it is difficult to tell whether they are the result of wake encounters or the result of pilot attempts to encounter the wake. There are none of the large variations in static pressure that indicate that high velocity, low pressure vortex cores are present. The maximum rolling-moment coefficient for this run is approximately 0.045, and only one deviation of this magnitude occurs during the run. The deviation may be the result of B-747 pilot inputs that were somewhat out of phase with the oscillation inputs, so that there was a single hard spot in the wake. A comparison of figure 12 with figures 10(a) and 10(b) shows that in general the wake attenuated by oscillating the ailerons and spoilers causes much less roll and bank angle response than the wake produced by either of the other two configurations. In fact, the probe airplane pilots commented that oscillating the ailerons and spoilers produced a wake that was somewhat comparable to light or light-to-moderate atmospheric turbulence.

A summary of the maximum rolling-moment coefficients for the five oscillating aileron and spoiler runs is presented in figure 13. The induced rolling-moment coefficients fall mostly within the roll control power of the T-37B. Since the pilot's ability to control the airplane becomes marginal when the rolling-moment coefficients approximate the roll control power of the probe airplane, few uncontrollable bank angle excursions occurred at these values, allowing the probe pilot to report the nearly total conversion of rotary motion to random turbulence. The time histories that generated the data in figure 13 show only one or two large values of C_{l_v} during a run. Again, the larger deviations may be indicative of pilot inputs that were out of phase with the B-747 oscillations.

The attenuation achieved by oscillating the ailerons and spoilers of the B-747 is technically exciting, in that it demonstrates once again that essentially total wake vortex attenuation can be achieved as close as 2.5 nautical miles behind a large transport aircraft in the landing configuration. (Total wake vortex attenuation was first achieved at a separation distance of 2.5 nautical miles by altering the deflection of the inboard and outboard flaps (ref. 1), as shown in table I. However, the attenuation occurred only when the landing gear was not extended, thus making it impractical for operational use.) Obviously, oscillating the ailerons and spoilers and the resulting airplane roll is not practical for airline transports on final approach. However, the desire to understand the mechanism of the attenuation prompted further testing.

The first of these tests is being conducted in the Langley vortex flow facility with a B-747 model that has control surfaces capable of being oscillated. (The wing is kept level, however.) If the model tests reproduce the attenuation experienced in flight successfully, they will make it possible to refine the technique and minimize the objectionable airplane response.

Oscillating control tests were also conducted with the L-1011 aircraft to see whether the vortex attenuation could be duplicated with another aircraft configuration. The L-1011 was particularly attractive for this test because it incorporates a direct lift control (DLC) system and an active aileron control system (AACS), which assured flexibility for oscillating the control surfaces. The capabilities of the two systems are described in tables IV and V, respectively. The AACS provides gust load alleviation.

The L-1011 tests were completed in the summer of 1980. Table VI summarizes the results of those tests. The table identifies the concepts that were tested, the configurations used to test the concepts, and the results. Perhaps the most significant result was that the L-1011 could not reproduce the B-747 vortex attenuation that resulted from oscillating the ailerons and spoilers. The inability to reproduce the attenuation may be due to the L-1011 control system, which did not permit the exact duplication of the B-747 maneuver. The L-1011 spoilers 2, 3, and 4 can be extended but not retracted from a preset position as a result of a pilot roll control input, whereas the B-747 spoilers did both. Therefore, to simulate the B-747 maneuver, the copilot had to retract the spoilers from the preset position by using the speed brake control handle while the pilot was making roll control inputs. Further, the speed brake handle activates spoiler panel 5 in addition to three other spoiler panels. These differences, though subtle, may underlie the inability of the L-1011 to reproduce the extremely favorable attenuation achieved by the B-747.

Perhaps the most interesting result of the recent L-1011 flight tests was that oscillating the spoilers alone permitted the Crow instability (ref. 7) to be manipulated. It could also be manipulated by oscillating the ailerons and spoilers in combination, whether asymmetrically or symmetrically. Even though the Crow instability could be manipulated, however, the total time necessary for the vortices to decay did not seem to decrease until the control oscillation rate was high. The 2.3 second per cycle symmetrical oscillation of the ailerons and spoilers did cause the vortices to decay significantly more rapidly than the vortices generated during the 9.2 or 4.6 second per cycle oscillations. However, both visual observation and probing flights (fig. 14) indicated that the configuration still had an unacceptable upset potential. Nevertheless, high frequency control oscillation may have potential for purposes of wake vortex attenuation.

CONCLUDING REMARKS

Flight tests have shown that the wake vortices of large transport aircraft can be attenuated by several methods, including altered span loading, turbulence ingestion, altered span loadings and turbulence ingestion in combination, and by the excitation of dynamic vortex instabilities. Only two of the methods have resulted in the nearly total attenuation of vortices at the 3-nautical-mile separation distance desired for air traffic operation in terminal areas. They are altered span loading and the excitation of dynamic instabilities. Both of these methods are impractical for operational use, however. The reason for the attenuation that results from altered span loading is already understood, but further testing will be necessary to understand the reason for the attenuation that results from oscillating the lateral controls. An understanding of the mechanism might allow refinements of the method that would make it more attractive in airline applications.

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TABLE I.—VORTEX ATTENUATION FLIGHT EXPERIMENTS CONDUCTED TO 1976

Method of attenuation	Means of attenuation	Vortex-generating aircraft	Vortex-probing aircraft	Number of test flights	Time period for test flights
Altered span loading	Altered inboard/ outboard flap deflections	B-747	Learjet-23 (LR-23) Cessna T-37B	≈17	1974
Turbulence ingestion	Splines	C-54G	Piper Cherokee (PA-28)	≈20	1973
Mass and turbulence ingestion	Altered inboard/ outboard engine thrust levels	B-747	LR-23 T-37B	≈2	1974/1975
Altered span loading and turbulence ingestion	Wingtip-mounted spoiler	CV-990	LR-23	≈2	1969
	Altered spoiler deflections	B-747	LR-23 T-37B McDonnell Douglas DC-9	≈15	1975/1976

TABLE II.—VORTEX ATTENUATION FLIGHT EXPERIMENTS CONDUCTED FROM 1976 to 1980

Method of attenuation	Means of attenuation	Vortex-generating aircraft	Vortex-probing aircraft	Number of test flights	Time period for test flights
Altered span loading and turbulence ingestion	Altered spoiler deflection	B-747, L-1011	T-37B, QF-86	45	1976 to 1980
Excitation of dynamic instabilities	Oscillating spoilers and ailerons	B-747, L-1011	T-37B	9	1979 to 1980

TABLE III.—VORTEX ATTENUATION WITH FIXED AND OSCILLATING B-747 CONTROLS

Control oscillated	Number of tests	Results
Spoilers 2, 3, and 4 (0° to 45°) and ailerons	5	Wake devoid of coherent rotary flow at 3 nautical miles
Aileron oscillation only (spoilers locked in retracted position)	1	Wake similar to unattenuated wake
Spoiler oscillation only (spoilers 2, 3, and 4 modulated symmetrically 15° to 30° at 6 sec/cycle)	1	Wake similar to statically attenuated spoiler wakes

TABLE IV.—L-1011 SPEED BRAKE AND DIRECT LIFT CONTROL SYSTEM
[Six spoiler panels per wing]

Normal operation:

In cruise configuration (flaps up), spoilers 1 to 6 can be used manually as speed brakes. Maximum deployment is 60°.

In approach configuration (flaps down)—

Spoilers 2 to 6 can be deployed for roll assistance. Deflection is proportional to inboard aileron position. Maximum overall spoiler deflection is 40°.
With direct lift control system operating, spoilers 1 to 4 modulate ±8° about 8° null. Modulation is proportional to pitch control column motion about its trim position.

Test aircraft capabilities:

If flaps are down, spoilers 1 to 6 can be operated manually or through DLC system, but this defeats roll assist.
Spoilers can be activated in symmetrical left/right pair combinations.

TABLE V.—L-1011 ACTIVE AILERON CONTROL SYSTEM

Normal operation:

Outboard ailerons modulate symmetrically about a null bias that is proportional to a combination of wingtip and body vertical accelerations

Null bias position is variable—

In cruise configuration (flaps up), null is at 2° down aileron
In approach configuration (flaps down), null is at 8° up aileron

Authority (command limits)—

Production aircraft: 21.1° trailing edge up, 17.4° trailing edge down
Test aircraft: 12° trailing edge up, 12° trailing edge down

Test aircraft capabilities:

Null bias is variable according to outboard aileron position
Outboard ailerons can be oscillated symmetrically by using a separate function generator
Computation command path can be open or closed loop

TABLE VI.—L-1011 1980 TEST CONFIGURATIONS AND RESULTS

Concept being evaluated	Configuration	Test results
Baseline	Normal landing configuration: gear down, flaps deflected 33°, no DLC, no AACS	------------------------------
Baseline with AACS and DLC	AACS and DLC	No significant improvement over baseline configuration
Effect of selected spoiler deflection on vortex wake	Spoilers 2, 3, and 4 deflected 45°	Same as previous test (table II)
Effect of aileron and selected spoiler oscillation on vortex wake	Ailerons and spoilers 2, 3, 4, and 5 oscillated Ailerons and spoilers 2 and 5 oscillated Ailerons oscillated alone	Could not reproduce B-747 result
Effect of static outboard aileron and spoiler deflection on wingtip vortices	Ailerons up 5°, 7½°, 10° and 15° Ailerons down 5°, 7½°, 10°, and 15° Spoilers 2, 3, and 4 deflected 30° for all tests	Up ailerons diffused tip wake Down ailerons augmented tip wake Small down aileron deflection shows a slight attenuating effect
Effect of spoiler modulation on vortices	Spoilers modulated through selected ranges: 0° to 10°, 0° to 15°, 20° to 35°, 15° to 45°, and 0° to 45° Frequencies tested were 9.2 and 4.6 sec/cycle	Excites and changes period of Crow instability
Vortex attenuation through inciting instability by pulsing spanwise center of lift	Oscillate ailerons and spoilers 2, 3, and 4 at 9.2, 4.6, and 2.3 sec/cycle asymmetrically and symmetrically	2.3 sec/cycle produced greatest L-1011 vortex attenuation to date. Pulsing excites and changes period of Crow instability
Incite instability through spanwise center of lift pulsing	Oscillate spoilers 1 and 6 asymmetrically and symmetrically, with or without ailerons	Potential for altering vortex characteristics on one side of airplane for comparative and vortex merging studies

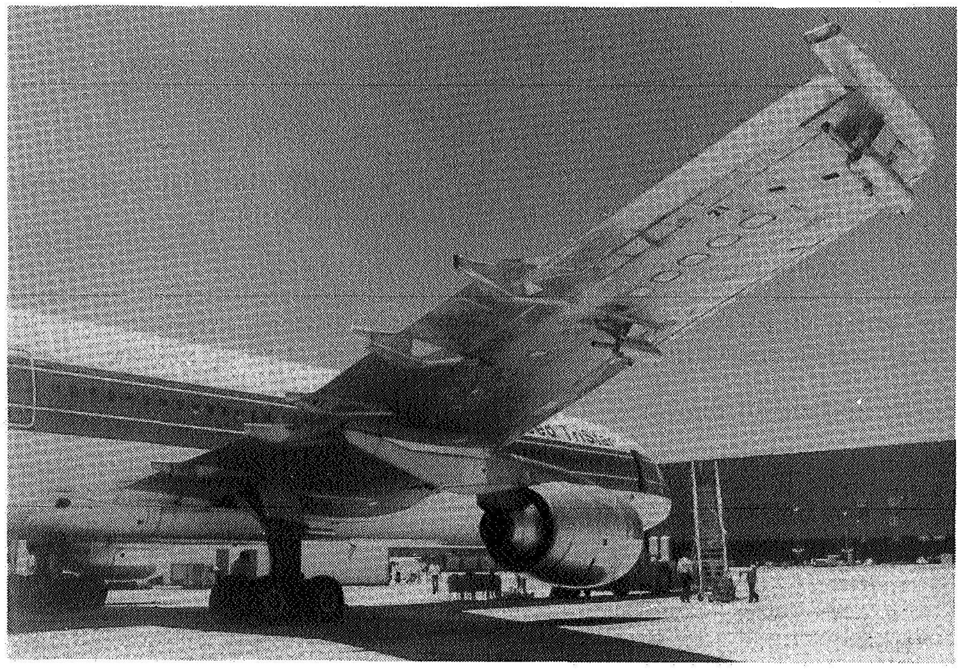


Figure 1. L-1011 vortex-generating test aircraft with vortex-marking smoke generators installed.

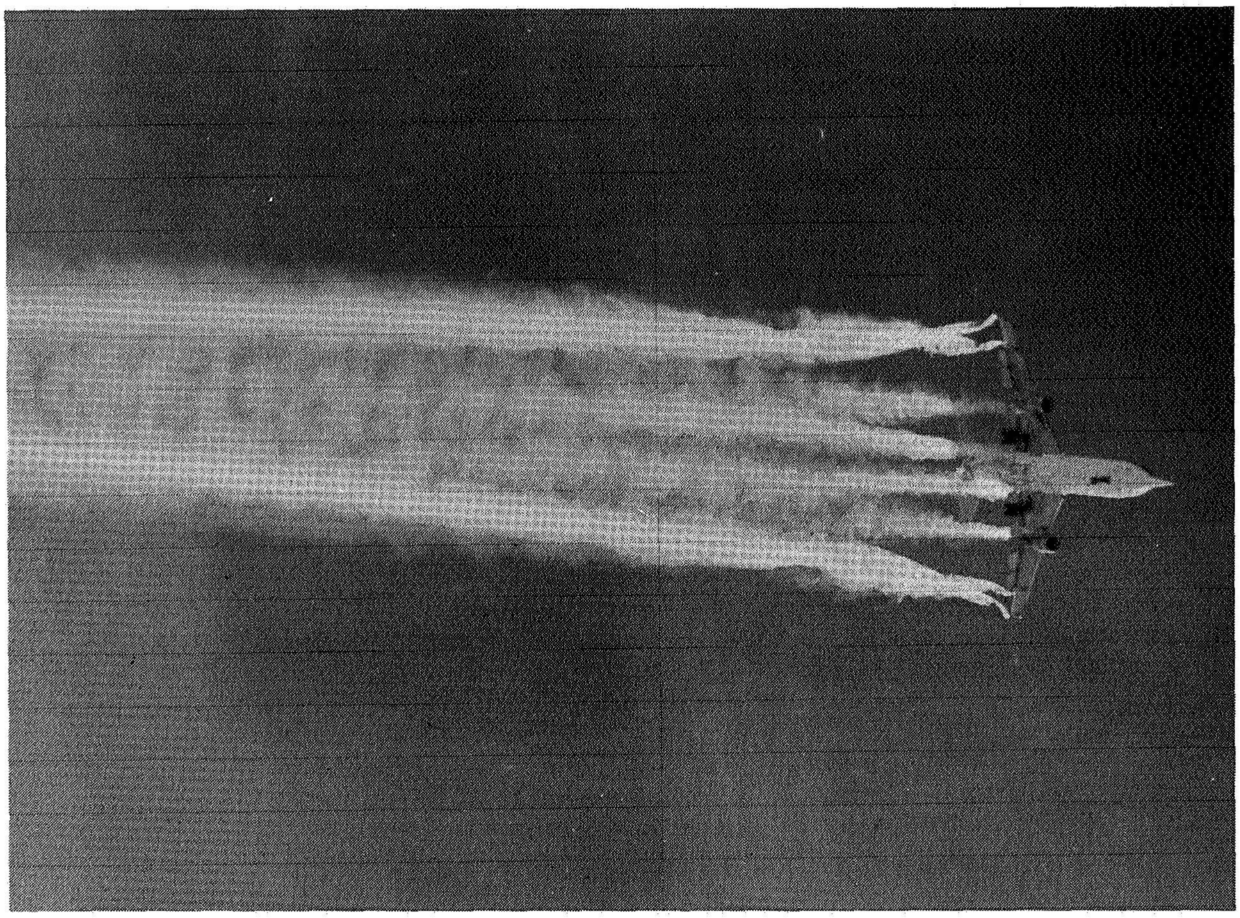


Figure 2. Smoke-marked vortices.

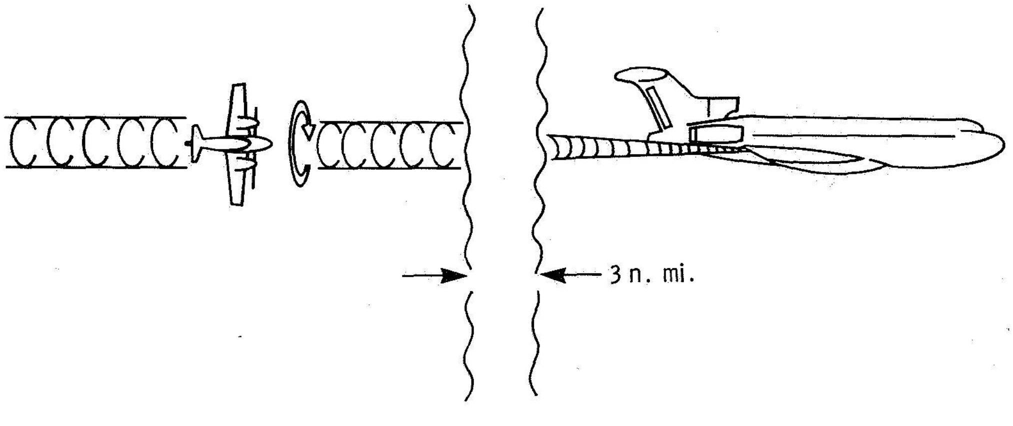


Figure 3. Light aircraft probes.

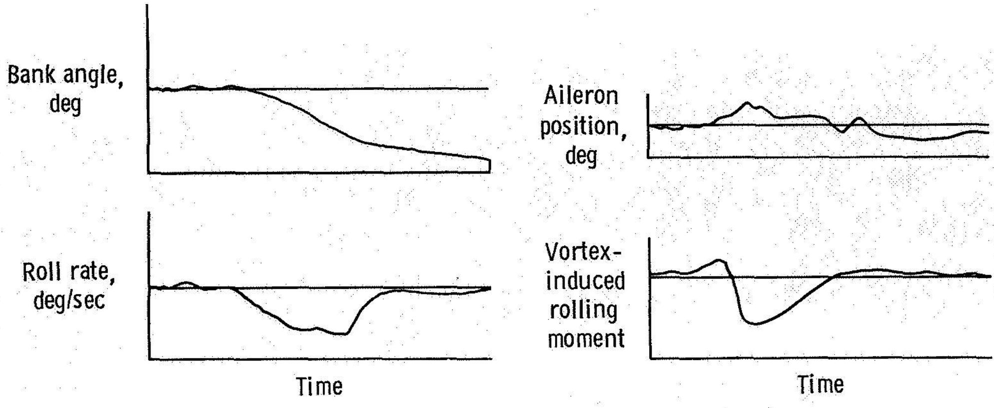


Figure 4. Real time wake vortex data reduction.

Figure 5. LDV system monitoring wake vortices generated by a B-747 aircraft at Rosamond Dry Lake.

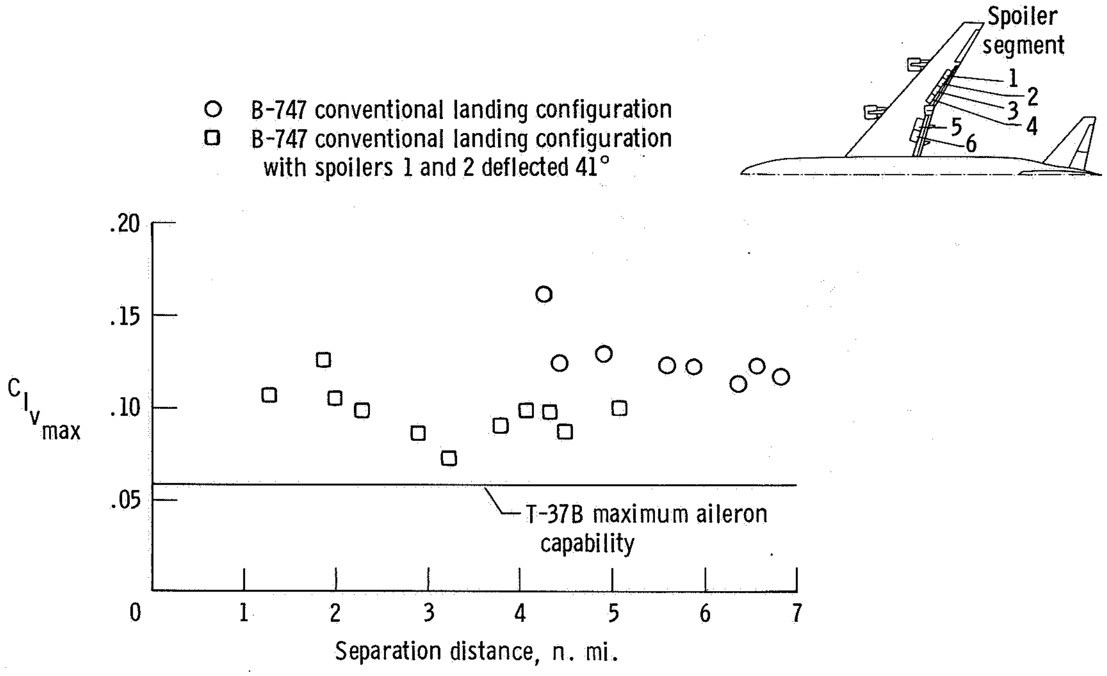


Figure 6. B-747 wake vortex upset potential for a T-37B probe airplane.

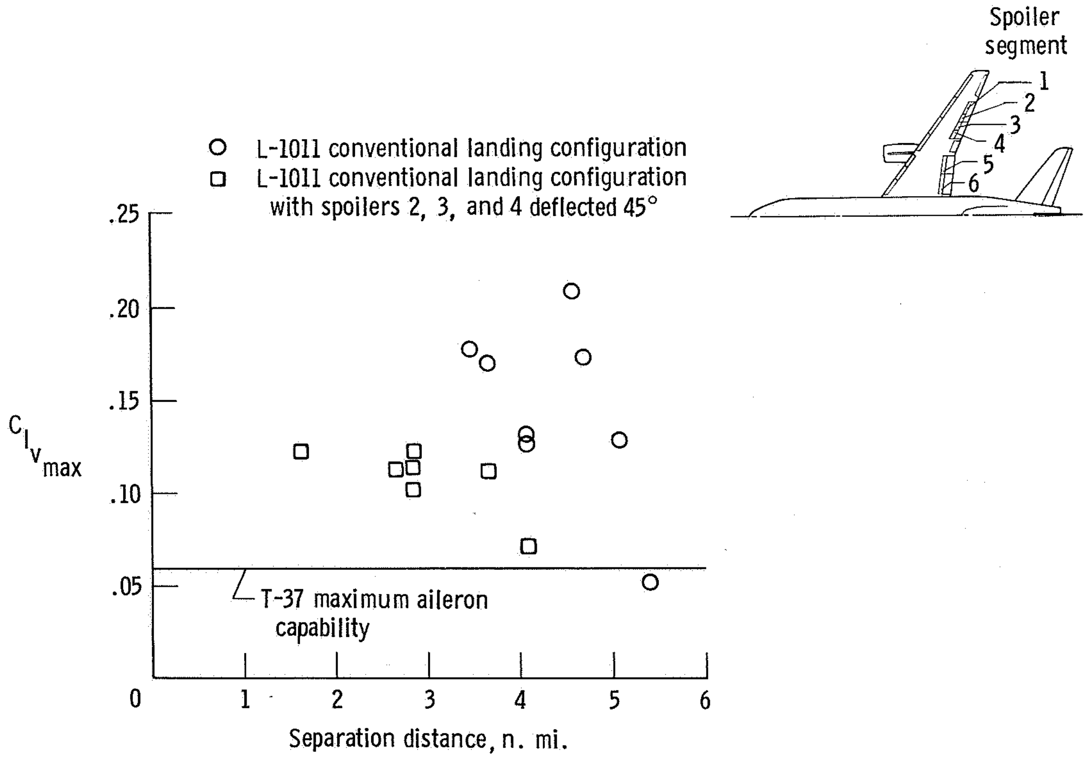


Figure 7. L-1011 wake vortex upset potential for a T-37B probe airplane.

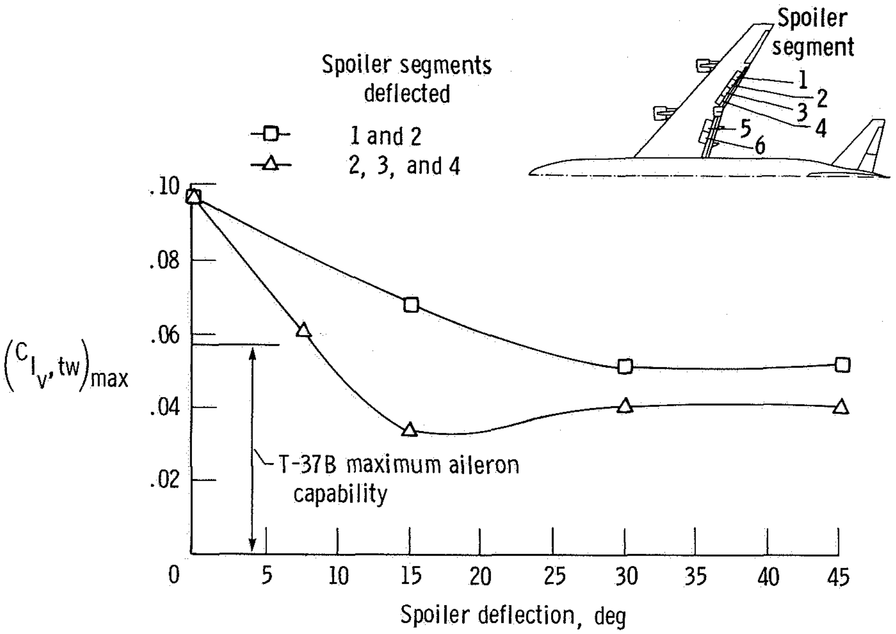


Figure 8. Trailing wing rolling-moment coefficient. B-747 model; gear down; $C_L = 1.2$. LearJet trailing model, 7.8 spans downstream.

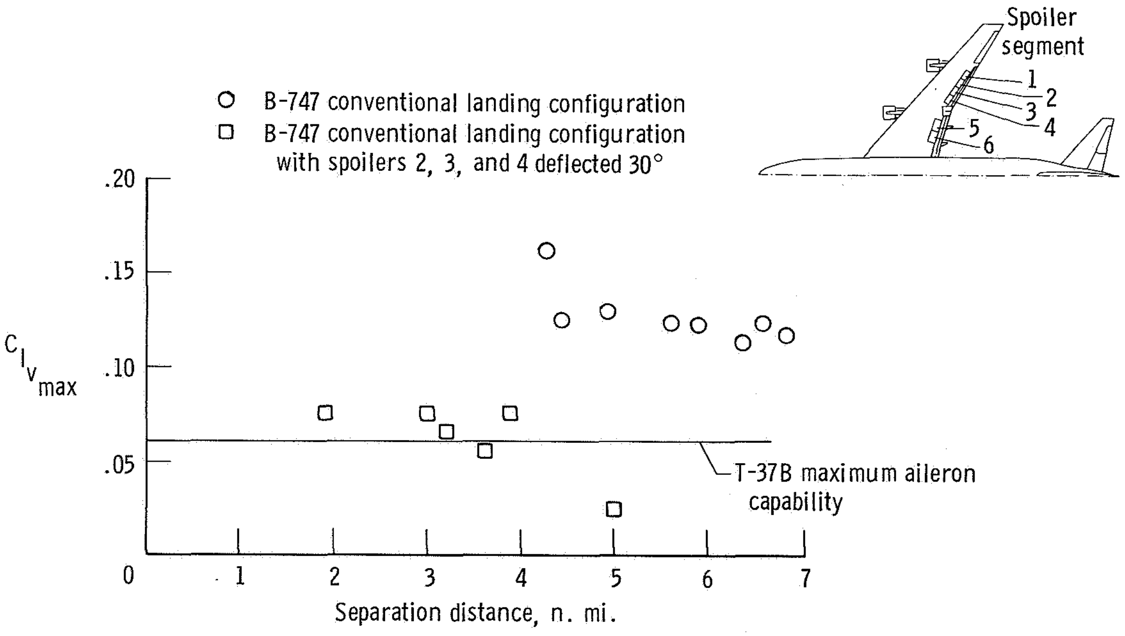
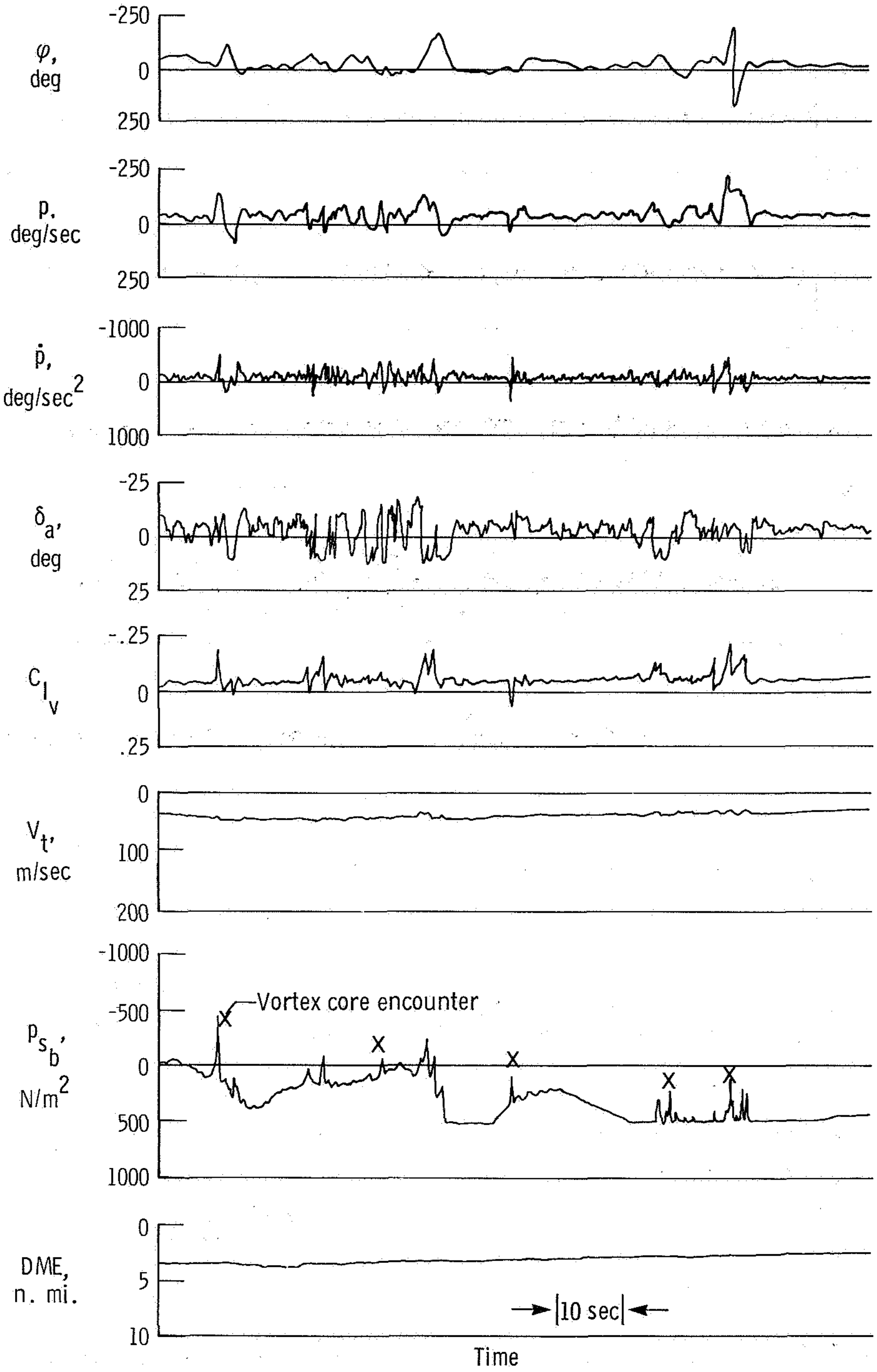
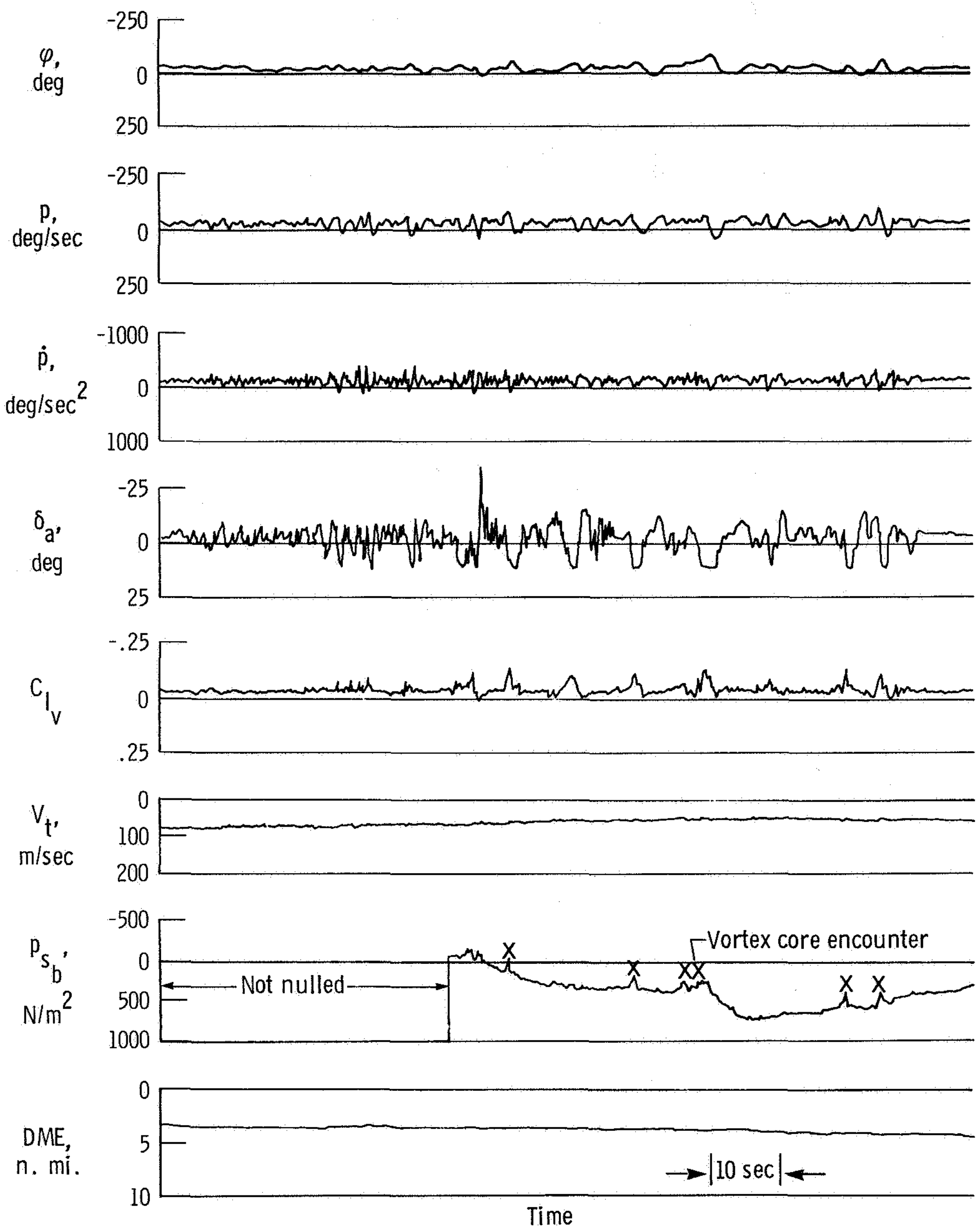


Figure 9. B-747 wake vortex upset potential for a T-37B probe airplane.



(a) B-747 in conventional landing configuration.

Figure 10. T-37B vortex encounter behind B-747 airplane.



(b) B-747 in conventional landing configuration with spoilers 2, 3, and 4 extended 30°.

Figure 10. Concluded.

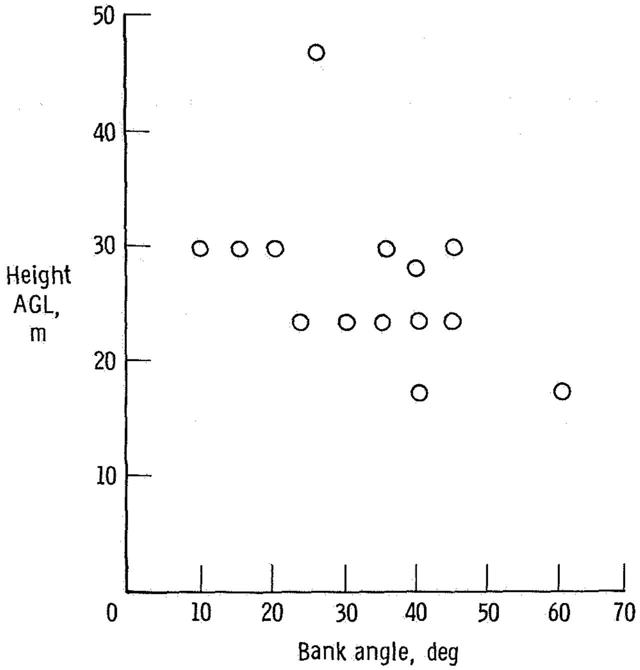


Figure 11. QF-86 bank angle excursions 3 nautical miles behind a spoiler-attenuated B-747 aircraft.

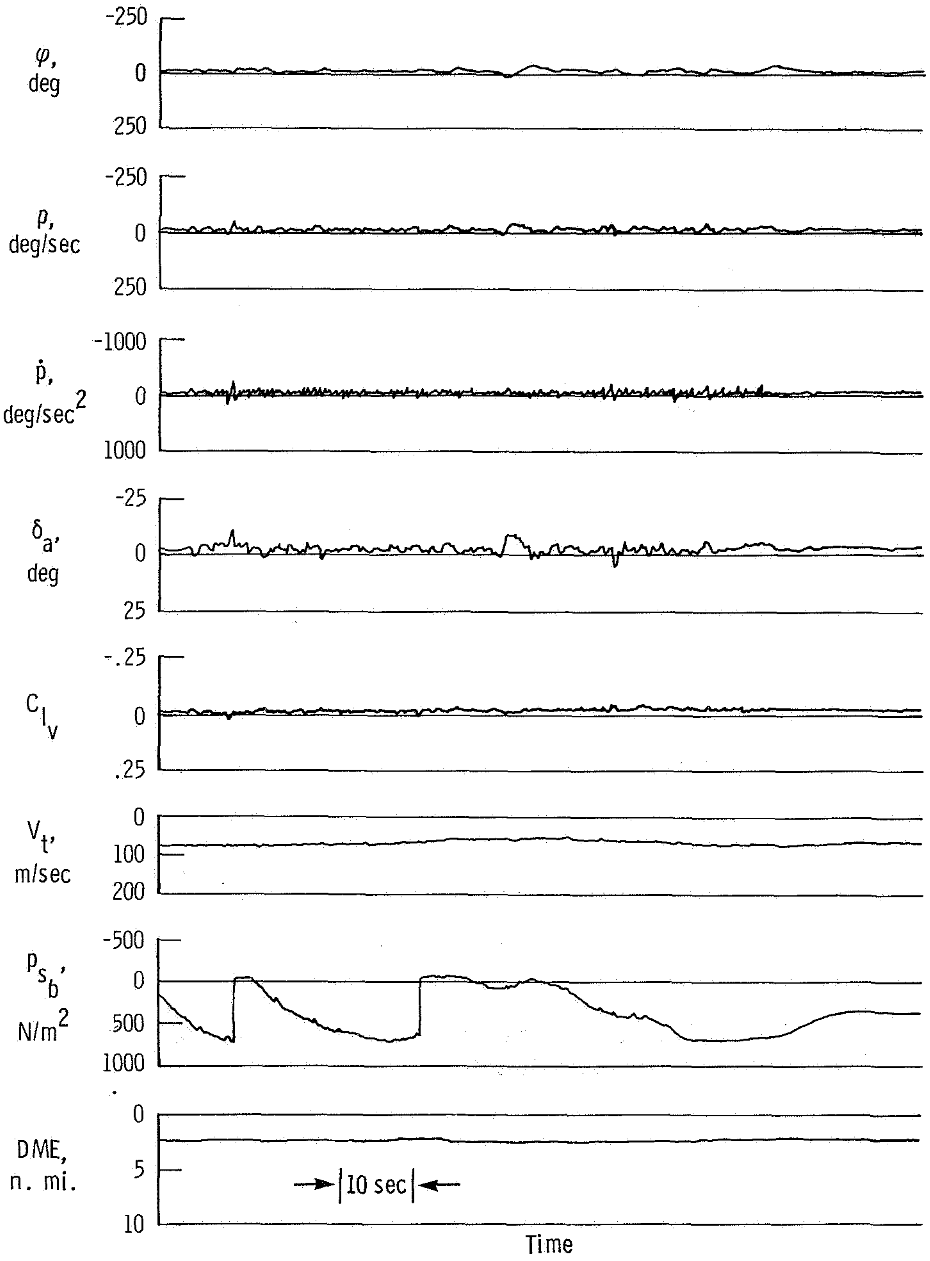


Figure 12. T-37B vortex encounter behind B-747 landing configuration with spoilers 2, 3, and 4 extended 30° and with oscillating ailerons and spoilers.

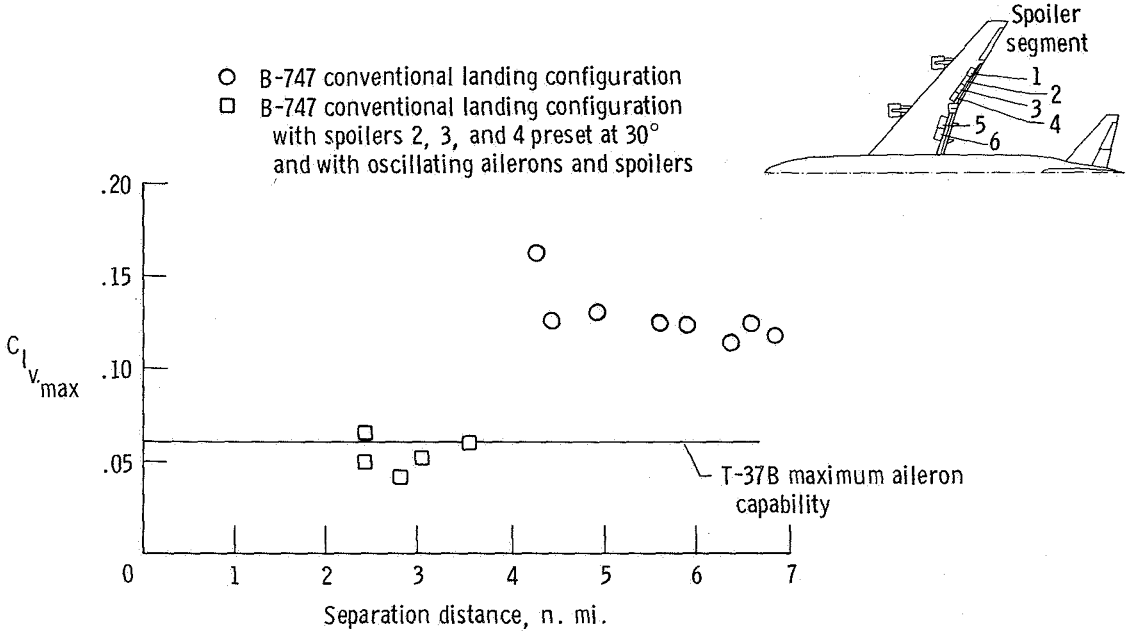


Figure 13. B-747 wake vortex upset potential for a T-37B probe airplane.

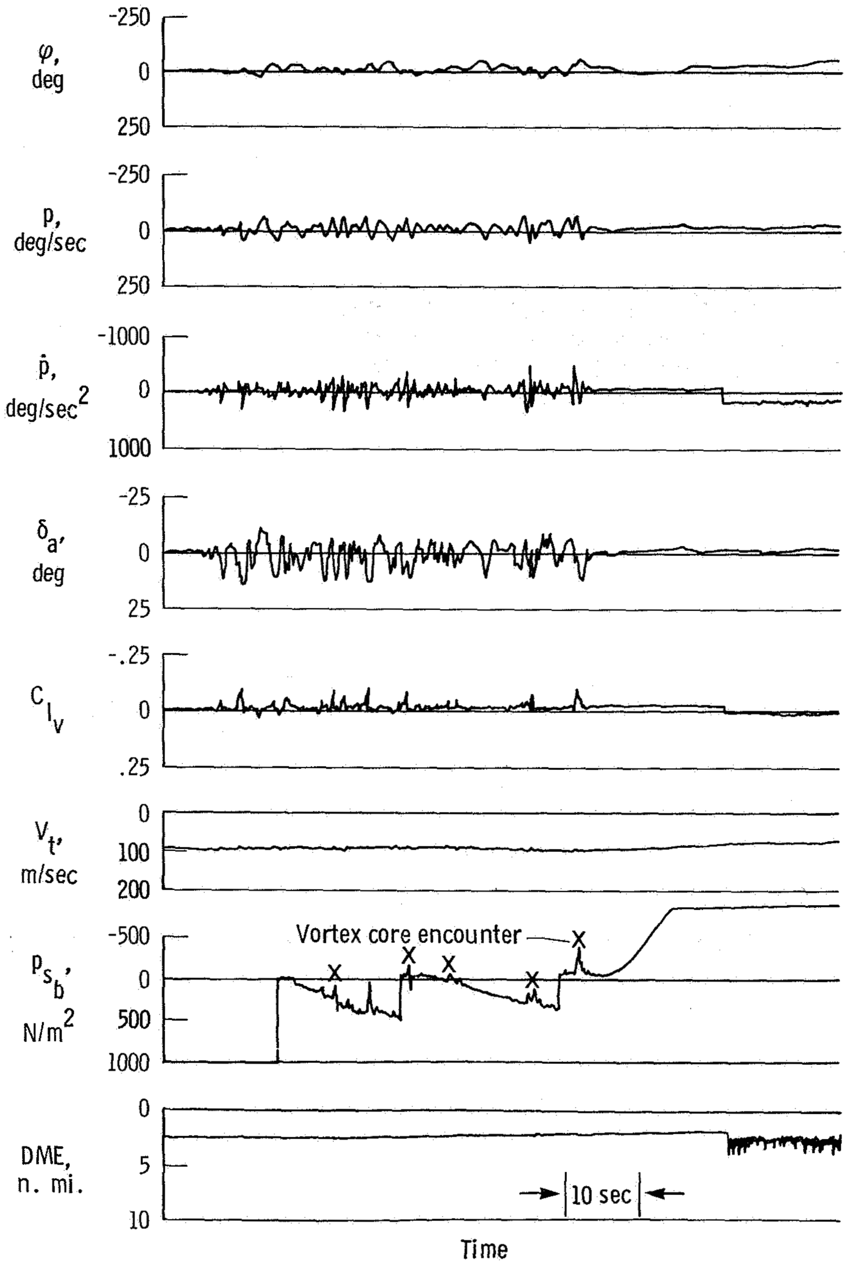


Figure 14. T-37B vortex encounter behind L-1011 landing configuration with spoilers 2, 3, and 4 extended 30° and ailerons and spoilers 2, 3, 4, and 5 pulsing asymmetrically at 2.3 seconds per cycle.