TM X-56031

A FLIGHT TEST INVESTIGATION OF THE ROLLING MOMENTS INDUCED ON A T-37B AIRPLANE IN THE WAKE OF A B-747 AIRPLANE

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(NASA-TM-X-56031) A FLIGHT TEST INVESTIGATION OF THE ROLLING MOMENTS INDUCED ON A T-37B AIRPLANE IN THE WAKE OF A B-747 AIRPLANE (NASA) 23 p HC $3.25 CSCL 01C

N75-20221

Unclas
G3/01 14758

April 1975

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NASA Flight Research Center
Edwards, California 93523

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TM X-56031		

4. Title and Subtitle

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5. Report Date

April 1975

6. Performing Organization Code

7. Author(s)

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8. Performing Organization Report No.

9. Performing Organization Name and Address

NASA Flight Research Center
P. O. Box 273
Edwards, California 93523

10. Work Unit No.

514-52-01

11. Contract or Grant No.

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, D. C. 20546

13. Type of Report and Period Covered

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A flight test investigation of the B-747 vortex wake characteristics was conducted using a T-37B as a probe aircraft. The primary purpose of the program was the validation of the results of B-747 model tests which predicted significant alleviation of the vortex strength when only the inboard flaps were deflected. Measurements of the vortex-induced rolling moments of the probe aircraft showed that the predicted alleviation did occur. Unfortunately, this alleviation could not be fully realized for realistic operations: the effects of landing gear extension, increased lift coefficient, idle thrust, and sideslip were investigated, and all had an adverse effect on the alleviated condition as evidenced by increased induced rolling moments of the T-37B probe aircraft. Idle thrust also increased the strength of the B-747 wake vortexes with both inboard and outboard flaps extended.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Wake vortex Aircraft response	Unclassified - Unlimited Category: 01

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	21	

For sale by the National Technical Information Service, Springfield, Virginia 22151

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INTRODUCTION

The wake vortexes generated by heavy jet transports are of great concern to the aviation community because of the severe safety hazard for following aircraft. Moreover, the separation distances required to avoid the hazard are unacceptable for efficient use of our nation's airports. Reference 1 reviews recent flight test experience with vortex encounters and the responses of following aircraft. Considerable effort is being devoted to finding acceptable solutions to the problems resulting from wake vortexes. These efforts include detection monitoring and avoidance systems (ref. 2), attenuation schemes (refs. 3 to 7), and automatic control systems designed to minimize the aircraft upset (ref. 8).

Encouraging results on wake vortex reduction have been obtained from water channel and wind tunnel tests conducted at the NASA Langley and Ames Research Centers on a model of a B-747 airplane. These tests predicted significant alleviation of the wake vortex strength if greater inboard than outboard flap deflections were used to obtain the same lift coefficient (ref. 7). In August and September of 1974, a flight test program using a T-37B airplane and a Learjet airplane as probe aircraft was conducted at the NASA Flight Research Center to obtain full scale data to validate these results. This report documents the roll response resulting from the T-37B probes.

SYMBOLS

C_L	lift coefficient
C_l	rolling moment coefficient
$C_{l_{\delta_a}}$	lateral-control-effectiveness derivative, per deg

L rolling moment, normalized with respect to maximum control power

P_{ST} static pressure, psi

p rolling velocity, deg/sec

$\dot{p}$ rolling acceleration, deg/sec^2

$\dot{q}$ pitching acceleration, deg/sec^2

$\dot{r}$ yawing acceleration, deg/sec^2

δ_a aileron deflection, deg

φ bank angle, deg

Subscripts:

MAX maximum

T total

V vortex

TEST AIRPLANES

A B-747 airplane was used to generate the vortex wakes in these tests and a T-37B airplane was used as the probe aircraft (fig. 1). Pertinent aircraft physical characteristics are given in table 1. Three smoke generators were mounted on each wing of the generating aircraft to mark the vortexes. The smoke generators were mounted on the wingtips and the outboard edges of both inboard and outboard flaps. The probe aircraft was instrumented to measure total rigid body response.

INSTRUMENTATION

Airspeed, altitude, and the standard handling qualities parameters of the probe aircraft were recorded. Response data were acquired by means of a pulse code modulation (PCM) system, which converts analog signals from standard sensors to digital format and records the digital data on magnetic tape. The data were also telemetered to a ground station for real time monitoring. Angle of attack and angle of sideslip were determined from differential pressure measurements from a boom mounted on the nose of the aircraft. Separation distances between the generating and probe aircraft were measured by means of air-to-air ranging distance measuring equipment (DME). Airplane gross weights were determined from onboard fuel gage readings, which were called out by the pilot.

TEST DESCRIPTION

The test program reported herein consisted of 11 flights. The procedure used in these tests involved having the probe aircraft fly in the visible wake at various separation distances. The pilot kept the probe airplane in the wake as much as possible.

The B-747 flights were made at an altitude of approximately 3 810 meters (12 500 feet) and at airspeeds ranging from 150 knots indicated airspeed (KIAS) to 180 KIAS. The gross weight of the generator aircraft varied from 217 000 kilograms to 272 150 kilograms (480 000 pounds to 600 000 pounds). The generator aircraft configurations investigated are outlined in table 2, along with the objectives for each investigation. The configuration used as the basis for comparison was both inboard and outboard flaps at 30° (30/30 flap configuration), gear up, level flight thrust, and a lift coefficient of 1.2. The other flap configuration investigated was inboard flaps at 30° and outboard flaps at 1° (30/1 configuration). The vortex patterns for the two flap configurations are shown in figures 2(a) and 2(b).

DATA ANALYSIS

An important aspect of any study of the wake vortex problem is an accurate determination of the rolling moments induced by the vortex on the encountering aircraft. Not only is rolling moment a measurement of aircraft upset; it is also useful for assessing the effectiveness of vortex alleviation schemes.

Vortex-induced rolling moments in flight are obtained from measured rolling accelerations. Because of noisy accelerometer outputs, angular accelerations were obtained for these tests from the measured angular rates by means of a differentiating filter. The filter was a second order digital filter and was applied twice to remove the phase lag associated with digital filtering.

A difficulty in determining vortex-induced rolling moments from flight data arises from the fact that the aircraft's response in flight is due to the pilot's control inputs as well as to the vortex-induced moments. To account for the effect of the control inputs, the response of the aircraft to the pilot inputs was calculated by using flight-determined stability derivatives, and these effects were subtracted from the total aircraft accelerations. In this way a time history of vortex-induced rolling moments is determined from which the aircraft upset due to the vortex alone can be calculated. The calculations of induced rolling moment and resulting aircraft response were made by using a six-degree-of-freedom digital program. A detailed description of this analysis is beyond the scope of this paper.

Because of the large quantity of data, it was not practical to compute rolling moment time histories for all the data that were recorded; therefore, a criterion had to be found that would indicate when the probe aircraft was in or near the core of the vortex. Figure 3 presents a sample recording of some of the data that were telemetered to the ground station. It is not obvious from the angular accelerations or rolling velocity exactly where the aircraft enters the vortex; however, the static pressure measurements give a clear indication of a core penetration. Therefore, static pressure measurements were used to determine which data should be further analyzed. Rolling moments were calculated for only those periods where jumps in the static pressure occurred.

DISCUSSION OF RESULTS

The lateral response of the T-37B airplane resulting from deliberate encounters with the vortex wake of a B-747 airplane was investigated for several B-747 configurations. A representative time history of the pertinent roll parameters is shown in figure 4. The encounter shown occurred at a separation distance of 8.1 kilometers (4.4 nautical miles) with the B-747 airplane at a lift coefficient of 1.4 and in the 30/30 flap configuration. The response shown in the figure is the combined result of the vortex-induced moments and the pilot's control inputs.

The rolling moments induced by the vortex on the T-37B airplane were obtained by calculating the roll response due to the pilot's inputs and subtracting this from the total rolling accelerations. Figure 5 shows a time history of the vortex-induced rolling moment and the resulting lateral response calculated for that induced moment for the encounter shown in figure 4. The rolling moment shown in figure 5 is normalized with respect to the maximum rolling moment available from the ailerons. In this example, the rolling moment induced on the T-37B airplane by the B-747 vortex wake is 1.5 times the roll control capability of the aircraft. A comparison of figures 4 and 5 also shows that during this encounter the pilot's control inputs had a slightly adverse effect on the rolling motion. Although this was not usually true, it was not uncommon.

Figure 6, which is based on unpublished data, shows wind tunnel and water channel results predicting an attenuation of the B-747 vortex strength when only the inboard flaps are deflected. The data shown are for a Learjet model probing the wake of a B-747 model at a scaled separation distance of 0.8 kilometer (0.5 mile). At a lift coefficient of 1.2, the strength of the vortex when only the inboard flaps are deflected is predicted to be approximately half that for the conventional (30/30) configuration.

The vortex-induced rolling moments on the T-37B airplane were obtained from flight tests for the purpose of evaluating the effects on the vortex wake of different B-747 flap configurations. A summary of these data for the two flap configurations investigated is presented in figure 7. The rolling moment coefficients, plotted here versus separation distance, are the maximum values obtained at that separation distance plus or minus 100 meters (0.054 nautical mile). Although no data were obtained for both configurations at the same separation distance, the data do appear to substantiate the wind tunnel predictions. These results indicate that significant alleviation is possible with the 30/1 flap configuration. All these data are for the B-747 airplane at level flight thrust, with gear up, and at a lift coefficient of 1.2. The dashed line shown in this figure indicates the maximum roll control power of the T-37B airplane. This parameter has been used as a criterion for determining the minimum safe separation distance, which is assumed to be the distance at which the vortex-induced moments are equal to the maximum rolling moments produced by the ailerons (ref. 9). The pilot's qualitative assessment of separation requirements obtained during these tests and reported in reference 1 are also shown in this plot. The pilot's assessment reflects concern for the total hazard, including the structural safety of the aircraft, and would tend to be conservative.

Figure 8 shows the effect on the B-747 vortex strength of extending the landing gear. The gear up data from figure 7 are repeated for comparison with the gear down data. Extending the gear had no appreciable effect on the wake with the B-747 airplane in the conventional (30/30) configuration; however, rolling moment increased significantly for the alleviated condition (30/1 flap configuration). Pilot opinion confirmed the adverse effect of gear extension.

The effect of thrust on vortex strength was also investigated, and these results are shown in figure 9. The level flight data from figure 7 are repeated again for comparison. Idle thrust for the B-747 airplane corresponds to a rate of descent of approximately 0.6 kilometer per minute (2 000 feet per minute). The vortexes generated by the B-747 airplane were significantly stronger when the engines were idle than when they were at level flight thrust. This was true for both flap configurations, as illustrated in figure 9 by the greatly increased rolling moments measured on the T-37B airplane. The pilot's assessment of separation requirements for the idle thrust configuration also increased.

Figure 10 compares the rolling moment coefficients of the T-37B airplane for the generator aircraft at a lift coefficient of 1.4 with those for the generator aircraft at a lift coefficient of 1.2. Although lift coefficient has little effect on the vortex with the B-747 airplane in the conventional 30/30 flap configuration, the effect on the attenuated vortex (30/1 flap configuration) appears to be significant. These results disagree with the model results shown in figure 6, which show lift to have a greater effect for the 30/30 configuration. The pilots did not report any significant effect of lift coefficient for either configuration.

During the flight program, the pilots of the probe aircraft observed occasional hard spots in the vortex wake behind the B-747 airplane in the 30/1 flap configuration. After the vortex patterns during low altitude flyovers were observed, it was suggested that sideslip, like the extension of the landing gear, might adversely affect the vortex strength. Therefore, the effect of sideslipping the B-747 airplane with the flaps in the 30/1 configuration was investigated. Sideslip did have an adverse effect on the trailing wing vortex (fig. 11). Sideslip is indicated by the pilot's ball and slip indicator, where 1 ball width displacement represents approximately 1.5° to 2° of sideslip on the B-747; therefore, sideslips of as little as 0.5° approximately double the rolling moments induced on the probe aircraft. The pilot's qualitative separation requirement (ref. 1) is shown for 1/4 ball sideslip, and this also indicates a stronger vortex for the sideslipped condition.

CONCLUSIONS

A flight investigation of the B-747 vortex wake was conducted for the purpose of validating the results of wind tunnel and water tank experiments which predicted significant alleviation of the vortex strength when only the inboard flaps were deflected. The two flap configurations investigated were the conventional configuration with both inboard and outboard flaps deflected 30° (30/30) and a configuration with the inboard flaps deflected 30° and the outboard flaps deflected 1° (30/1). The flight program showed that:

(1) The predicted alleviation of the vortex strength for the 30/1 flap configuration did occur for the gear up configuration at a lift coefficient of 1.2 and with level flight thrust.

(2) Extending the landing gear had a detrimental effect on the vortex alleviation due to the 30/1 flap configuration, as evidenced by the increased rolling moments measured on the T-37B airplane. No appreciable effect of landing gear was observed for the conventional configuration.

(3) The vortex-induced rolling moments of the T-37B airplane were significantly higher when the B-747 was at idle thrust. This increase was evident for both the 30/30 and 30/1 flap configurations.

(4) Increasing the B-747 lift coefficient from 1.2 to 1.4 had a pronounced adverse effect on the vortex alleviation effects of the 30/1 flap configuration, but no apparent effect on the vortex for the conventional 30/30 configuration. This finding disagrees with the results of the model tests.

(5) Sideslip angles as small as 0.5° for the B-747 airplane resulted in significant increases in the rolling moments induced on the probe aircraft by the trailing wing vortex when the B-747 airplane was in the 30/1 flap configuration.

Flight Research Center
National Aeronautics and Space Administration
Edwards, Calif., April 7, 1975

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TABLE 1 – AIRCRAFT PHYSICAL CHARACTERISTICS

(a) B-747 generator

Length, m (ft)	70.51 (231.33)
Height, m (ft)	19.33 (63.42)
Wing:	
Area, m^2 (ft^2)	511 (5 500)
Span, m (ft)	59.64 (195.67)
Aspect ratio	6.96
Sweep at quarter chord	37.5
Mean aerodynamic chord, m (ft)	8.33 (27.32)
Incidence angle, deg	2
Dihedral angle, deg	7
Taper ratio	0.356
Control surfaces:	
Rudder area, m^2 (ft^2)	22.9 (247)
Rudder deflection, deg	15
Elevator area, m^2 (ft^2)	32.5 (350)
Elevator deflection, deg	-23 to 17
Aileron area (total), m^2 (ft^2)	20.9 (222)
Aileron deflection, deg –	
Inboard	20
Outboard	-25 to 15
Spoiler area (total), m^2 (ft^2)	30.8 (331)
Spoiler deflection, deg –	
Panels 6 to 8	20
Panels 1 to 4, 9 to 12	45
Trailing edge flap area (total), m^2 (ft^2)	78.7 (847)
Trailing edge flap deflection, deg	30
Leading edge flap area (total), m^2 (ft^2)	48.1 (518)
Weight, kg (lb):	
Empty	158 220 (348 816)
Maximum take-off	322 050 (710 000)

TABLE 1 – Concluded

(b) T-37B probe

Length, m (ft)	8.92 (29.28)
Height, m (ft)	2.80 (9.20)
Wing:	
Area, m^2 (ft^2)	56.05 (183.9)
Span, m (ft)	10.31 (33.83)
Aspect ratio	6.23
Sweep at 22.5-percent chord	0
Mean aerodynamic chord, m (ft)	1.70 (5.58)
Incidence angle, deg	1
Dihedral angle, deg	3
Control surfaces:	
Rudder area, m^2 (ft^2)	0.58 (6.24)
Rudder deflection, deg	25
Elevator area, m^2 (ft^2)	1.08 (11.64)
Elevator deflection, deg	-26 to 15
Aileron area, m^2 (ft^2)	1.05 (11.30)
Aileron deflection, deg	15
Wing flap area, m^2 (ft^2)	1.40 (15.10)
Wing flap deflection, deg	40
Speed brake area, m^2 (ft^2)	0.36 (3.87)
Speed brake deflection, deg	66.07
Weight, kg (lb):	
Empty	1 967 (4 337)
Take-off	3 048 (6 721)
Moments of inertia, kg-m^2 (slug-ft^2):	
Roll (empty)	4 081 (3 010)
Roll (full)	11 301 (8 335)
Pitch (empty)	5 216 (3 847)
Pitch (full)	5 377 (3 966)
Yaw (empty)	8 666 (6 392)
Yaw (full)	16 026 (11 820)

TABLE 2 — B-747 CONFIGURATIONS

Flap deflection, deg		C_L	Gear	Thrust	Sideslip	Object of investigation
Inboard	Outboard					
30	30	1.2	Up	Level flight	0	(Baseline)
		1.2	Up	Idle	0	Thrust
		1.2	Down	Level flight	0	Gear
		1.4	Up	Level flight	0	Lift
30	1	1.2	Up	Level flight	0	Flaps
		1.2	Up	Idle	0	Flaps, thrust
		1.2	Down	Level flight	0	Flaps, gear
		1.4	Up	Level flight	0	Flaps, lift
		1.2	Up	Level flight	1/4 ball	Flaps, sideslip
		1.2	Up	Level flight	1 ball	Flaps, sideslip

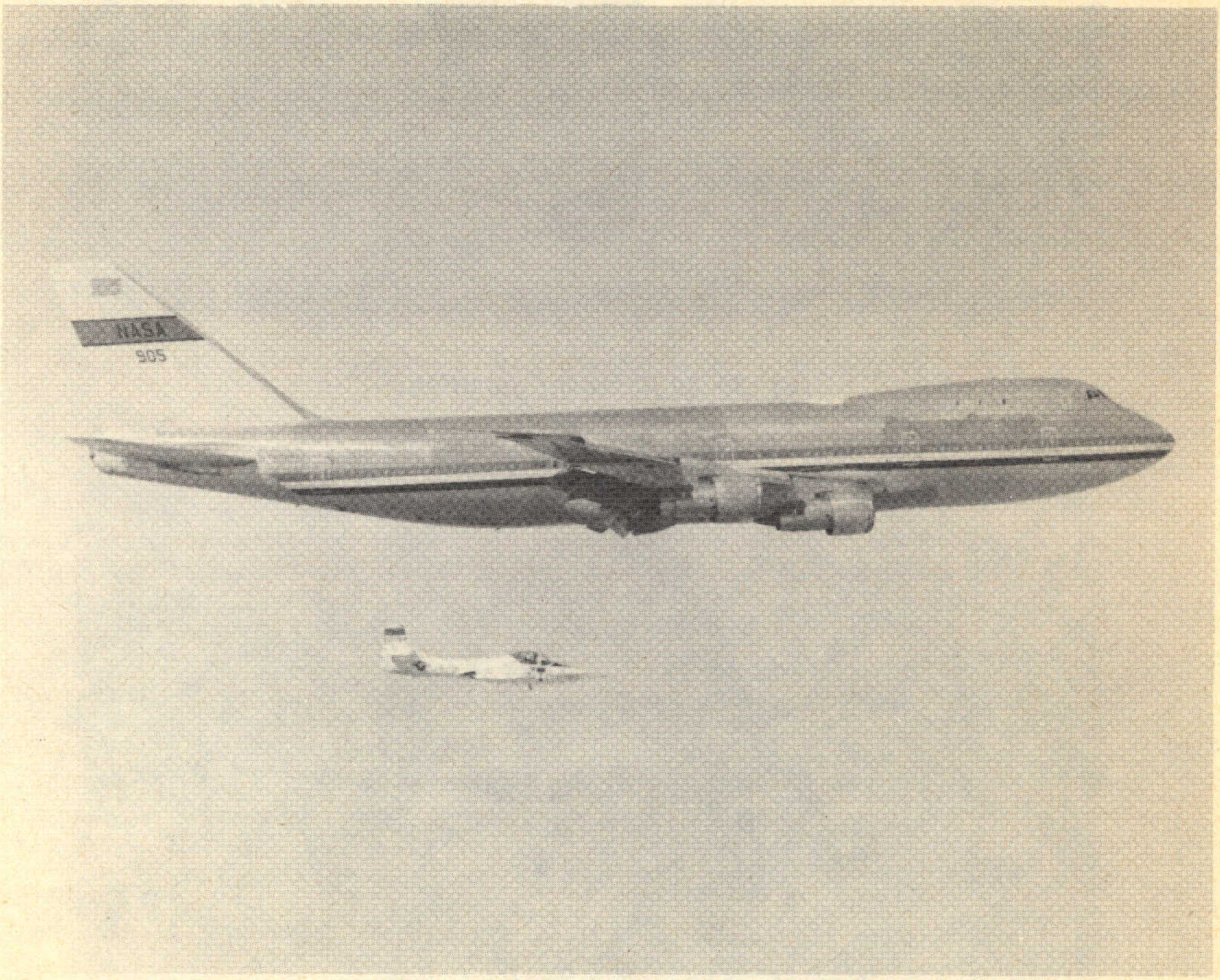
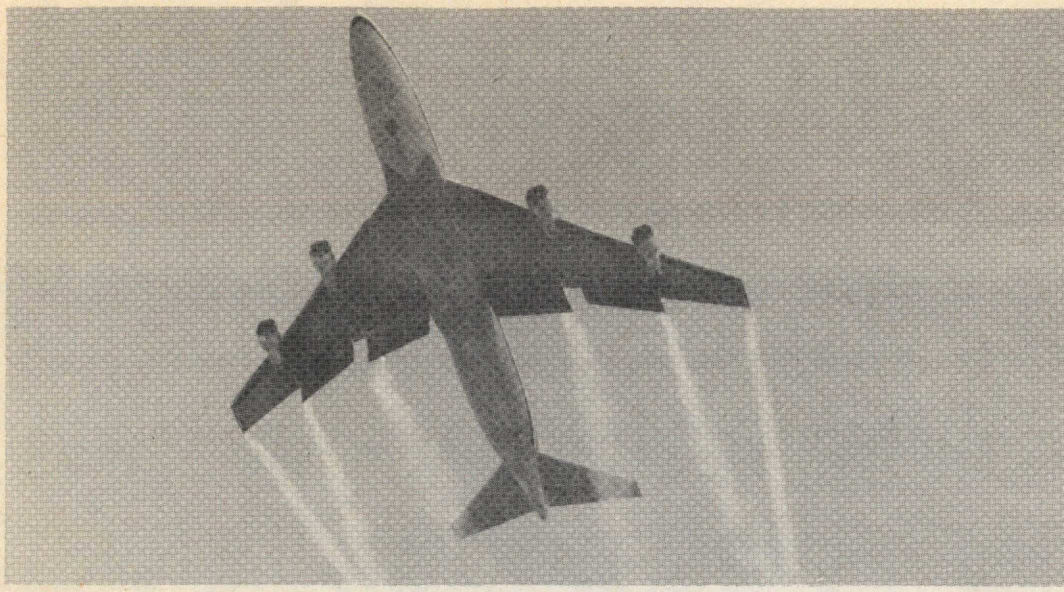


Figure 1. B-747 and T-37B aircraft.



(a) 30/30 flap configuration.

(b) 30/1 flap configuration.

Figure 2. B-747 wake vortex patterns.

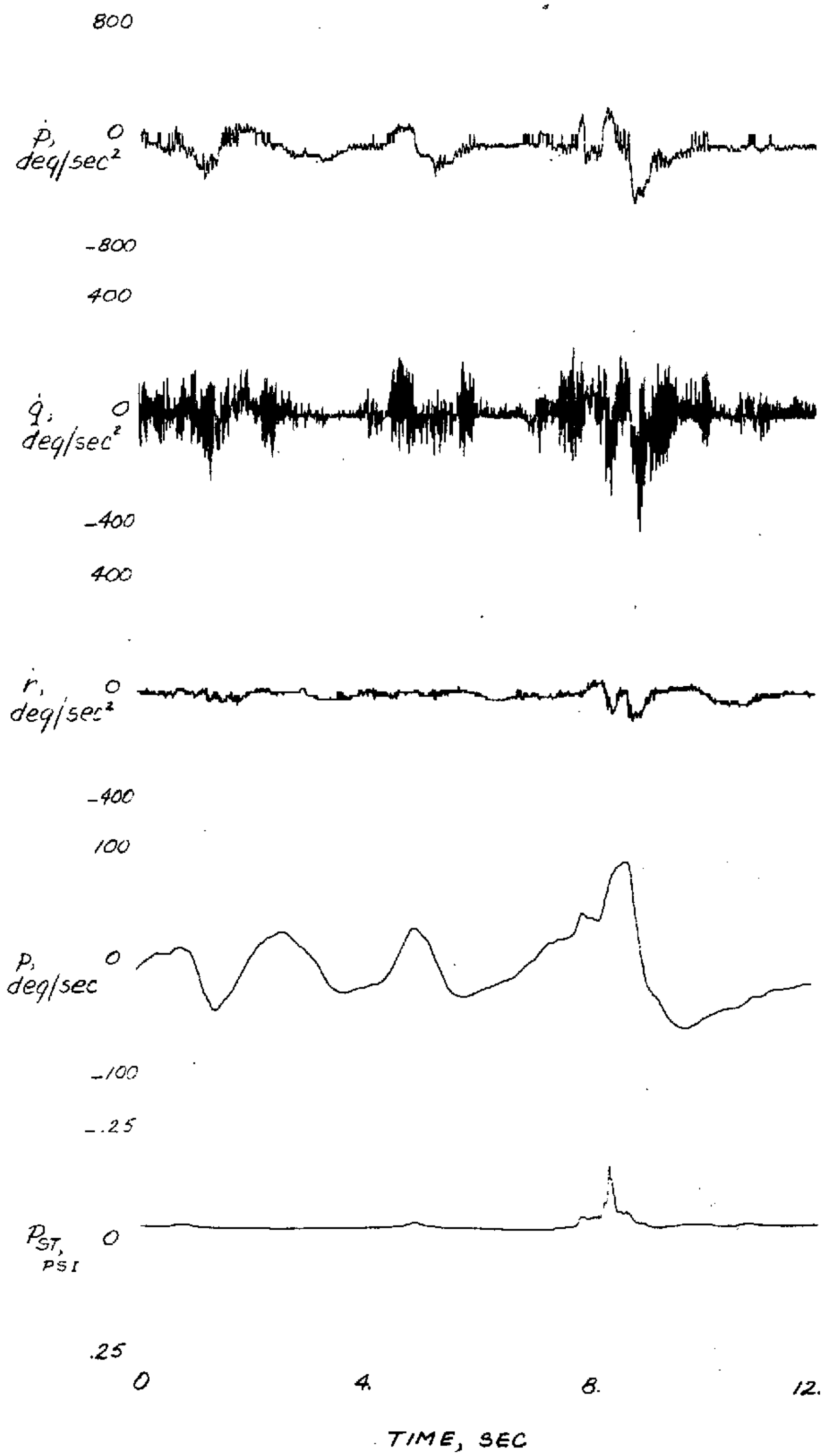


Figure 3. Record of T-37B response during encounter with B-747 wake vortex.

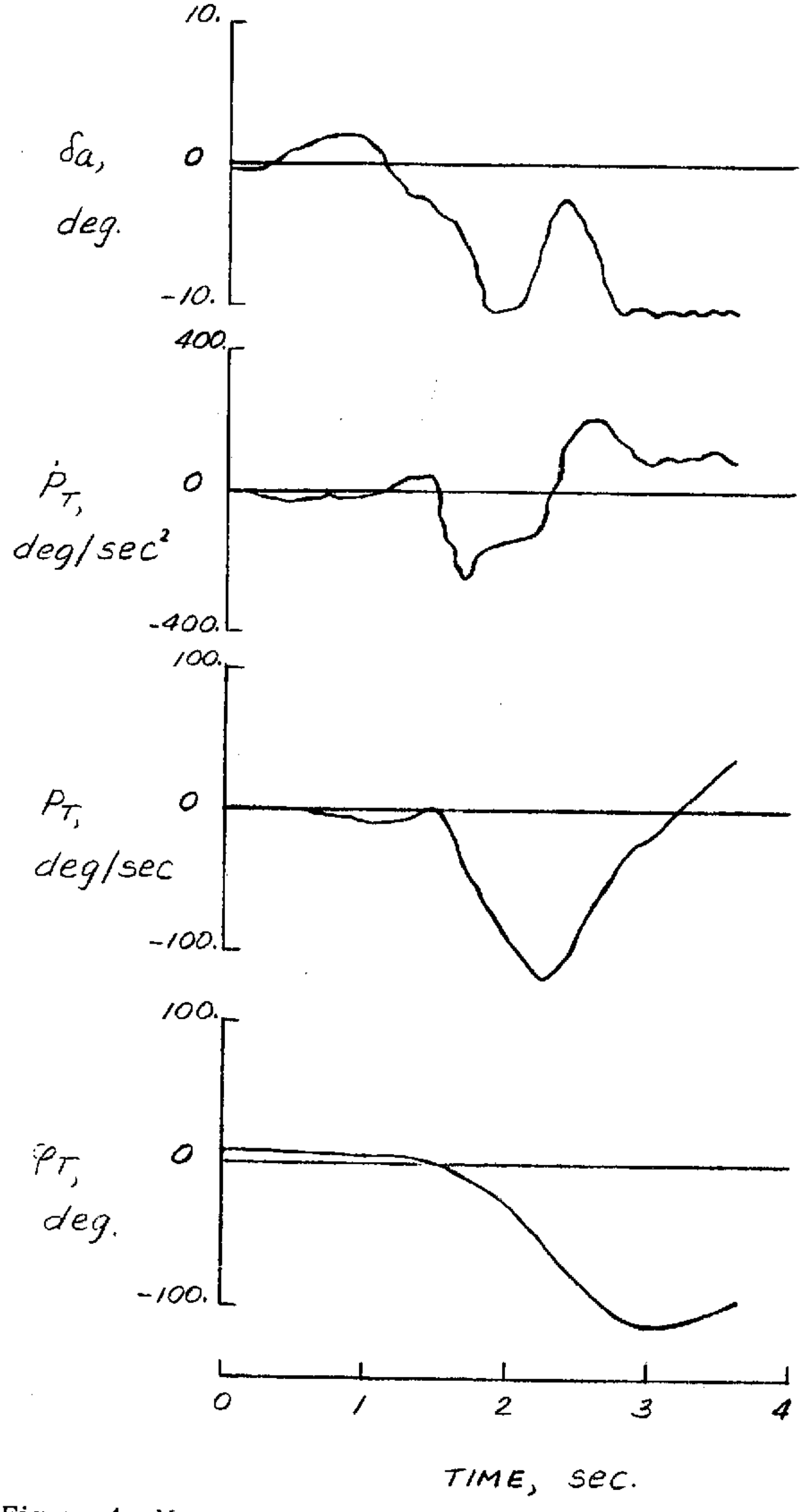


Figure 4. Measured response of T-37B airplane to B-747 wake vortex encounter, including pilot's control inputs.

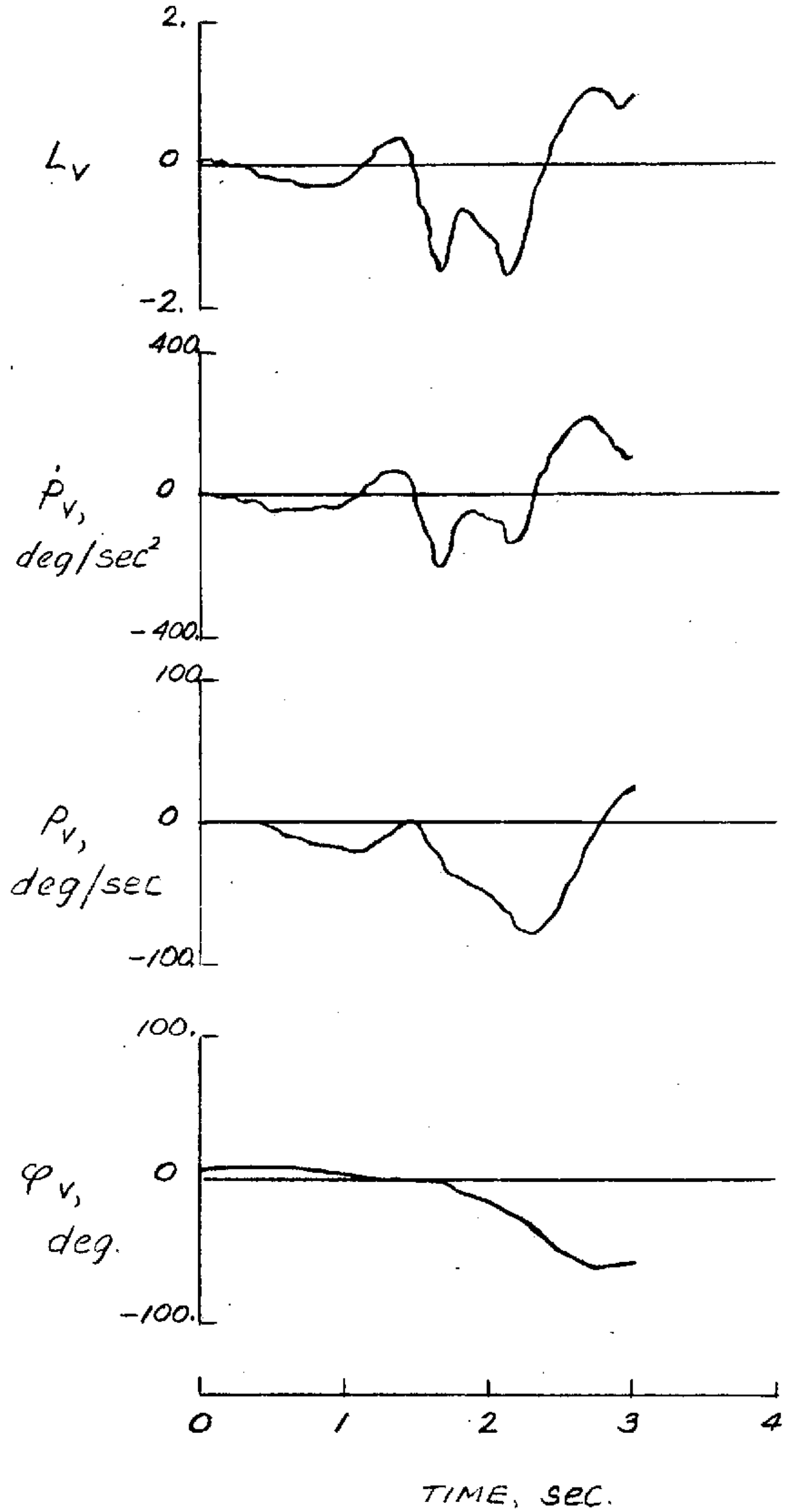


Figure 5. Calculated response of T-37B airplane to B-747 vortex-induced moments.

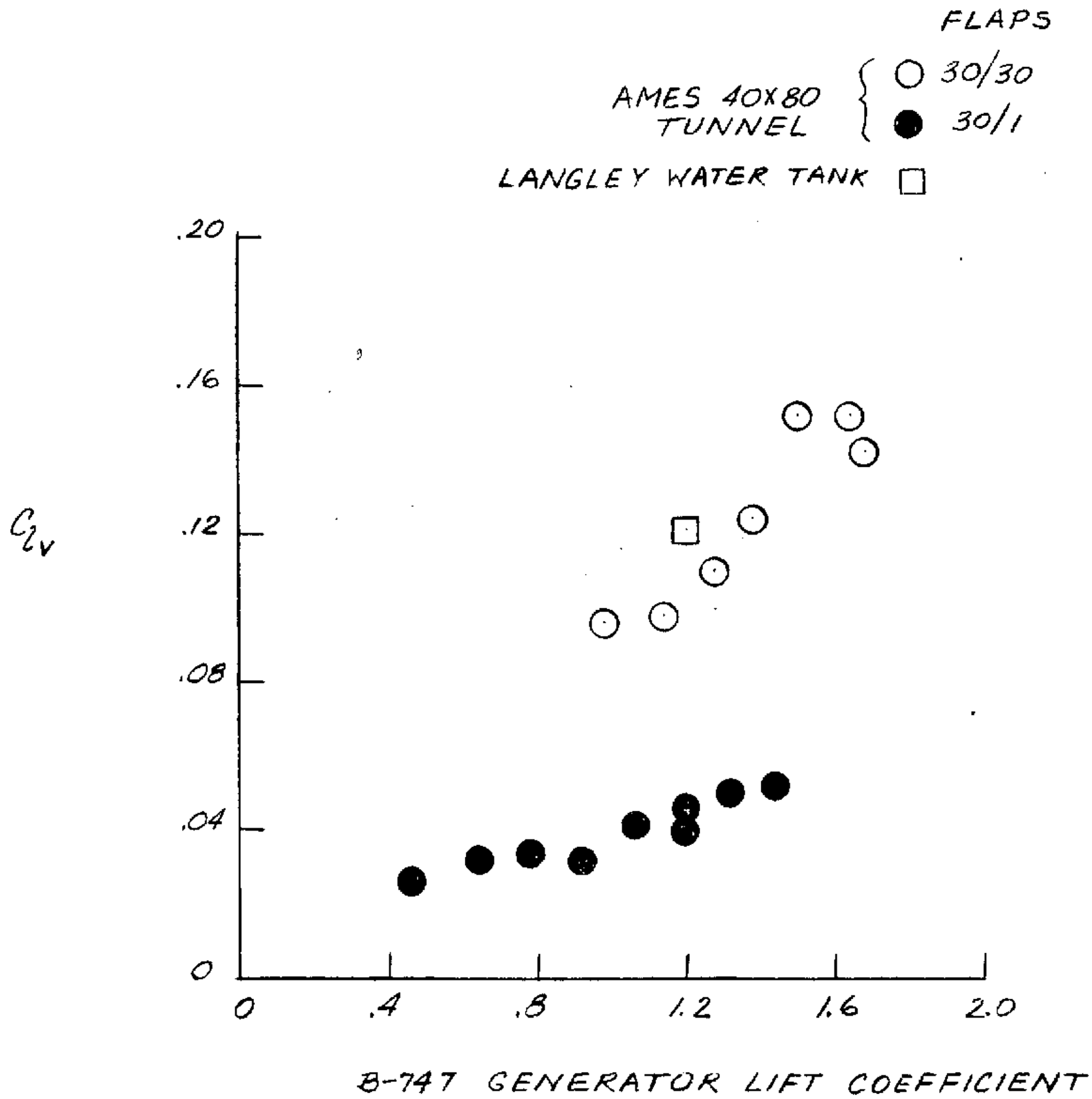


Figure 6. Rolling moment coefficients measured on Learjet model behind model of B-747 airplane at a scaled separation distance of 0.80 kilometer (0.5 mile).

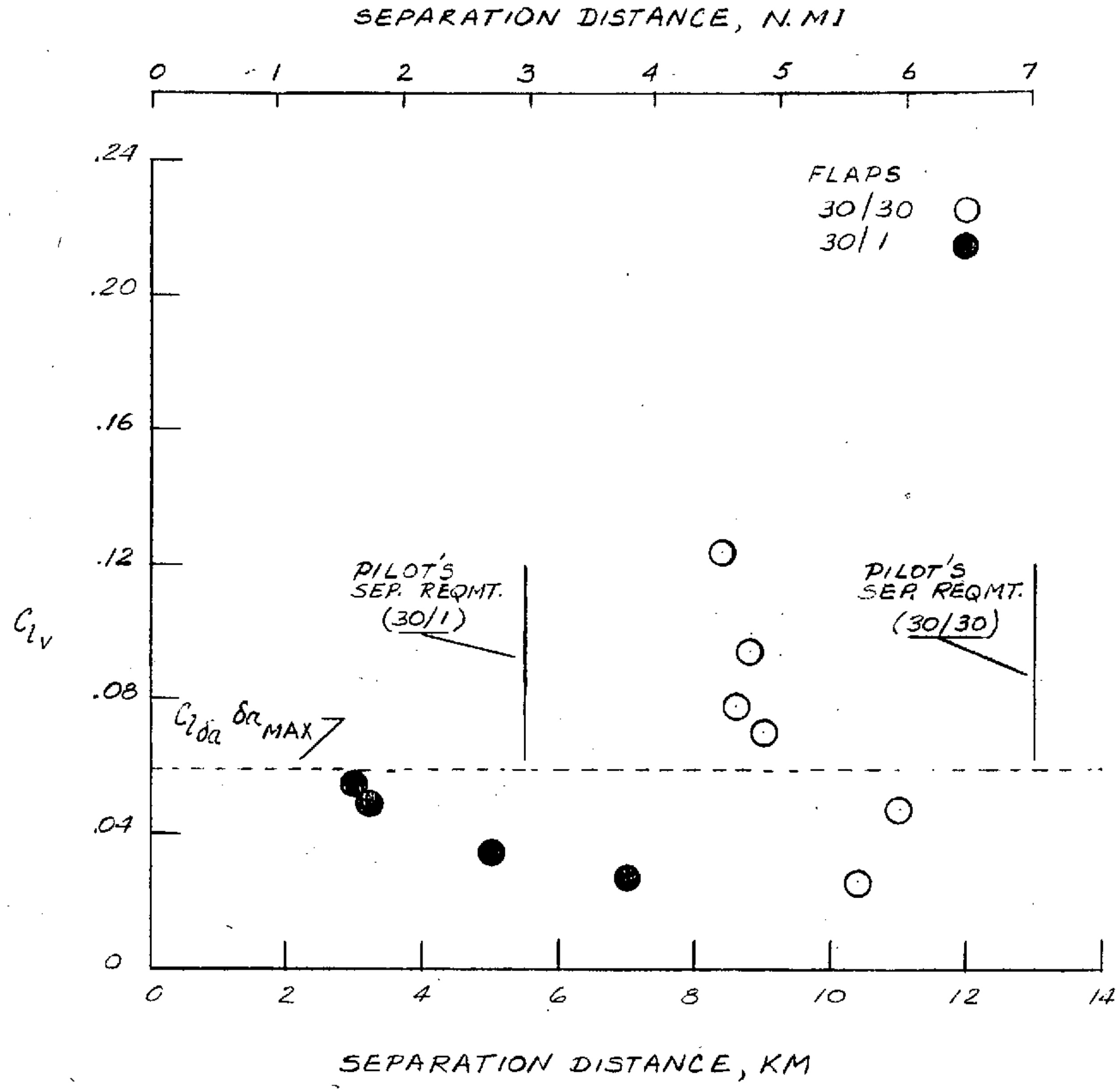


Figure 7. Effect of B-747 flap configuration on vortex-induced rolling moments measured on T-37B airplane.

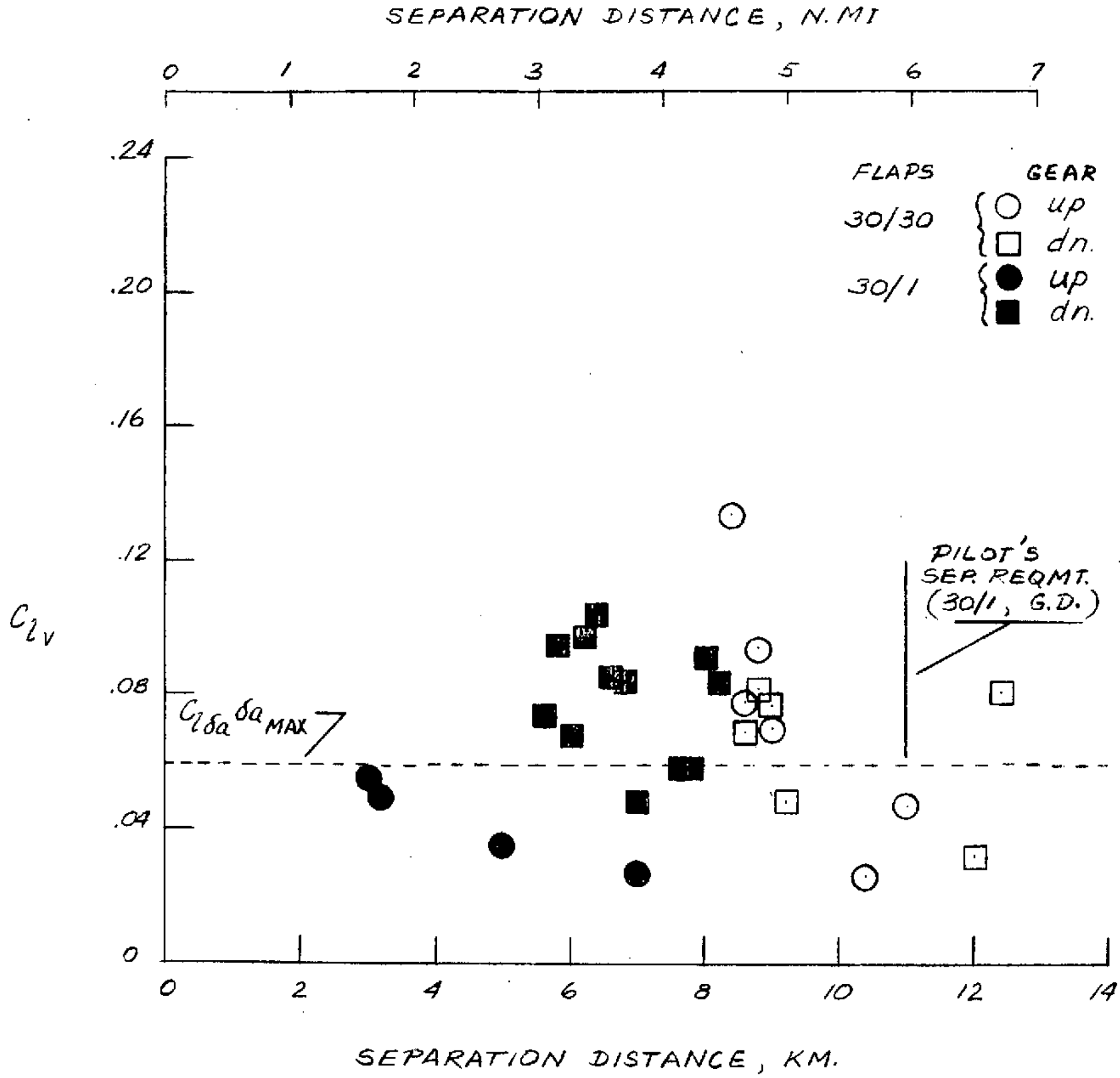


Figure 8. Effect of B-747 landing gear on vortex-induced rolling moments measured on T-37B airplane.

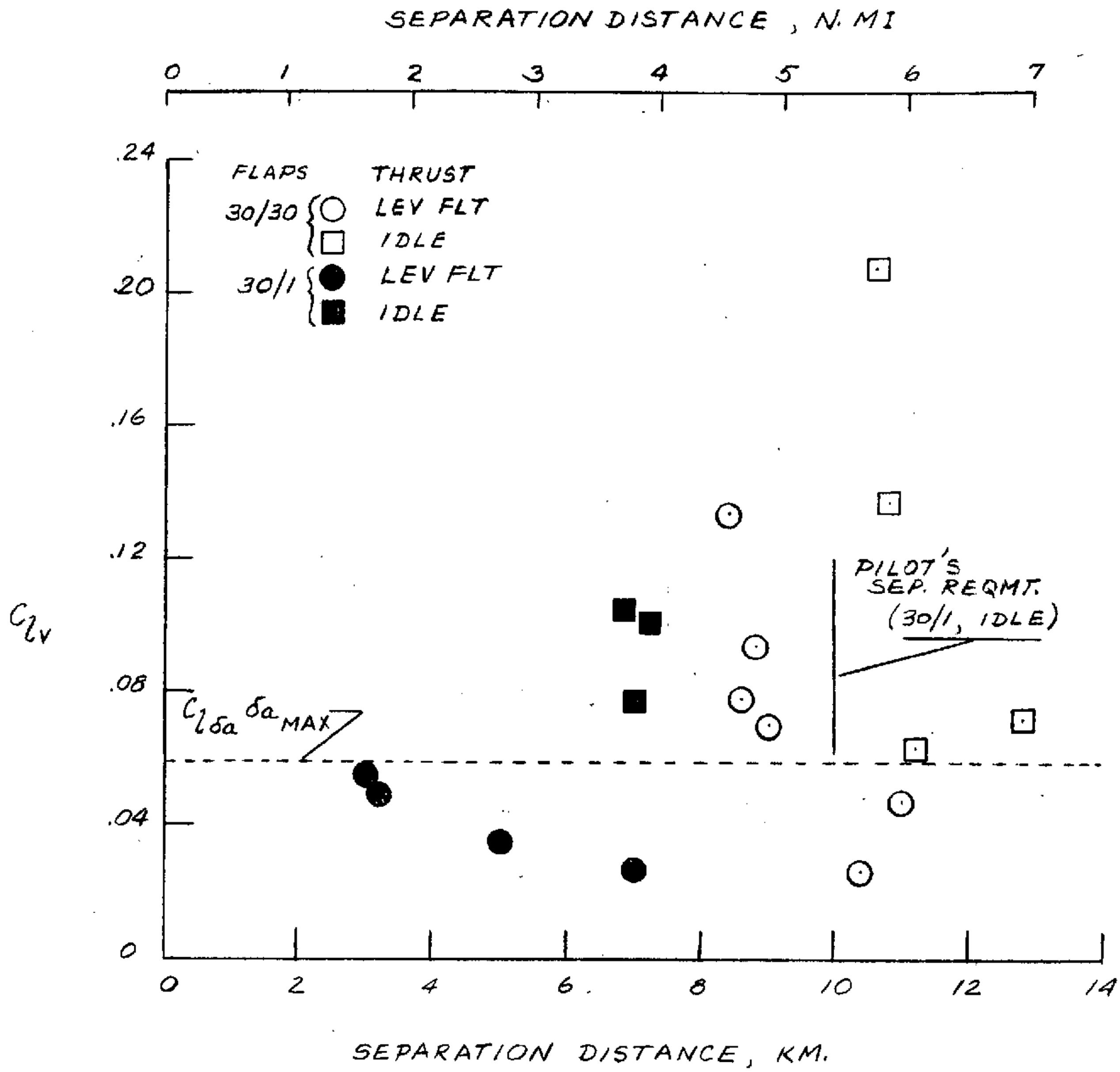


Figure 9. Effect of B-747 thrust on vortex-induced rolling moments measured on T-37B airplane.

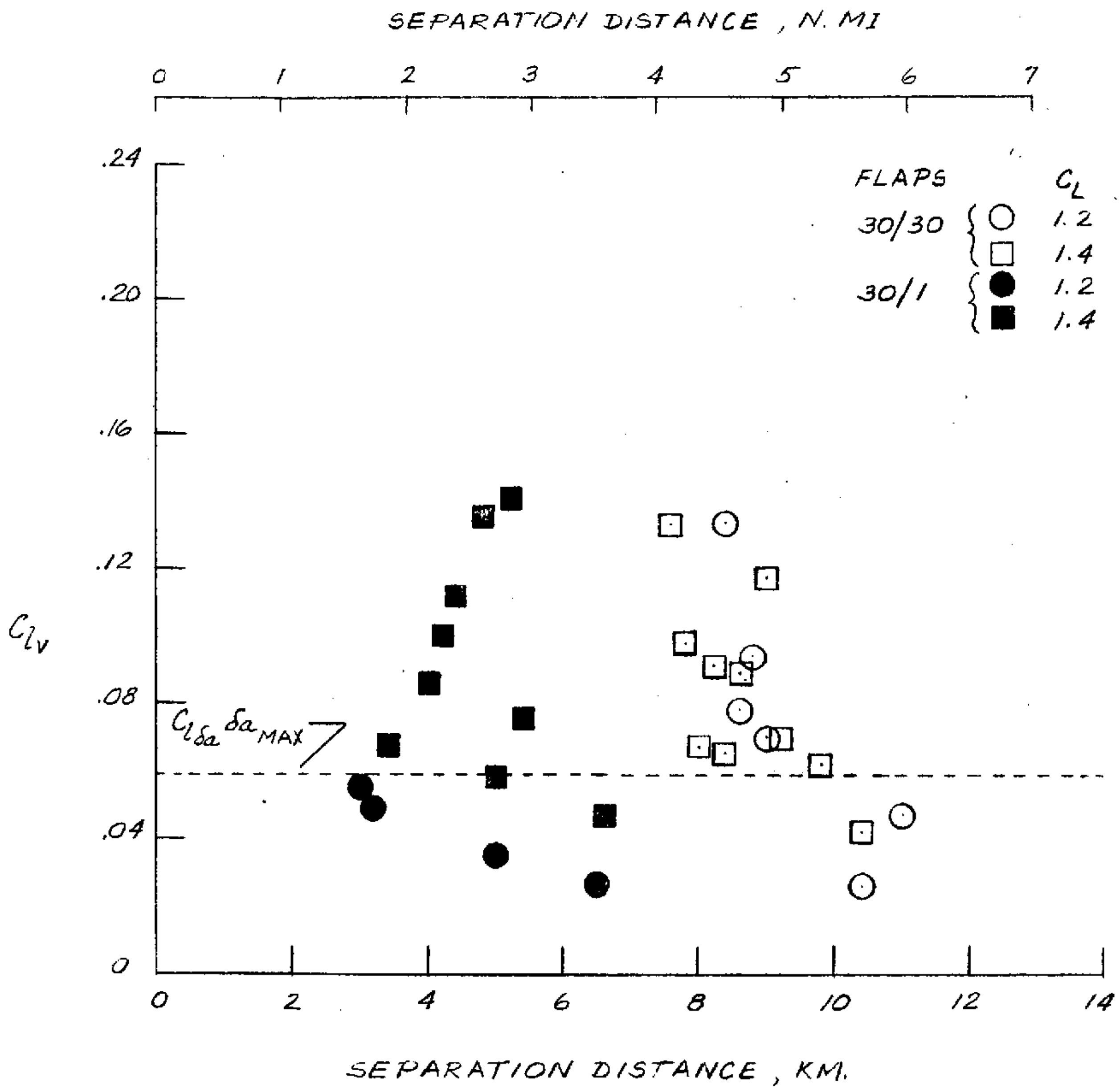


Figure 10. Effect of B-747 lift coefficient on vortex-induced rolling moments measured on T-37B airplane.

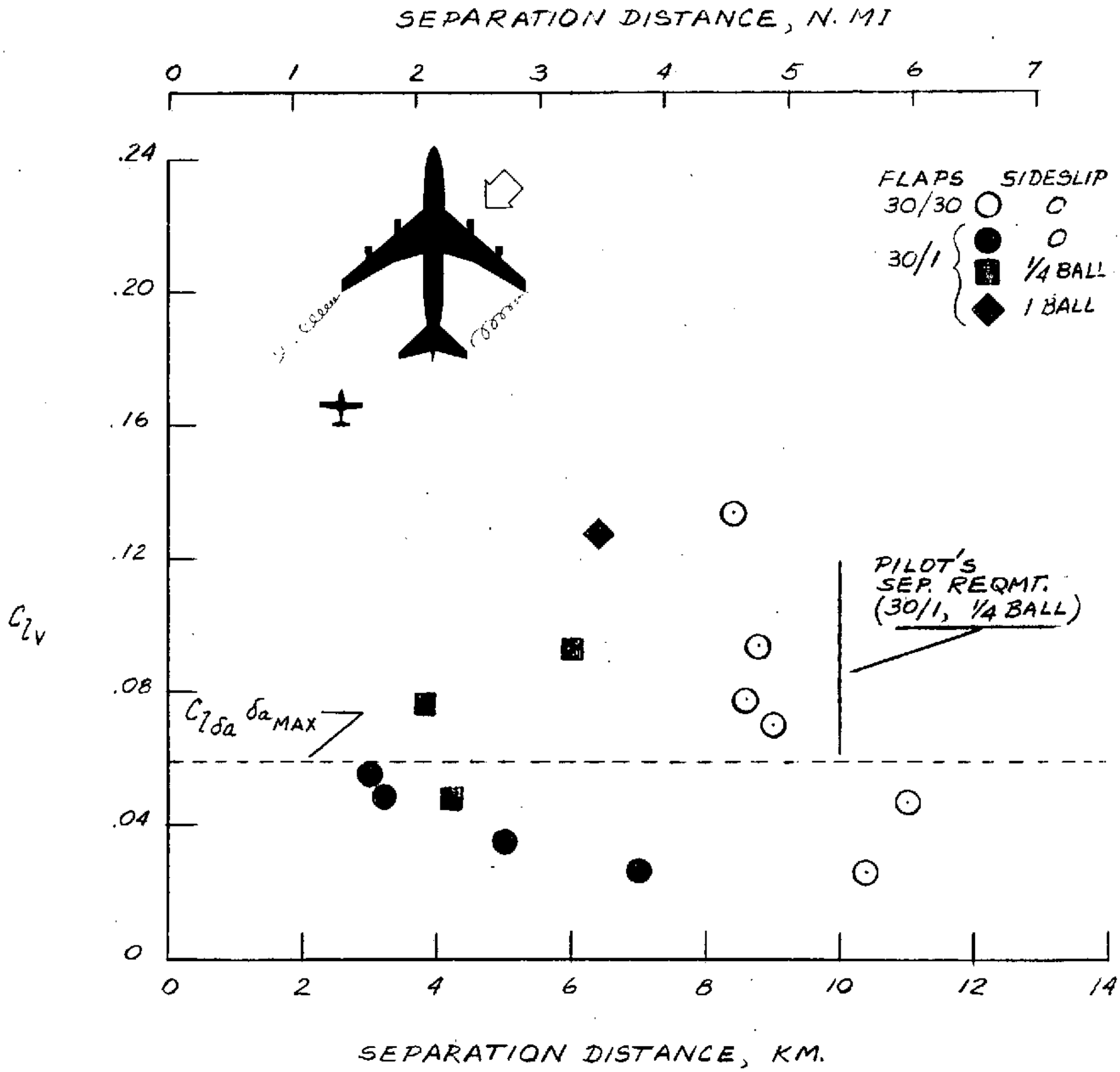


Figure 11. Effect of B-747 sideslip on vortex-induced rolling moments measured on T-37B airplane.