NASA TECHNICAL MEMORANDUM

NASA TM-73,267

(NASA-TM-73267) ESTIMATES OF THE EFFECTIVENESS OF AUTOMATIC CONTROL IN ALLEVIATING WAKE VORTEX INDUCED ROLL EXCURSIONS (NASA) 15 p HC A02/MF A01 CSCL 01C G3/08

N77-30129

Unclas
42009

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ESTIMATES OF THE EFFECTIVENESS OF AUTOMATIC CONTROL IN ALLEVIATING WAKE VORTEX INDUCED ROLL EXCURSIONS

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August 1977

SYMBOLS

K_p	roll rate gain constant
K_D	ratio of elevator angle to wheel deflection
L_p	rolling acceleration due to roll rate
k	fraction of control authority commanded
p	roll rate
$\dot{p}$	roll acceleration
s	Laplace variable
δ_a	aileron angle
δ_{wheel}	wheel deflection angle
τ	actuator time constant

ESTIMATES OF THE EFFECTIVENESS OF AUTOMATIC-CONTROL IN ALLEVIATING WAKE VORTEX INDUCED ROLL EXCURSIONS

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SUMMARY

Estimates were made of the effectiveness of a model following type control system in reducing the roll excursion due to a wake vortex encounter. The estimates were obtained from single degree-of-freedom computations with inputs derived from the results of wind tunnel, flight, and simulation experiments. As might be anticipated, the analysis indicates that the control power commanded by the automatic system must be roughly equal to the vortex induced roll acceleration if effective limiting of the maximum bank angle is to be achieved.

INTRODUCTION

A solution to the wake vortex problem that permits airport capacity to be increased with no reduction in safety is essential to the success of the upgraded third generation air traffic control system proposed for the 1980's (ref. 1). Research is in progress on two different approaches to the problem. One is to develop a wake vortex avoidance system for the terminal approach airspace. Such a system is being developed under the direction of the Department of Transportation. The other approach to the wake vortex problem, finding an aerodynamic means to reduce the hazards, has been the subject of a NASA research program for several years. A number of alleviation techniques has been developed in NASA ground-based research facilities and several have shown sufficient promise to warrant evaluation in flight (see ref. 2).

Estimates of the vortex-induced roll excursions based on flight and simulation results (ref. 3) have indicated that the roll excursions will be large for small aircraft encountering the wake of large jet transports even when the wake has been alleviated to a considerable extent. These estimates assume that control of the encountering aircraft will be manual. The piloted response to a vortex encounter (ref. 4) has been shown to typically consist of a pure time delay on the order of 0.4 sec, followed by a response that commands roll acceleration proportional to perceived roll rate. A considerable reduction in the roll excursion due to an encounter might result if an automatic system were employed to command immediate corrective action. The requirement for such systems in the aerodynamic alleviation scheme would place some of the burden for reduction in wake hazard on the encountering aircraft rather than solely on the generator.

Some computations have been made of the effectiveness of automatic systems in reducing the response to a vortex and are reported in reference 5. These results compared the upsets with and without automatic control systems with no pilot inputs. The current research is an extension of the estimation of roll excursions due to vortex encounters reported in reference 3 to include the effects of automatic control as well as pilot inputs. Estimates are made of the excursions for aircraft that vary in weight from a light twin to a medium jet transport. The aircraft are assumed in each case to be following a large heavy jet transport with a separation of 3 n. mi. The vortex characteristics are assumed to be representative of those measured in flight for a B-747 for the unalleviated case (ref. 2) and equivalent to the best alleviation observed in ground-based facilities for the alleviated case (ref. 6).

The automatic control system used was derived from the state-rate-feedback model follower described in reference 7. This system has the property of following the commanded input, within limits of control power, regardless of external disturbances. Systems were considered that were limited to 30 percent of the control authority, which would permit the pilot to maintain control in the event of an autopilot hardover failure which applies all of the control available. An automatic system having 100 percent control authority power, was also considered. Such systems, of course, require sufficient redundancy in their design to preclude the possibility of spurious commands of full control authority.

ESTIMATION PROCEDURE

Vortex Characteristics

The vortex model was based on the variation of circulation with distance from the vortex center as given by Iversen (ref. 8) and estimates of the large radius circulation as computed from the aircraft span and weight. Definition of the vortex model, therefore, requires values of either the peak tangential velocity or the radius of the vortex core.

The peak tangential velocity for the unalleviated generating aircraft is assumed to be that given by the data for a B-747 with landing flaps given in reference 3. For the unalleviated case, the vortex is assumed to be equivalent to that causing a rolling moment coefficient of 0.04 to be imposed on a rectangular wing having a span of 17 percent of the generating aircraft. Reduction of the vortex-induced rolling moment to this level has been observed in wind-tunnel tests and is reported in reference 6. The peak tangential velocity corresponding to this rolling moment was estimated from strip theory according to the method described in reference 2.

For the calculations, the large radius circulation of the vortices shed by the generating aircraft was estimated to be 528 m^2/sec (5680 ft^2/sec) which corresponds to that for an elliptical span load distribution for an aircraft with the span of a B-747 which weighs 2.18×10^6 N (0.49×10^6 lb).

For this circulation and no aerodynamic alleviation the peak velocity, according to the results presented in reference 3, will be 20.4 m/sec (67 ft/sec). With aerodynamic alleviation, the peak velocity will be reduced to 4.5 m/sec (14.7 ft/sec). The corresponding core radii are 1.6 m (5.4 ft) and 7.5 m (24.6 ft).

Estimation of Piloted Response to a Vortex Encounter

The response to a vortex encounter was estimated by the method reported in reference 3. The maximum bank angles estimated by this method correspond to a worst case situation where the aircraft is exposed to the maximum impulse that would be expected to occur on the basis of analysis of flight test results from intentional encounters. The rolling moment in each case was estimated by the strip theory method described in reference 2. This method does not take the possibility of local stalling into account. Therefore, the estimates for encounters with the wake when no aerodynamic alleviation is employed will be somewhat high, particularly for the smaller aircraft. The model of the pilot's response was derived from the results of piloted motion simulation and is reported in reference 4.

The automatic control system chosen was of the state-rate implicit model following type. Details of the philosophy underlying the design of this system are given in reference 7, and a block diagram of the specific system considered in this study is shown in figure 1. A roll rate command system was used, and the roll damping parameter, K_p, was selected to be identical with the aerodynamic roll damping. The response to a roll command was therefore identical whether or not the automatic system was in use. This is illustrated in figure 2 where the response to a wheel input is shown to be the same providing $K_p = L_p$. For widely differing values of L_p small differences in response of the automatic system are evident.

Calculations were made for both a full and limited authority automatic system. For the limited authority system, it is assumed that the control system commands a separate surface with mechanical stops. Examples of typical calculations for the case where the imposed vortex acceleration equals the aircraft control power are shown in figure 3 for the case of no automatic system, a system with 30 percent authority, and a system with 100 percent authority. The advantage of the automatic system in imposing the nearly maximum aileron control authority available within several tenths of a second is evident compared to the pilot time delay and subsequent response proportional to perceived roll rate.

Encountering Aircraft

Four encountering aircraft were considered which ranged from a light twin to a medium sized jet transport. Characteristics of these aircraft pertinent to the calculations are given in table 1. The aircraft characteristics shown were taken from mathematical models of these aircraft obtained for piloted simulation by NASA.

EFFECTIVENESS OF AUTOMATIC CONTROL SYSTEM

Typical responses, in terms of maximum bank angle, to vortex-induced roll acceleration is shown in figure 4. The automatic system maintains the maximum bank angle to only a few degrees providing the control authority is not less than the magnitude of the disturbance. As would be expected, when the disturbance exceeds the control authority, further increase produces increases in bank angle at approximately the same rate as for a manual system.

The estimated response of the aircraft considered to encounters with the wake of a B-747 at 3 n. mi. is shown in figure 5. The estimated maximum bank angle for both the alleviated and unalleviated wake vortex are shown for cases where the roll control of the encountering aircraft was unaugmented, or augmented with a system that could command either 30 percent or 100 percent of the control authority. The maximum bank angles can be compared to several criteria that have been proposed. The most stringent criterion was developed from the results of a piloted moving-base simulation that is reported in reference 9. This criterion indicates that the bank angle should be limited to about 8°. The criterion is conservative in that the bank angle boundary was drawn to separate all simulated encounters into nonhazardous and possibly hazardous regions. Thus no encounter considered to be hazardous by any of the pilots participating in the study resulted in a bank angle less than the criterion, while the bank angle for many encounters judged to be nonhazardous exceeded the criterion. A maximum bank angle of 18° is stated as a preferable criterion by the authors in reference 10. This criterion was also developed from piloted simulation and was determined on the basis of a piloted rating scale concerned with maintaining control during the encounter. The criterion is based on an averaging of ratings rather than on "worst case" considerations as in reference 9.

Comparison of the bank angle estimates shown in figure 5 with either bank angle criterion indicates that automatic control does not provide a sufficient reduction in the roll excursion when no aerodynamic alleviation device is used on a large heavy generating aircraft. The only case where the maximum bank angle lies within the 18° boundary is for the heaviest encountering aircraft considered. The reason for the inability of the automatic system to reduce the bank angle is obviously that the vortex-induced rolling exceeds the available roll control power (see table 1). The use of automatic control alone, therefore, holds little promise for reducing aircraft separations to 3 n. mi.

If aerodynamic alleviation is feasible to the level assumed, considerable reduction in the maximum bank angle occurs. The maximum bank angle for the heaviest encountering aircraft considered is shown to be within the 18° bank angle boundary. The level of the vortex-induced rolling moment is roughly equal to the available control power for the business jet (LEAR 23) and less than the control power for the heavier aircraft. For this situation, a 100 percent authority automatic system is effective in limiting the bank angle to 5° or less. For the 30 percent authority system, the control power available to the automatic system is, of course, exceeded by the disturbance. However, sufficient reduction in maximum bank angle is obtained by the limited authority system to limit the bank angle to 18° or less for the three aircraft.

The vortex induced rolling moment exceeds the control power of the light twin (PA-30) by a factor of about 2 even for the assumed level of aerodynamic alleviation. However, there is some experimental evidence that suggests that the bank angle estimation procedure employed does not apply to light aircraft. The PA-30 has roughly one-third of the weight and moment of inertia of the LEAR-23, nearly the same span, and a slightly smaller wing area. For the assumptions used in the estimation procedure, therefore, the PA-30 is indicated to experience roughly three times the rolling acceleration of the LEAR-23 when subjected to the same vortex (see table 1). However, the experimental results available do not support these estimates. In reference 11, results are reported of intentional encounters of both the LEAR-23 and the PA-30 with the wake of a medium jet transport. The data indicate that the maximum roll acceleration was nearly the same for both aircraft. A possible explanation for the apparent discrepancy between the estimates and experiment is that the lighter aircraft might not have enough linear momentum to penetrate to the center of the vortex in the presence of the normal and side forces generated by the vortex flow field. The assumption in the estimates was based on analysis of the flight records from the LEAR-23 which indicated that the maximum impulse imparted was equivalent to the aircraft being centered in the vortex of 1 sec. This impulse obviously cannot be imparted to the light aircraft if normal and side forces imposed prevent it from getting close to the core. It is concluded that the simplified analyses upon which the estimation is based is not adequate for light aircraft. Conclusions concerning these aircraft should be based on six degrees-of-freedom calculations of entry into the vortex flow field so that the effects of lateral and vertical motion relative to the vortex core can be included. Additional piloted simulation may also be required to determine acceptable bounds on flight path excursions as well as bank angle excursions for these light aircraft.

CONCLUDING REMARKS

Estimates of the effectiveness of automatic control in reducing the maximum bank angle due to a wake vortex encounter have been made. The estimates were obtained from single degree-of-freedom computations with inputs derived from flight, and simulation results. As might be anticipated, the analysis indicates that the available control power must be roughly equal to the vortex-induced rolling acceleration if effective limiting of the maximum bank angle is to be achieved.

REFERENCES

1. Israel, David R.: Air Traffic Control: Upgrading the Third Generation. Tech. Review, vol. 77, February 1975, pp. 14-24.

2. Jacobsen, Robert A.; and Short, Barbara J.: A Flight Test Investigation of Wake Turbulence Alleviation Techniques on a B-747 Aircraft. NASA TM-73,263, 1977.

3. Tinling, Bruce E.: Estimation of Vortex-Induced Roll Excursions Based on Flight and Simulation Results. Proceedings of the DOT Aircraft Wake Vortices Conference, Cambridge, Mass., March 15-17, 1977.

4. Johnson, Walter A.; and Meyers, Thomas T.: A Model for Human Pilot Behavior During Wake Vortex Encounter Upsets. Report No. FAA-RD-76-8, 1976.

5. Johnson, Walter A.; Teper, Gary L.; and Rediess, Herman A.: Study of Control System Effectiveness in Alleviating Vortex Wake Upsets. AIAA J. of Aircraft, vol. 11, no. 3, 1974, pp. 148-154.

6. Rossow, Vernon J.: Effect of Wing Fins on Lift-Generated Wakes. AIAA Paper 77-671, June 1977.

7. Merrick, Vernon K.: Study of the Application of an Implicit Model-Following Flight Controller to Lift-Fan VTOL Aircraft. NASA TP, 1977.

8. Iversen, James D.: Correlation of Turbulent Trailing Vortex Decay Data. AIAA J. of Aircraft, vol. 13, May 1976, pp. 338-342.

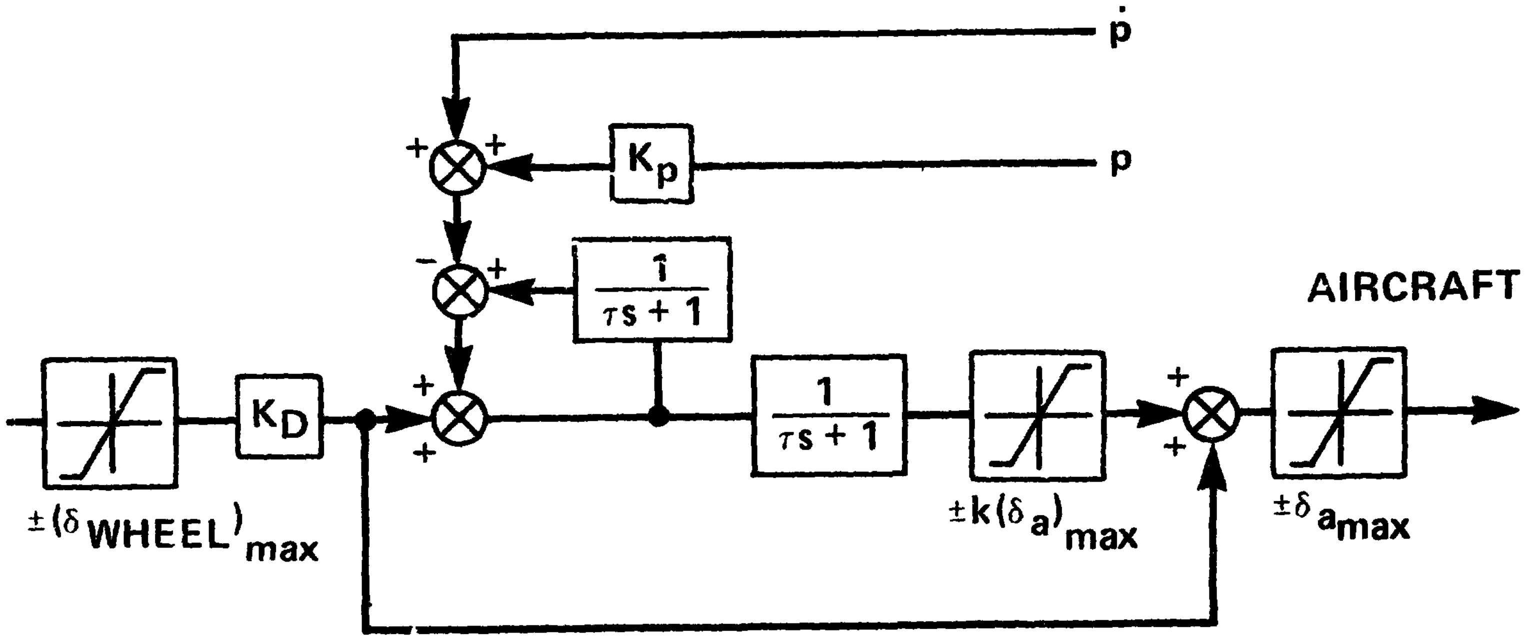
9. Sammonds, Robert I.; Stinnett, Jr., Glen W.; and Larsen, William E.: Wake Vortex Encounter Hazard Criteria for Two Aircraft Classes. NASA TM X-73,113, 1976.

10. Jenkins, Michael W. M.; and Meyer, Robert T.: Vortical Wake Hazard Advisory. AFFDL-TR-76-146, 1977.

11. Kurkowski, Richard L.; Barber, Marvin R.; and Garodz, L. J.: Characteristics of Wake Vortex Generated by a Boeing 727 Jet Transport During Two-Segment and Normal ILS Approach Flight Paths. NASA TN D-8222, 1975.

TABLE I.– PERTINENT AIRCRAFT CHARACTERISTICS AND ASSUMED WAKE ENCOUNTER DATA

Aircraft	Light twin (PA-30)	Business jet (LEAR-23)	Jet transports	
			(DC-9)	(B-727)
Weight, N	16,670	44,450	413,370	577,830
Moment of inertia, kg-m^2	4,960	16,680	488,100	1,153,000
Wing				
Area, m^2	16.54	21.55	93.00	157.94
Span, m	10.97	10.39	28.47	32.91
Aspect ratio	7.27	5.01	8.71	6.86
Taper ratio	.48	.51	.30	.30
Approach speed, m/sec	42.7	62.2	66.8	66.8
Roll damping, sec^{-1}	2.6	1.0	1.4	1.3
Roll control power, rad/sec^2	1.87	1.15	.97	.62
Acceleration due to vortex at 3 n. mi.				
No alleviation, rad/sec^2	14.3	5.90	2.18	1.21
Alleviated, rad/sec^2	3.2	1.17	.90	.57
Encounter duration, sec	1	1	1	1



$$K_D = \frac{\delta_a}{\delta_{WHEEL}}$$

$$\frac{p(s)}{p(s)_{command}} \approx s + K_p \text{ for } \delta_{a_{command}} < k\delta_{a_{max}}$$

Figure 1.- Block diagram of state-rate-feedback implicit model following (SRFIMF) control system for a roll rate command system.

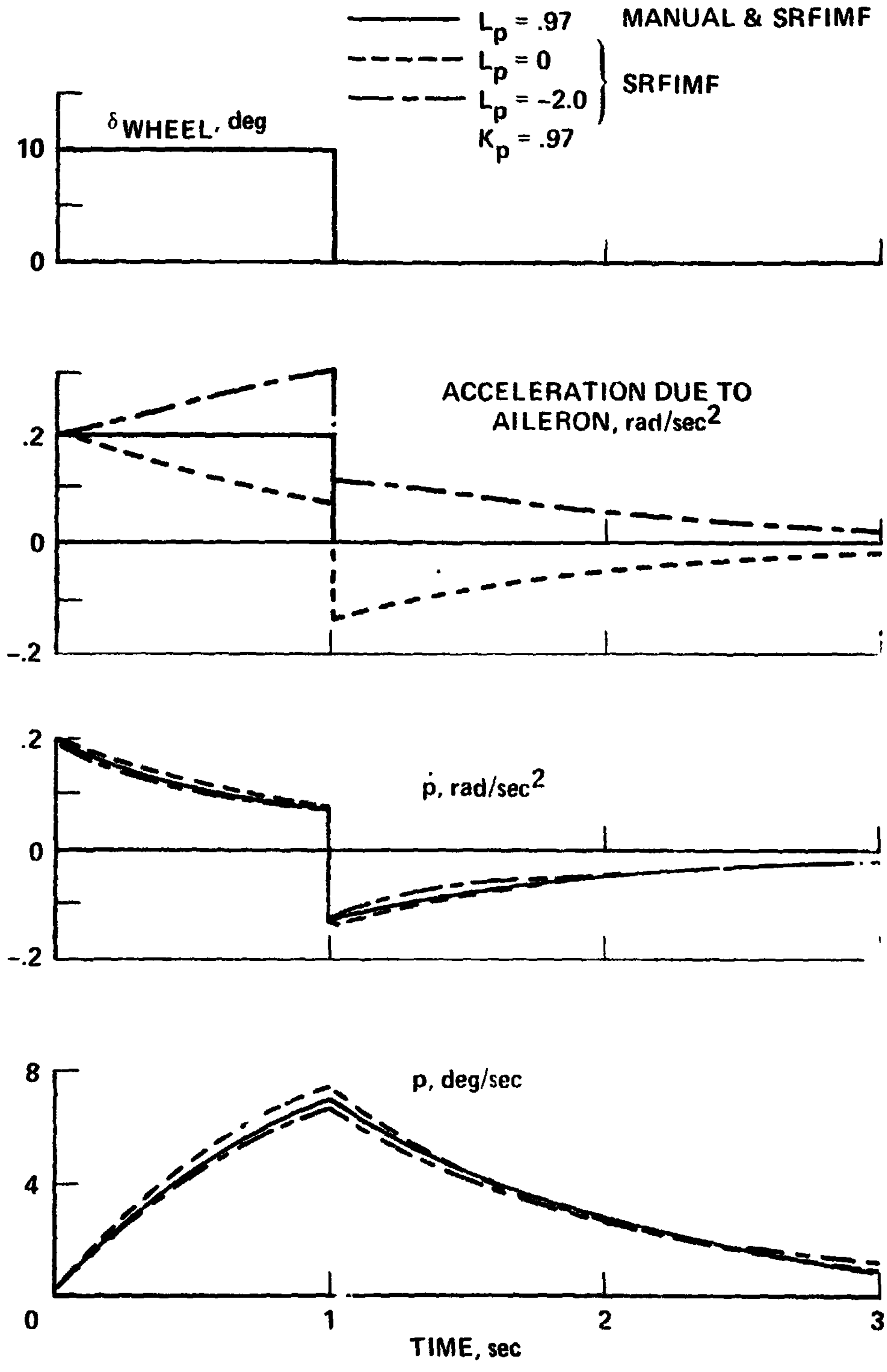


Figure 2.- Typical response to wheel command.

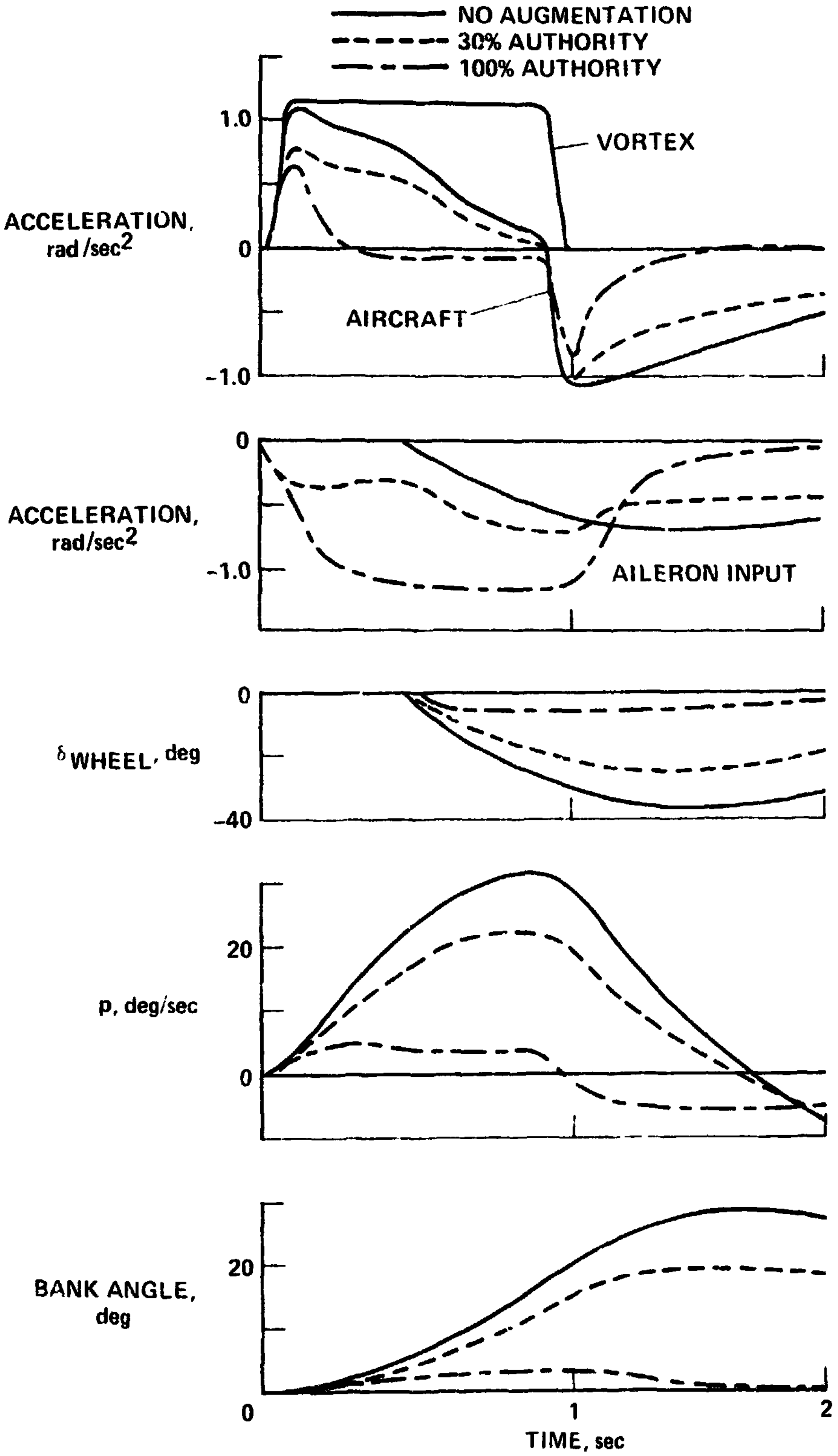


Figure 3.- Piloted response to vortex induced acceleration equal to control power for LEAR 23 aircraft.

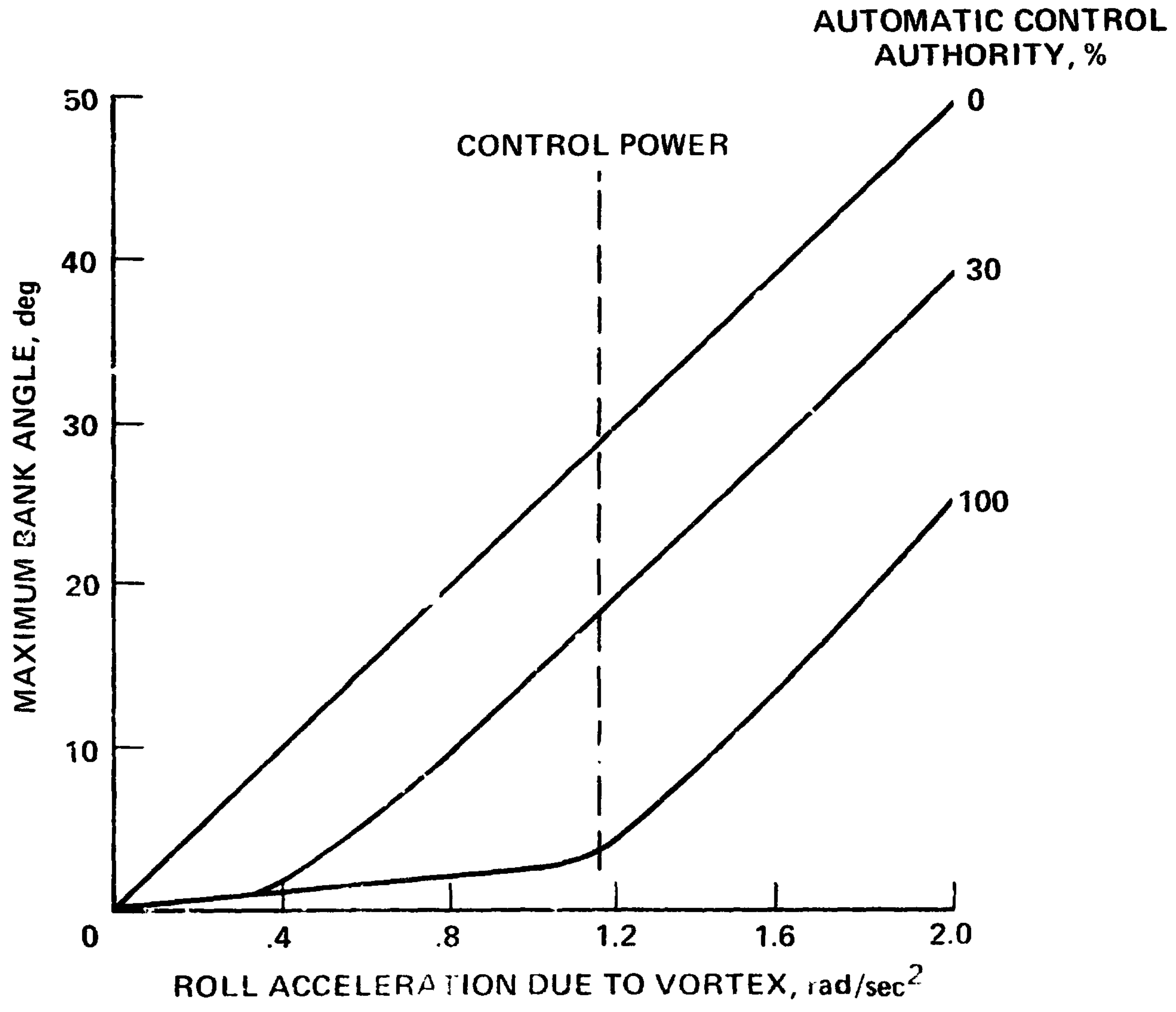


Figure 4.- Maximum bank angle for several levels of control authority for automatic system.

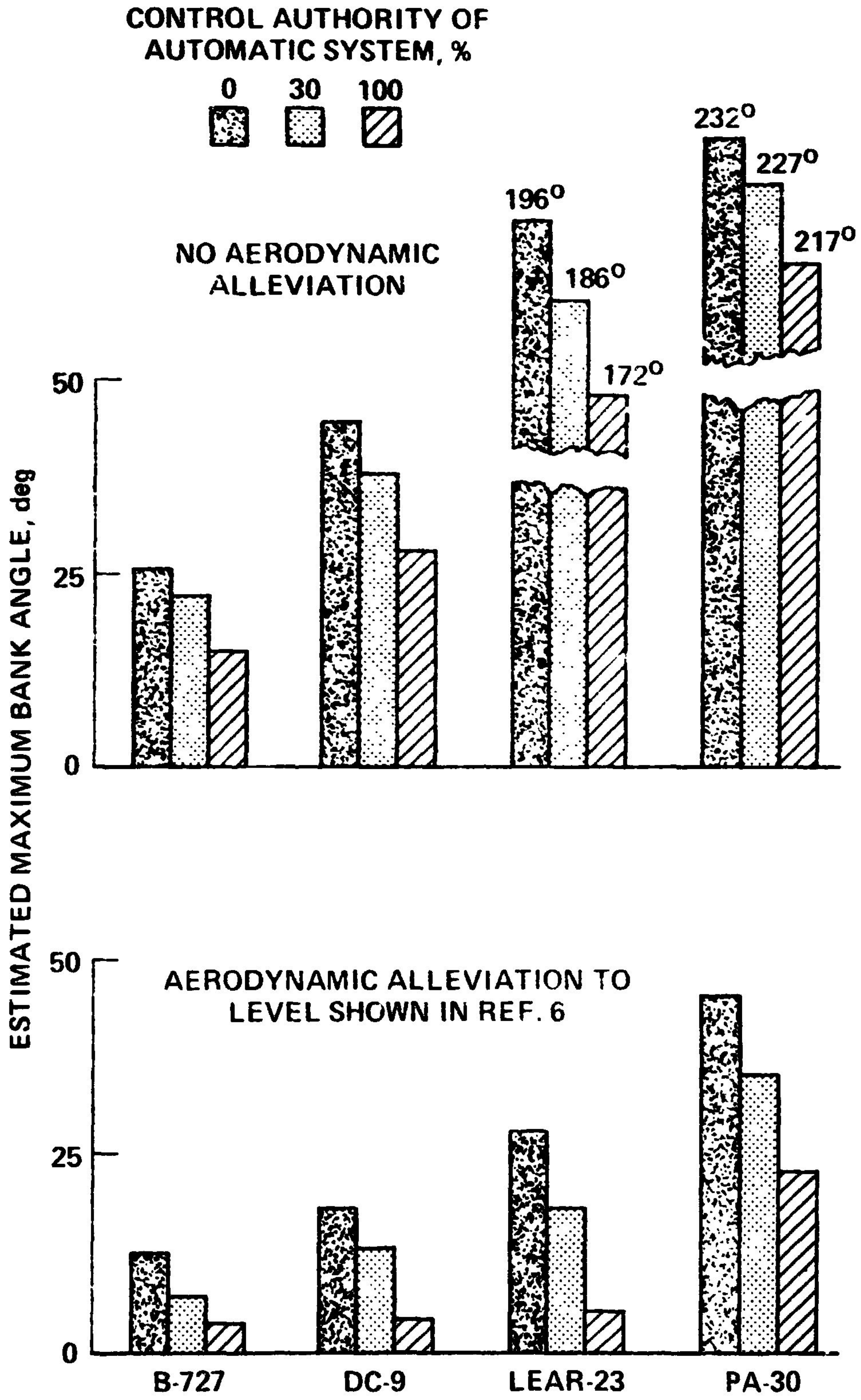


Figure 5.- Results of bank angle estimates for encounters with vortex from alleviated and large heavy jet transport at three miles separation.

1 Report No NASA TM-73,267	2 Government Accession No	3 Recipient's Catalog No

4 Title and Subtitle
Estimates of the Effectiveness of Automatic Control in Alleviating Wake Vortex Induced Roll Excursions

5 Report Date

6 Performing Organization Code

7 Author(s)
Bruce E. Tinling

8 Performing Organization Report No
A-7127

9 Performing Organization Name and Address
Ames Research Center
Moffett Field, Calif. 94035

10 Work Unit No
505-08-22

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
Technical Memorandum

14 Sponsoring Agency Code

15 Supplementary Notes

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17 Key Words (Suggested by Author(s)) Wake vortex	18 Distribution Statement Unlimited STAR Category – 08

19 Security Classif. (of this report) Unclassified	20 Security Classif (of this page) Unclassified	21 No of Pages 14	22. Price* $3.25

*For sale by the National Technical Information Service, Springfield, Virginia 22161