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CORRELATION OF FLIGHT AND ANALOG INVESTIGATIONS OF ROLL COUPLING

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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RESEARCH MEMORANDUM

CORRELATION OF FLIGHT AND ANALOG INVESTIGATIONS OF ROLL COUPLING[1]

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SUMMARY

A brief review of NACA flight experience relating to the roll-coupling problem is presented. Conditions rated by pilots as intolerable, marginal, and good are discussed and correlated with calculated results. A suggested flight test procedure for roll-coupling investigations and a discussion of several other items of general interest are also presented.

Good correlation was obtained between calculated motions and flight data in a number of instances. It would appear that intolerable conditions should be predictable from general analog studies. The primary difference between the marginally acceptable and intolerable roll-coupled maneuvers would appear to be the much larger negative normal acceleration attained in the latter maneuvers, as well as a somewhat higher sideslip angle. The suggested approach of close coordination of flight test results with calculations should greatly lessen the possibility of encountering an unpredictable violent roll-coupled maneuver.

INTRODUCTION

Since severe coupled motions in rolling maneuvers were first experienced in October 1954 at the NACA High-Speed Flight Station, Edwards, Calif., considerable effort has been devoted to studying various phases of the problem.

A fairly comprehensive analog study has been completed and the results of this work (ref. 1) were very useful in determining the

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[1]This paper is based on material originally presented at the WADC Inertia Coupling Symposium held February 29 to March 1, 1956, at Wright-Patterson Air Force Base, Ohio.

relative importance of various aerodynamic and mass parameters which influence the overall problem. Another phase of the work at the High-Speed Flight Station and at the NACA Langley Aeronautical Laboratory has dealt with a preliminary investigation of the roll rates used and considered desirable in tactical-type rolling maneuvers. Some of these results are reported in reference 2. The primary effort of the High-Speed Flight Station in the field of roll coupling, however, has been the flight evaluation of three airplanes with a total of six configurations (refs. 3 to 5, and unpublished data).

This paper presents a brief review of NACA flight experience relating to the roll-coupling problem.

SYMBOLS

a_n normal acceleration at center of gravity, g units

a_t transverse acceleration at center of gravity, g units

b wing span, ft

C_l rolling-moment coefficient

C_L lift coefficient

C_m pitching-moment coefficient

C_n yawing-moment coefficient

C_Y side-force coefficient

$\bar{c}$ wing mean aerodynamic chord, ft

g acceleration due to gravity, ft/sec^2

h_p pressure altitude, ft

I_X moment of inertia of airplane in roll, slug-ft^2

I_{X_e} moment of inertia of rotating engine parts, slug-ft^2

I_Y moment of inertia of airplane in pitch, slug-ft^2

I_Z moment of inertia of airplane in yaw, slug-ft^2

I_{XZ} product of inertia referred to X- and Z-axes, slug-ft^2

i_t stabilizer deflection (positive when trailing edge is down), deg

M Mach number

$N_\beta = C_{n_\beta} qSb$

p rolling velocity, radians/sec

$\bar{p}$ average rolling velocity, radians/sec

$\bar{p}_{cr}$ lower undamped critical roll rate, radians/sec

q pitching velocity, radians/sec

q dynamic pressure, lb/sq ft

S wing area, sq ft

t time, sec

V true airspeed, ft/sec

α angle of attack of airplane body axis, deg

α_1 angle of attack at which roll maneuver is initiated, deg

α_p maximum positive or negative angle of attack attained in maneuver, deg

β angle of sideslip, radians or deg

δ_{a_t} total aileron deflection (positive for right rolls), deg

δ_e elevator deflection (positive when trailing edge is down), deg

δ_r rudder deflection (positive when trailing edge is left), deg

ϵ angle between body axis and principal X-axis, positive when reference axis is above principal axis at the nose, deg

φ bank angle, deg

$\Delta\varphi$ change in angle of bank, deg

ω_e rotational velocity of engine rotor, radians

$C_{l_{\delta_a}}$, $C_{l_{\delta_r}}$, C_{l_β}, C_{m_α}, C_{m_β}, $C_{m_{i_t}}$, $C_{n_{\delta_a}}$, C_{n_β}, $C_{n_{\delta_r}}$, C_{Y_β}, C_{L_α} indicates derivative with respect to subscript

C_{l_p}, C_{l_r}, C_{n_p}, C_{n_r} indicates derivative with respect to $\frac{b}{2V} \times$ subscript

C_{m_q}, $C_{m_{\dot{\alpha}}}$ indicates derivative with respect to $\frac{\bar{c}}{2V} \times$ subscript

Subscript:

max maximum

DISCUSSION

Several extremely violent roll maneuvers have been encountered in NACA flight tests (refs. 3 and 4). A time history of an abrupt aileron roll made on the delta-wing YF-102 airplane is shown in figure 1. The maneuver was made at a Mach number of 0.75 and an altitude of 39,500 feet. Presented are control deflection, roll and pitch velocity, and angle of attack and sideslip. The results indicate a large increase in the rate of sideslip buildup at about 4 seconds ($\varphi = 256^\circ$). This caused the pilot to reverse the aileron control; however, appreciable rolling velocity was retained and the sideslip buildup continued at an ever-increasing rate. At about 360° bank angle, the angle of attack suddenly diverged negatively causing a large reinforcement of roll velocity. The up-elevator, put in at about 4 seconds, aggravated this particular maneuver to some extent. The pilot was unaware of this elevator input. He was, however, familiar with a similar maneuver previously encountered on the original F-100A airplane and personally had experienced several violent maneuvers on the X-3 airplane. In the instance of the F-100A, up-elevator had aggravated the motion and, recalling this, the pilot put in down-elevator at about the time of the α divergence ($t = 5$ sec).

When this appeared to be to no avail, he pulled back on the stick and, although the recorders failed at about $t = 7$ sec, the controls were finally neutralized for recovery. The futility of trying to control such a maneuver is evident.

It should be noted that in several earlier rolls on the YF-102 airplane the pilot arrested the roll at about 10° of sideslip and the airplane recovered immediately. In this instance he allowed the roll to proceed further, with the results shown. This indicates that even the most cautious flight program with no supporting analytical work can be extremely dangerous.

Figure 2 presents a comparison of the previous flight history with the calculated motion using flight control inputs. The major aerodynamic derivatives used in the calculations were obtained from flight data (table I). The only derivative not assumed constant with α was $C_{l_{\beta}}$. The exact simulation of a maneuver of this type can be critically dependent on small changes in many of the controlling parameters. The first attempts at correlation using the flight derivatives resulted in maximum amplitudes of the same order as flight, but the phasing was rather poor. A reduction of 20 percent in the parameter $C_{n_{\delta_a}}$ produced the good agreement shown in figure 2.

It should be noted that the preliminary attempts at the simulation of the maneuver shown in figure 1 were much less successful. These calculations (ref. 4), were made early in the flight test program immediately following the violent maneuver and insufficient information was available for many of the derivatives.

Figure 3 summarizes the results of calculations for a number of 360° left rolls in which the operator used a control stick to stop the roll motion at about 360°. Presented are plots of aileron control angle, maximum sideslip angle, and maximum α excursions as a function of the average roll velocity in a roll maneuver. The average roll velocity was computed as the bank angle at control reversal divided by the time required to reach the specified bank angle. The vertical dashed line represents the lower undamped critical roll rate calculated by the formula shown. The value of $\bar{p}_{cr}$ depends on the static stability, inertia characteristics, and engine momentum. It was found in the general analog study of reference 1 that the lower critical roll rate usually corresponded to the average roll rate at which near maximum amplitudes occurred. The results shown in figure 3 indicate maximum sideslip angles of the order of 26° and large angle-of-attack excursions with the most extreme motions occurring near critical roll rate. In this same roll range there is a break in the δ_{a_t} plotted against $\bar{p}$ curve such that in a range of $\bar{p}$ of 0.5 radian/sec greatly different motions are attainable for the same aileron deflection. The flight maneuver presented in the previous figures is represented by the symbol and, although the control manipulation differed somewhat from that used in the general calculations, the flight maneuver occurred in a roll range where the more violent motions could be expected. Although the exact control inputs (elevator as well as aileron) can play an important part in a specific roll maneuver, it is evident that simple general calculations of the type shown with elevator fixed would have indicated the intolerable nature of this flight condition had they been available at the proper time.

A time history of a roll made on the F-100A with the original production vertical tail is shown in figure 4. The maneuver was made at an altitude of 32,000 feet and a Mach number of 0.70. Control deflections are shown at the top of the figure, and angles of attack and sideslip in the lower portion. The flight roll record was not available. The similarity of this maneuver with the maneuver presented in figure 1 is apparent both in the initial development of the motions and in the final violence attained. The calculated motions were obtained using all flight-derived linear derivatives with the exception of the C_{l_β} variation with α, which was estimated from low-speed wind-tunnel tests (table I). Although the exact phasing of the motion could be improved, the basic correlation is fairly good.

Figure 5 shows calculations of this flight condition in terms of rudder- and elevator-fixed 360° rolls. Aileron angle, maximum sideslip angle, and angle-of-attack excursions are plotted against average roll velocity. The break in the curve of δ_{a_t} plotted against $\bar{p}$ again occurs in the range of peak motions. Since no roll record was obtained in the maneuver shown in figure 4, the flight value is not plotted; however, the 20° aileron deflection at which that violent maneuver was made would place it in the most critical region. Although the extreme flight negative angle-of-attack change would not be predicted from the stabilizer-fixed general study, the peak motions indicated are rather large.

Shown in figure 6 is a flight condition obtained with the present F-100A airplane configuration, which at times was considered marginal near maximum aileron deflection. Flight data for the condition of 360° rolls at $M = 0.93$ and 40,000 feet, obtained from reference 5, are shown by the symbols. The results obtained from calculations using unmodified derivatives estimated from flight data are shown by the dashed line. The agreement between the calculated and flight results is seen to be good. Had the maximum aileron deflection been slightly more than the 31° shown, a much more serious condition might exist.

Inasmuch as these rolls were made by pilots who were aware of the potentialities of roll-coupling, the effects of psychological factors such as a sudden increase in the maximum amplitudes with small changes in aileron deflection affect pilot opinion as much as the general uncomfortable feeling of the rolls and sensitivity to small stabilizer inputs. All the 360° rolls were to be made with stabilizer fixed. However, 2° or more of inadvertent input was fairly common on the F-100A as well as on several other airplanes. Some typical effects of small stabilizer motions are illustrated in references 1 and 5. The location of the cockpit above the roll axis frequently gave the pilot the impression of more negative g than would be indicated from a center-of-gravity accelerometer.

Figure 7 illustrates a flight condition that NACA pilots generally considered acceptable and found completely controllable. The symbols represent flight data obtained on the F-100A airplane with the large tail at a Mach number of 1.26 and 40,000 feet. The maximum angle-of-attack change was $\pm 2^{\circ}$ (approximately ± 1g) and a maximum sideslip angle of some 8° was attained at the highest roll rate corresponding to a peak transverse acceleration of from 0.6 to 0.7. This flight condition was also fairly insensitive to inadvertent stabilizer inputs. The calculated results show good agreement and indicate a maximum sideslip angle of about 13° and -2g normal acceleration could be attained if a somewhat higher aileron deflection were available.

A number of approaches were tried in an effort to summarize the several intolerable flight roll maneuvers and the larger number of marginally tolerable conditions. Considering the information available, the approach shown in figure 8 was thought to be adequate for a preliminary evaluation. The rolls summarized covered a Mach number range from 0.64 to 1.05 and a dynamic pressure range from 150 to 600 psf. The maximum sideslip angle attained in a rolling maneuver is plotted against normal acceleration. The symbol designating pilot opinion is located at the g level from which the roll was initiated and the extent of the excursions is noted by the length of the arrows. The marginal points, defined as rolls in which a pilot would at times hesitate to repeat a maneuver and would generally feel strongly against extending the condition to a higher roll rate, are shown as half-filled symbols. Three NACA maneuvers and one company maneuver clearly fall in the violent-uncontrollable category and are shown plotted as solid symbols. The results indicate several interesting points. The average β_{max} for the marginal points was about 14° to 16°, whereas all the uncontrollable rolls had sideslip angles greater than 20°. Possibly an even more interesting consideration is the much greater negative g level reached in the violent maneuvers. Actually, the design negative g was exceeded in each of these rolls.

The establishment of a criterion separating the marginal and intolerable maneuvers is still nebulous because of the many factors entering into a pilot's evaluation, as previously mentioned. Therefore, no attempt will be made to specify a definite boundary separating the two classes of maneuvers. A preliminary assessment of NACA pilots' feelings, however, is that no 360° roll made in the lower dynamic pressure range (below $q = 400$, for example) should exceed 14° to 16° of sideslip or about -1g normal acceleration.

Inasmuch as most of the roll maneuvers were 360°, a short program was conducted to determine the actual roll rates used by pilots and the part roll coupling might play in tactical-type maneuvers, such as turn entries and reversals and general tracking. Two F-100A airplanes equipped with the standard enlarged tail were used in the program and no restrictions were placed on the pilots. A considerable amount of maneuvering was performed in the supersonic speed range as well as in the subsonic speed range where 10° to 15° of sideslip could be expected in 360° maximum deflection rolls. In the tactical maneuvers, the tracking pilot rarely had to use more than half the available aileron control to keep the target airplane in his sights. Only 15 percent of the time did p_{max} exceed 1.25 radians/sec, with the highest value attained equaling 2.25 radians/sec. The total change in bank angle seldom approached 180° and the sideslip angles attained were generally on the order of 2°, never exceeding 5°. No pitch or yaw dampers were used in either airplane and the pilots were more aware of the generally poor damping, particularly in pitch, than of any roll-coupling problem.

A series of tests was also made to determine the ability of a pilot to use rudder control to minimize the sideslip development in abrupt roll maneuvers. It was found virtually impossible to coordinate at the higher roll rates, primarily because of the rapidity of the maneuvers. In addition, the location of the cockpit on many airplanes is such that the forces acting on the pilot would not result in the proper control inputs for coordination, even if the time element did not exist.

Most of the NACA experience with the more violent forms of roll coupling occurred at least a year ago when the flight problem was relatively new. Although the High-Speed Flight Station has never had the opportunity to apply a fully coordinated flight and analytical program, the following approach is recommended.

The first step should be implemented during the design stage long before the flight test program is initiated, and should involve a series of calculations to define the critical problem areas. Derivatives obtained from wind-tunnel studies or theory, corrected for aeroelasticity, would be used. When the results of the initial calculations are available early in the design, it is assumed that necessary steps would have been taken to insure that dangerous coupling would not exist in an important segment of the flight envelope.

Next, as early as possible in the actual flight test program, it is strongly recommended that as complete a determination as possible be made of stability and control derivatives from analysis of flight data. A check is thus furnished on the validity of the derivatives used in the preliminary calculations. This is important where there are large aeroelastic corrections or gaps in wind-tunnel data. There are a number of adequate methods for determining the critical stability derivatives from pulses and sideslips and, frequently, the average value obtained from several methods has been utilized. The High-Speed Flight Station has also been successful in obtaining the control parameters such as $C_{l_{\delta_a}}$, Cn_{δ_a}, and Cm_{i_t} from the initial angular acceleration following an abrupt control input.

After the flight derivatives have been obtained, a representative coverage of flight conditions should be chosen and final roll calculations made for flight correlation. General computations of the type previously presented in this paper would appear to be ideal. In these general calculations the sensitivity to several degrees of inadvertent stabilizer should be included.

Next, a flight check of noncritical roll maneuvers should be made and compared with the calculated results. If the correlation is reasonably good, marginal maneuvers can be approached with some confidence.

A critical aileron deflection should always be checked, first at small bank angles, then the bank angle increased in reasonable steps. It is felt there is no sound reason to roll beyond 360°; therefore, studies have been limited to that value. If unpredictable violent maneuvers develop, the pilot should neutralize all controls; the futility of trying to control such a motion has been demonstrated earlier.

CONCLUSIONS

This brief review of NACA flight experience relating to the roll-coupling problem has indicated:

1. Good correlation has been shown between calculated motions and flight data in a number of instances. In these calculations the major aerodynamic derivatives used were obtained from flight data. This fact, of course, is not too significant in the design stage of the airplane but should be useful in the flight test stage. Maximum motions in 360° rolls usually occurred at an average roll rate approximately equal

to the simple undamped lower critical frequency. It would appear that intolerable conditions should be predictable from general analog studies.

2. The primary difference between the marginally acceptable and intolerable roll-coupled maneuver would appear to be the much larger negative normal accelerations attained in the latter maneuvers, as well as a somewhat higher sideslip angle.

3. The suggested approach of close coordination of flight test results with calculations should greatly lessen the possibility of encountering an unpredictable violent roll-coupled maneuver.

High-Speed Flight Station,
National Advisory Committee for Aeronautics,
Edwards, Calif., May 17, 1956.

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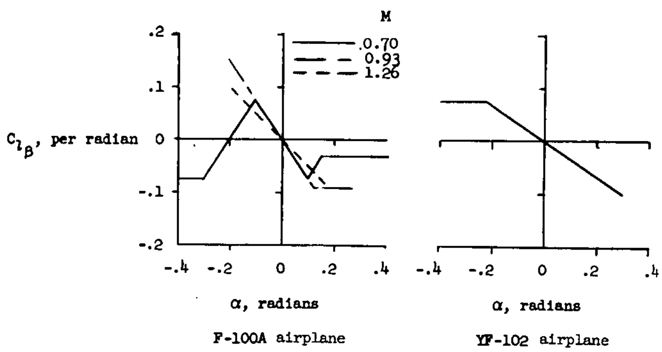
TABLE I

DERIVATIVES AND CONSTANTS USED IN CALCULATIONS

	YF-102 airplane	F-100A airplane		
		Original tail	Large tail	
	M = 0.75	M = 0.70	M = 0.93	M = 1.26
Basic flight conditions				
h_p, ft	39,500	32,000	40,000	40,000
q, lb/sq ft	158	197	237	435
α_1, deg	7.5	4.8	3.6	2.0
Mass characteristics				
I_X, slug-ft^2	13,200	11,000	11,000	11,000
I_Y, slug-ft^2	106,000	57,100	57,100	57,100
I_Z, slug-ft^2	114,600	65,000	65,000	65,000
I_{XZ}, slug-ft^2	3,540	942	942	942
ϵ, deg	2.0	1.0	1.0	1.0
Aerodynamic derivatives				
$C_{l_{\delta_a}}$	0.066	0.054	0.051	0.039
$C_{l_{\delta_r}}$	-------	0.0057	------	------
C_{l_p}	-0.160	-0.26	-0.330	-0.41
C_{l_β}	Curve	Curve[a]	Curve	Curve
C_{l_r}	0.028[a]	0[b]	0[b]	0[b]
$C_{m_{i_t}}$	-0.332	-0.845	------	------
C_{m_α}	-0.200	-0.39	-1.00	-1.09
C_{m_β}	0[b]	0[b]	0[b]	0[b]
C_{m_q}	-1.50	-3.5	-3.5	-3.0
$C_{m_{\dot{\alpha}}}$	0	-1.5	-1.5	0
$C_{n_{\delta_a}}$	0.0155	0.0060	0.0060	0.0096
C_{n_β}	0.056	0.057	0.114	0.087
$C_{n_{\delta_r}}$	-------	-0.0286	------	------
C_{n_p}	0[b]	0[b]	0[b]	0[b]
C_{n_r}	-0.140	-0.200	-0.280	-0.22
C_{Y_β}	-0.570	-0.550	-0.68	-0.68
C_{L_α}	2.780	3.880	4.80	3.60

Note: Unless otherwise noted derivatives were estimated from flight results.
[a]Denotes wind-tunnel results used as guide in estimation.
[b]Denotes derivative assumed zero.



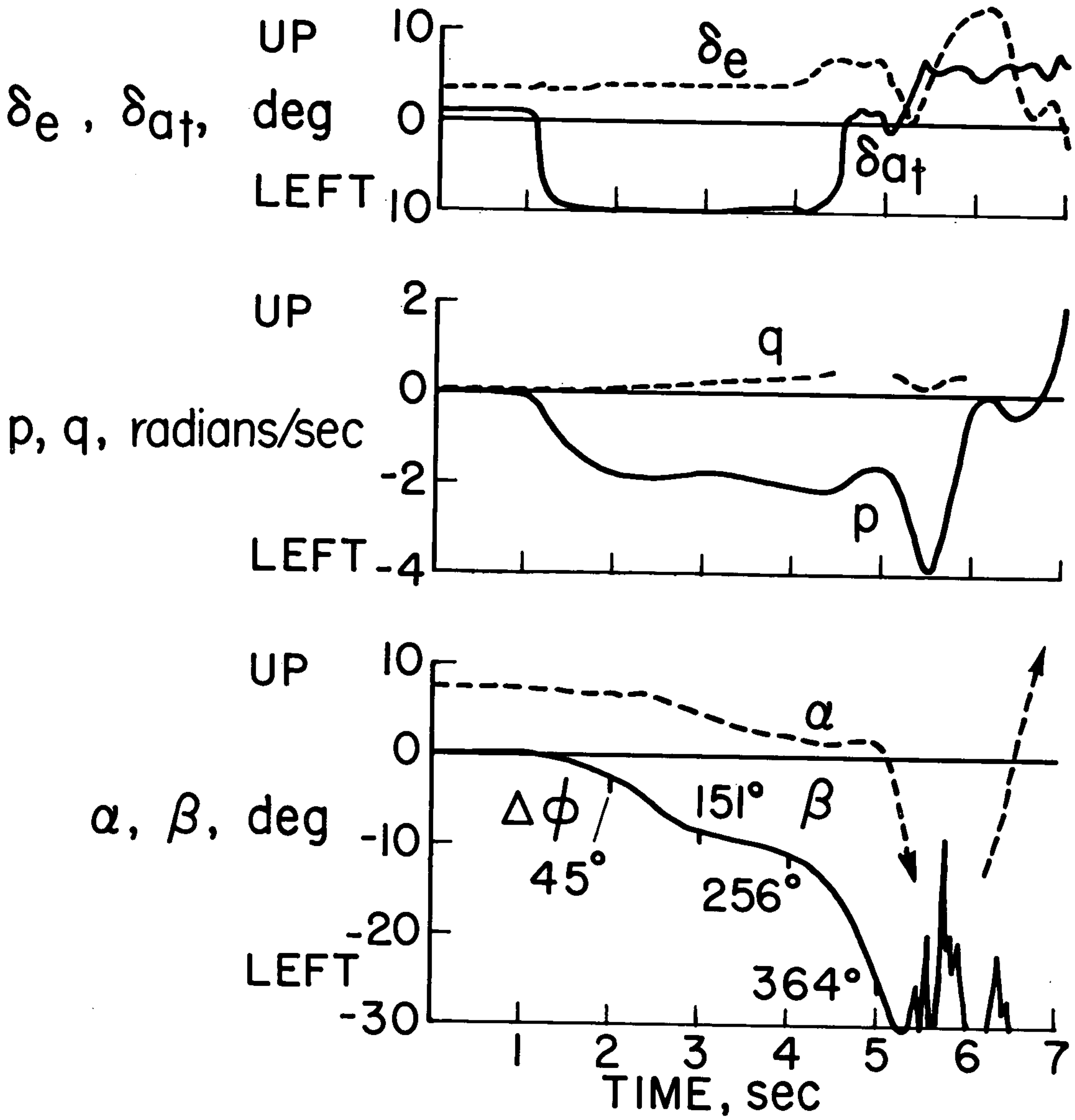


Figure 1.- Time history of abrupt aileron roll of the YF-102 airplane. M = 0.75; h_p = 39,500 feet.

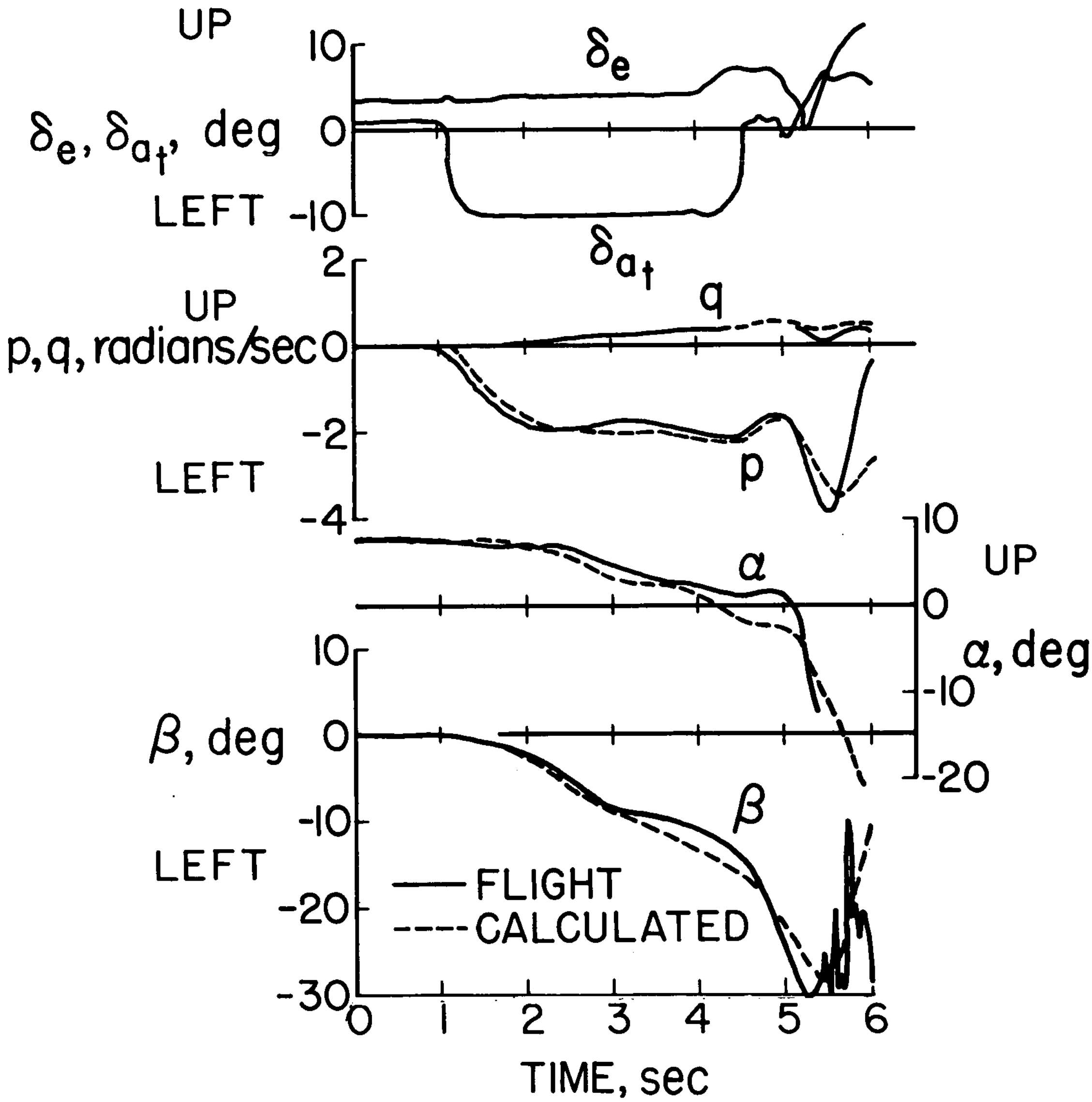
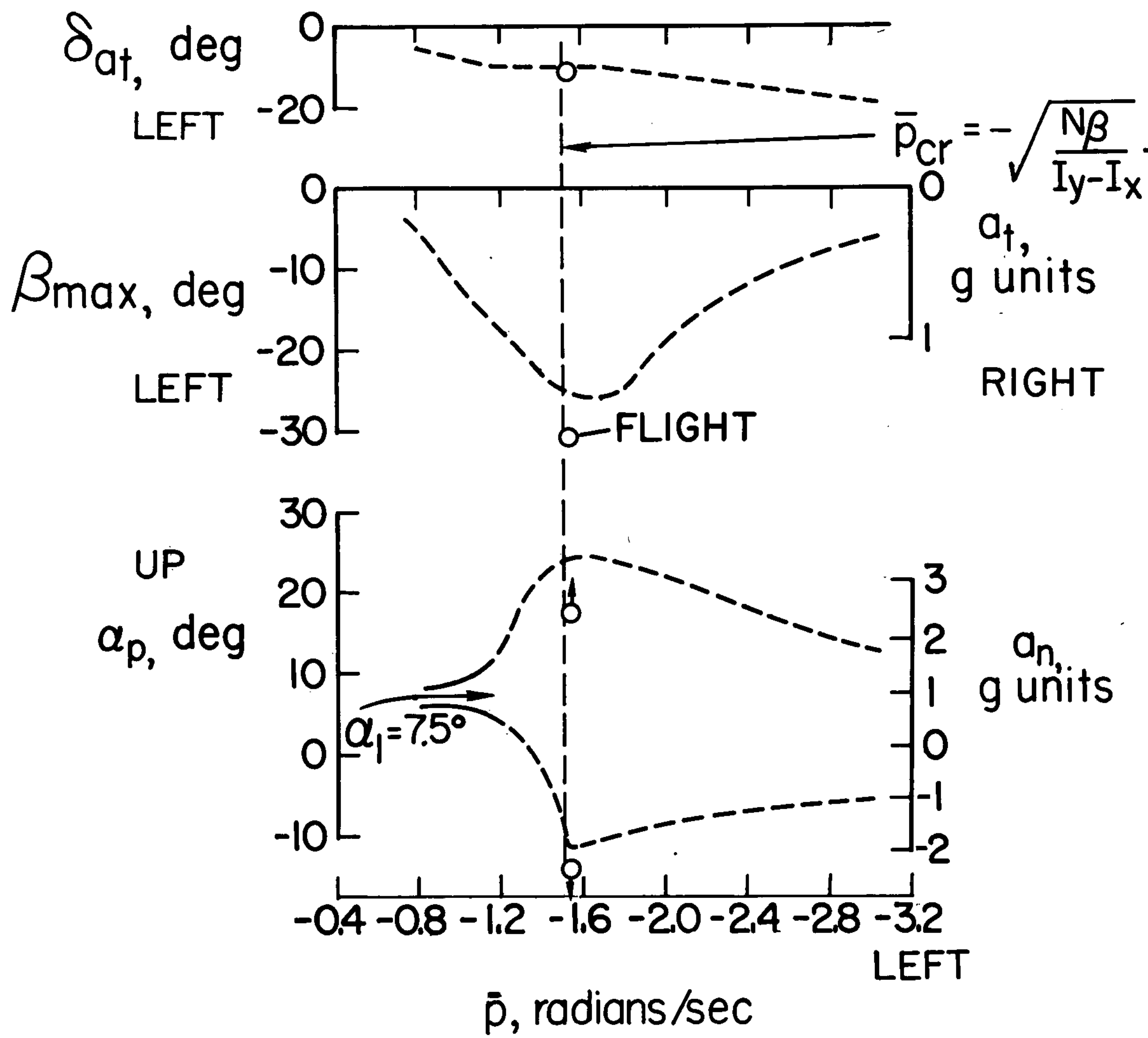


Figure 2.- Comparison between flight and calculated roll of the YF-102 airplane. M = 0.75; h_p = 39,500 feet.



$$\bar{p}_{cr} = -\sqrt{\frac{N_\beta}{I_y - I_x}} + \frac{I_{x_e}\omega_e}{2(I_y - I_x)}$$

Figure 3.- Calculated roll characteristics of the YF-102 airplane in 360° left rolls. M = 0.75; h_p = 39,500 feet.

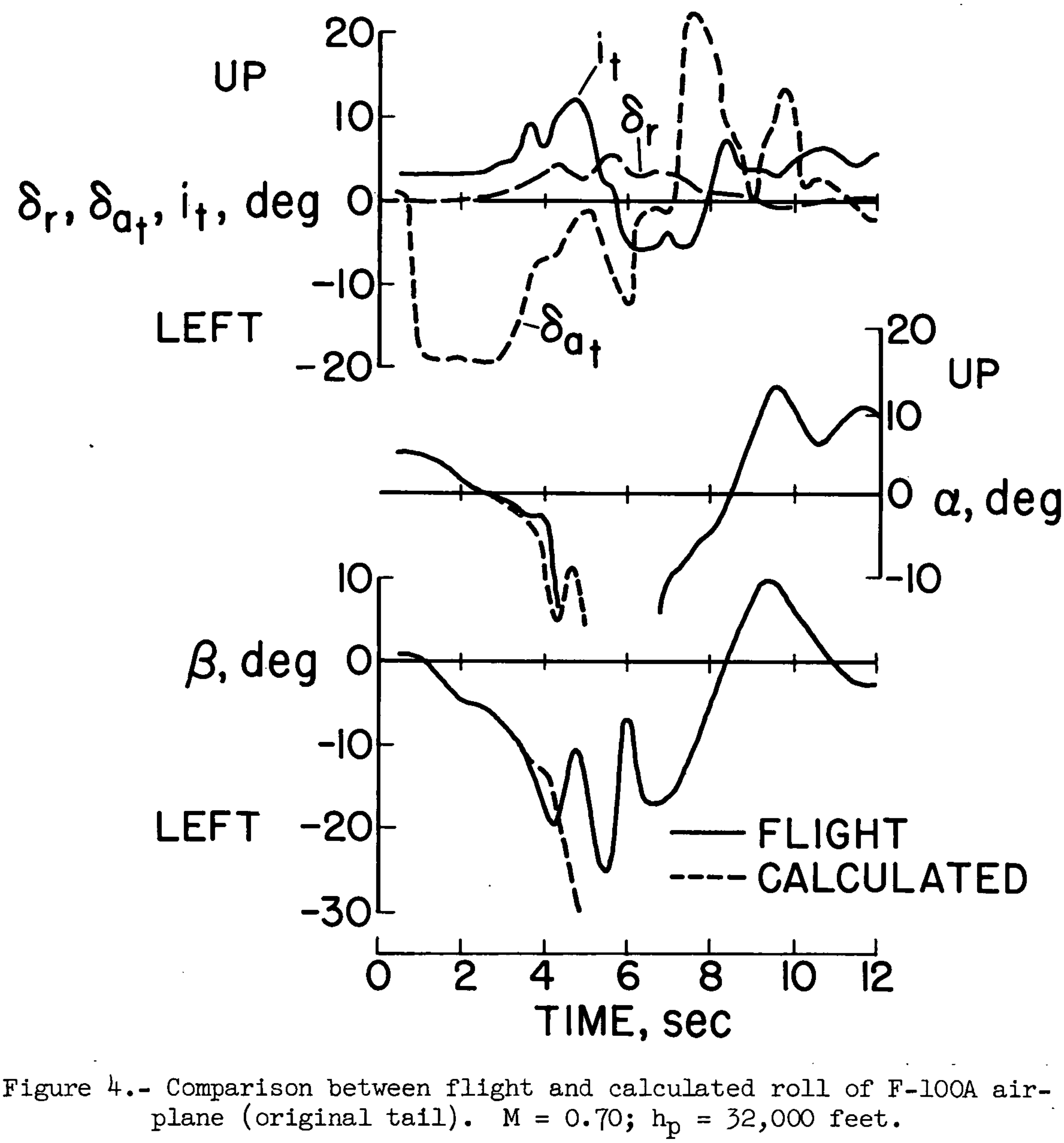


Figure 4.- Comparison between flight and calculated roll of F-100A airplane (original tail). M = 0.70; h_p = 32,000 feet.

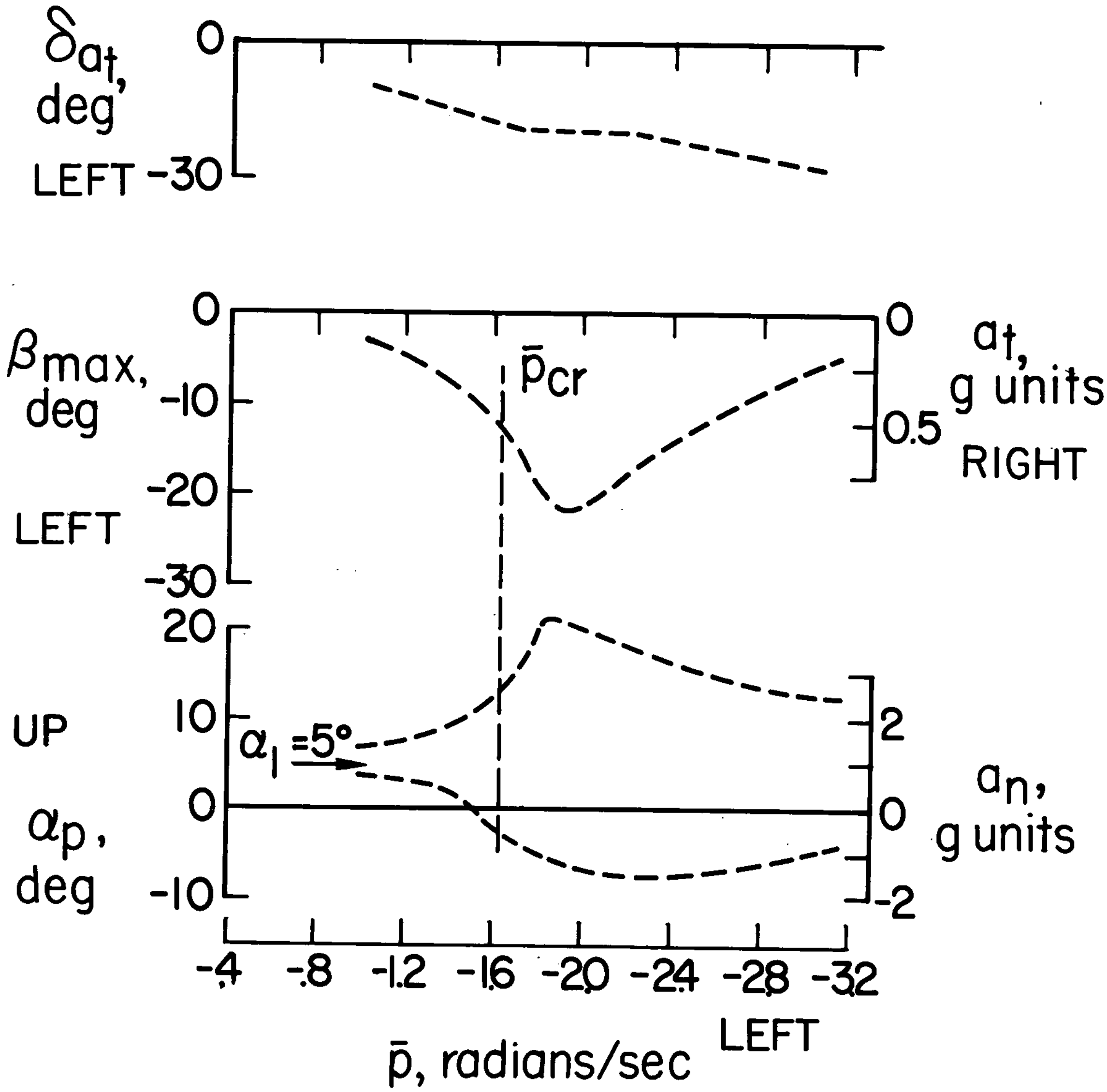


Figure 5.- Calculated roll characteristics of the F-100A airplane (original tail). M = 0.70; h_p = 32,000 feet.

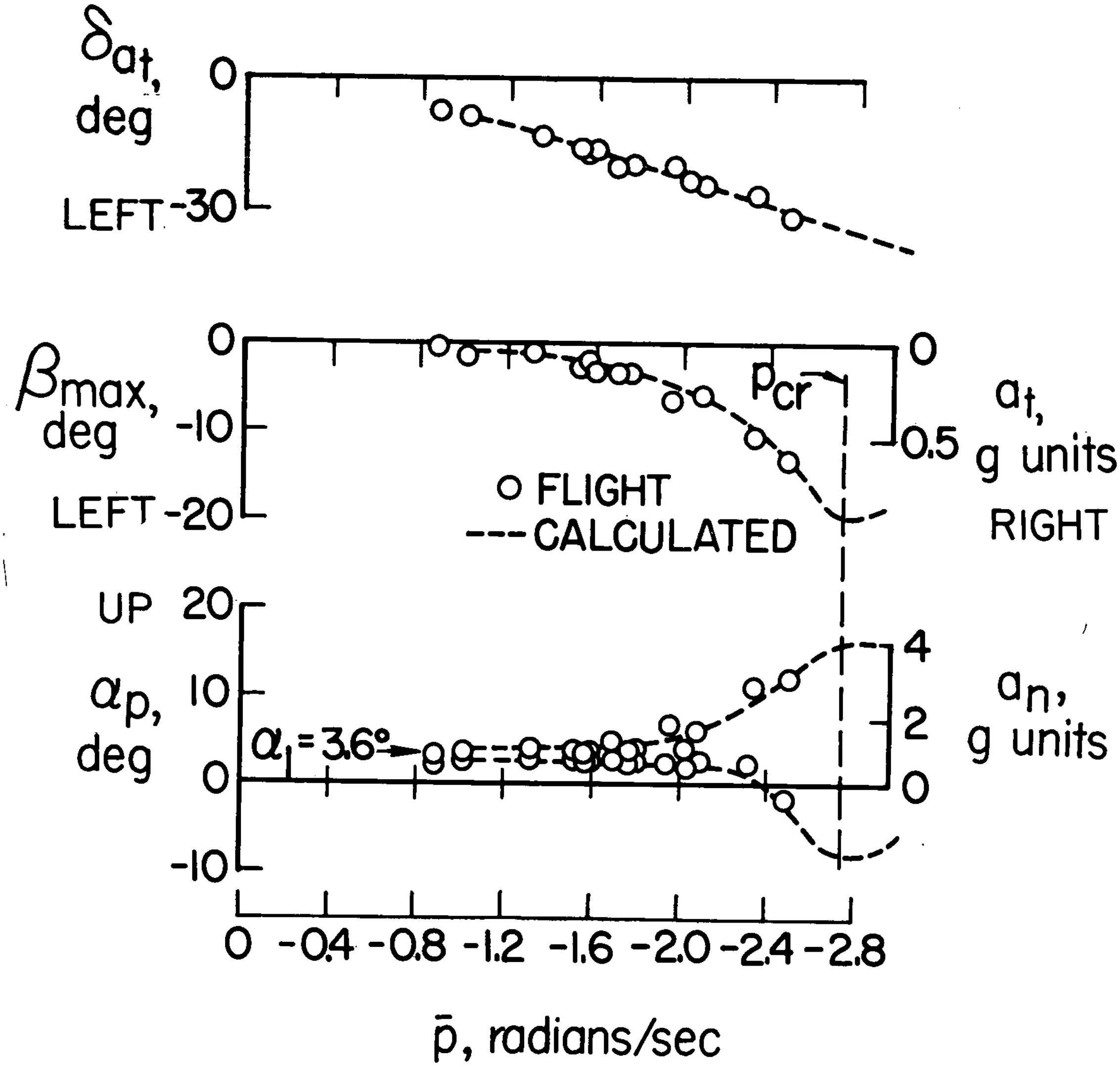


Figure 6.- Summary of 360° left rolls of the F-100A airplane (enlarged tail). M = 0.93; h_p = 40,000 feet.

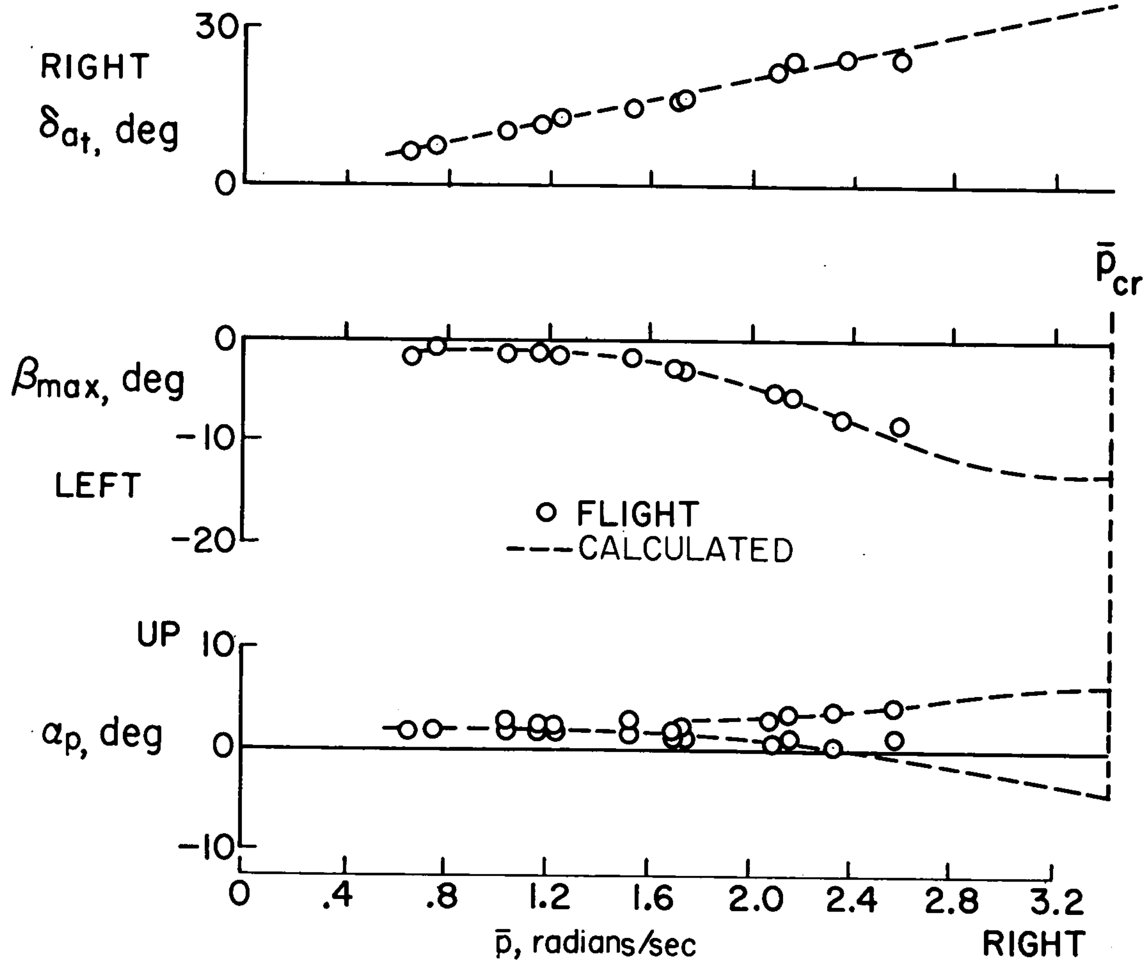


Figure 7.- Summary of 360° right rolls of the F-100A airplane (enlarged tail). M = 1.26; h_p = 40,000 feet.

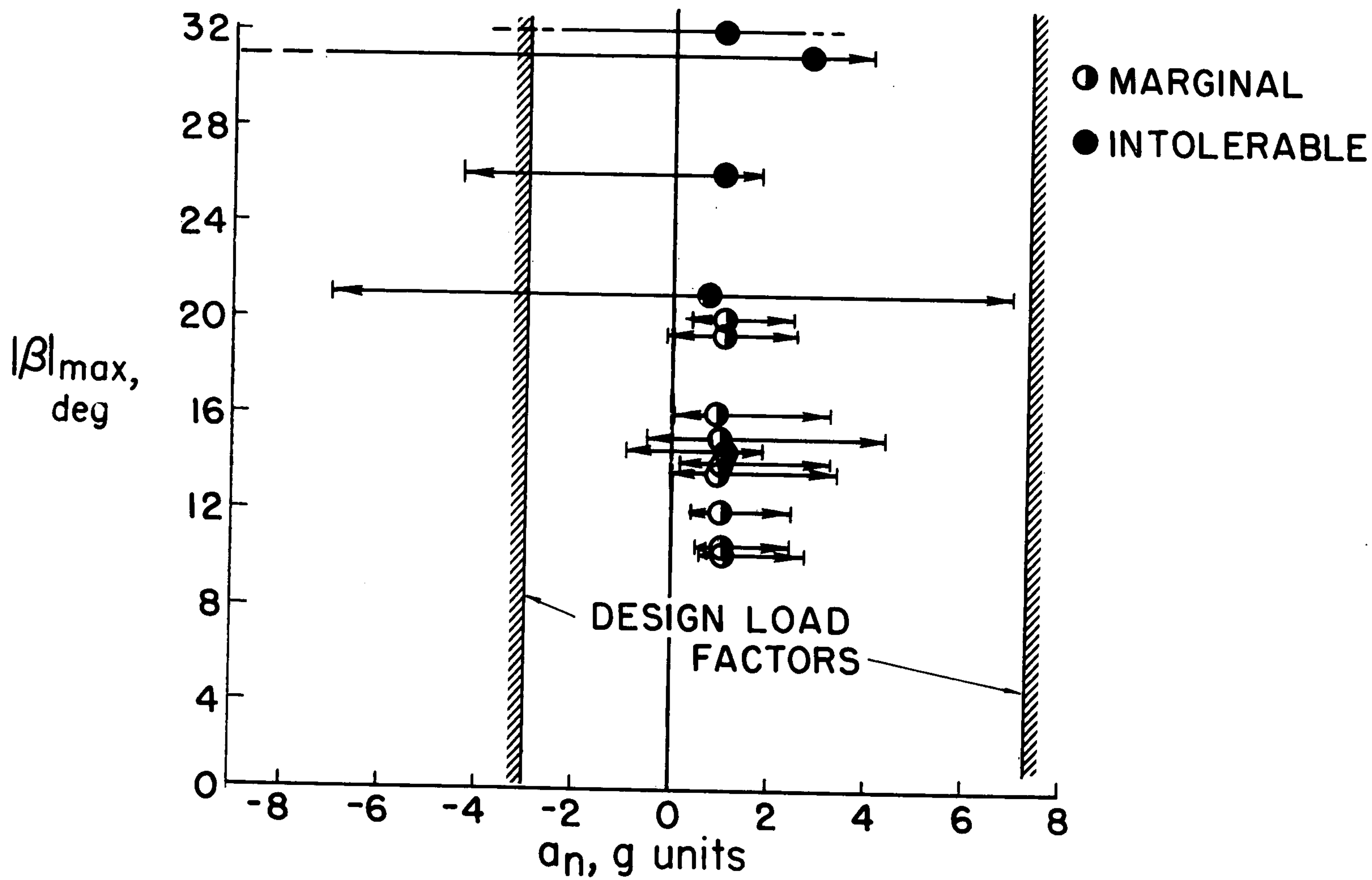


Figure 8.- Correlation of pilot opinion with quantities measured in rolling maneuvers. M range = 0.64 to 1.05; q range = 150 to 600 psf.