RESEARCH MEMORANDUM

INFLUENCE OF AUTOMATIC CONTROL OF ROLL COUPLING AND PITCH-UP ON TAIL LOADS

By Ralph W. Stone, Jr.

Langley Aeronautical Laboratory
Langley Field, Va.

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SUMMARY

An analytical study has been made of the effects of automatic augmentation or controlling systems on the tail loads experienced in rolling maneuvers and in pitch-up. The results were calculated on an analog computer and the equations of five degrees of freedom were used for the rolling maneuvers and three degrees of freedom for pitch-up. The results of this report are not intended to be of general application, but rather to point out some of the problems that may be encountered on any specific design and to indicate some probable trends.

The results indicate that, for the rolling cases calculated, most automatic systems tend to reduce not only the violence of the maneuver but also the tail load encountered. The results show, however, that if automatic systems are to be used, they must be considered in the initial design to obtain acceptable motions in rolls and to evaluate properly the tail loads.

For the pitch-up problem, the maximum tail loads are predominantly the result of control deflection, and systems which essentially reduce the input or pull-up deflections will generally improve the acceleration overshoots and reduce the horizontal-tail loads. In general, systems used for pitch-up may be compatible with problems of roll coupling. On the other hand, of the systems studied for roll coupling, only the pitch damper would be helpful for pitch-up.

INTRODUCTION

Trends in performance and design of airplanes have brought about some very serious stability deficiencies in recent years. In problems involving such deficiencies, aerodynamic changes, of course, should first be considered. There is a major trend, however, toward the use of automatic augmentation systems or controllers in meeting these deficiencies. This paper is concerned with the effects of such systems on the aerodynamic loading conditions for two of the more critical deficiencies, these being divergencies in rolls and pitch-up. The fundamentals of these problems have been discussed in numerous publications (refs. 1 to 10 and 11 to 20, respectively). This report, therefore, is confined primarily to the horizontal- and vertical-tail loads encountered when automatic systems are used. The results presented herein are indicative of only some of the problems and trends that may be expected and are not necessarily of general application.

SYMBOLS

C_L lift coefficient

C_D drag coefficient

C_Y side-force coefficient

C_l rolling-moment coefficient

C_m pitching-moment coefficient

C_n yawing-moment coefficient

I_X, I_Y, I_Z moments of inertia about the X, Y, and Z body axes, respectively, slug-ft^2

I_{XZ} product of inertia (positive when principal axis is inclined below X body axis), slug-ft^2

$I_{X_e}\omega_e$ angular momentum of engine rotating parts, ft-lb-sec

W weight, lb

m mass, W/g, slugs

g acceleration of gravity, 32.2 ft/sec^2

S wing area, sq ft

b wing span, ft

$\bar{c}$	mean aerodynamic chord, ft
X_{HT}	longitudinal distance from center of gravity to $\bar{c}/4$ of horizontal tail, ft
X_{VT}	longitudinal distance from center of gravity to $\bar{c}/4$ of vertical tail, ft
Z_{VT}	vertical distance from center of gravity to $\bar{c}/4$ of vertical tail, ft
ρ	air density, slugs/cu ft
V	velocity, ft/sec
M	Mach number
h_p	pressure altitude, ft
δ_a	aileron deflection, deg
i_T	stabilizer deflection, positive when trailing edge is down, deg
δ_r	rudder deflection, positive when trailing edge is to the left, deg
α	angle of attack, deg
β	angle of sideslip, deg
ϵ	downwash angle, deg
p	rolling angular velocity, radians/sec
q	pitching angular velocity, radians/sec
r	yawing angular velocity, radians/sec
t	time, sec
L_{HT}	horizontal-tail load, lb
L_{VT}	vertical-tail load, lb
n_Z	normal acceleration, g units

n_Y	lateral acceleration, g units
ζ	damping ratio
$\frac{d\zeta}{d\alpha}$	rate of change of damping ratio with angle of attack
Δ	increment

$$C_{L_\alpha} = \frac{\partial C_L}{\partial \alpha} \qquad C_{l_\beta} = \frac{\partial C_l}{\partial \beta}$$

$$C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha} \qquad C_{n_\beta} = \frac{\partial C_n}{\partial \beta}$$

$$C_{m_q} = \frac{\partial C_m}{\partial \frac{q\bar{c}}{2V}} \qquad C_{Y_\beta} = \frac{\partial C_Y}{\partial \beta}$$

$$C_{l_p} = \frac{\partial C_l}{\partial \frac{pb}{\partial V}} \qquad C_{n_p} = \frac{\partial C_n}{\partial \frac{pb}{\partial V}}$$

$$C_{l_r} = \frac{\partial C_l}{\partial \frac{rb}{\partial V}} \qquad C_{n_r} = \frac{\partial C_n}{\partial \frac{rb}{\partial V}}$$

$$C_{Y_{\delta_r}} = \frac{\partial C_Y}{\partial \delta_r}$$

Subscripts:

0	initial value
max	maximum
HT	horizontal tail
VT	vertical tail

Dot over a symbol indicates a first derivative with respect to time.

METHODS

The results discussed herein are based primarily on calculations for hypothetical airplanes typical of contemporary fighters. Table I lists the characteristics of the airplane used for the roll cases. Table II lists those of the airplane used for the pitch-up cases. In the calculations, five degrees of freedom were used for the roll cases and three degrees of freedom for the pitch-up cases. The equations for five degrees and three degrees of freedom appear in many references, for example, references 11 and 21, respectively. In the three-degree-of-freedom calculations, however, C_L, C_D, and C_m were introduced as functions of angle of attack and Mach number, these functions being nonlinear with angle of attack. For some rolling maneuvers, calculations were made of the loads from motions obtained in actual flights. The equations used for calculating the horizontal- and vertical-tail loads are:

$$L_{HT} = \frac{\rho V^2 S}{2} C_{L_{\alpha,HT}}\left[\alpha\left(1 - \frac{d\epsilon}{d\alpha}\right) + \frac{X_{HT}}{V} q + i_T\right]$$

and

$$L_{VT} = \frac{\rho V^2 S}{2}\left[C_{Y_{\beta,VT}}\left(\beta - \frac{X_{VT}}{V} r + \frac{Z_{VT}}{V} p\right) + C_{Y_{\delta_r,VT}}\delta_r\right]$$

DISCUSSION

Roll Coupling

Divergences in rolls are caused generally by rolling too rapidly for the directional stability that exists (ref. 1). Thus, rolling velocity and vertical-tail size are dominant factors in rolling divergences. The effects of these factors are shown in figure 1. Here, the maximum maneuvering horizontal-tail loads and the maximum vertical-tail loads encountered in rolls at different rolling velocities are plotted against the average rolling velocity of each maneuver.

Results are shown for an original tail size and for a tail size optimum for roll coupling. Also shown is the critical rolling velocity, which, as defined by Phillips in reference 1, is that rolling frequency which equals the lower of the pitching or yawing (in this case the yawing) natural frequency.

The results show a very large increase in the tail loads encountered as the rolling velocity approaches critical and then a drop-off in the loads beyond this value. Limiting the rolling velocity to some value less than critical would clearly solve the problem. How fast an airplane must roll, however, is a controversial subject and is not one for present discussion. It is sufficient to say herein only that pilots generally insist and (because of this insistence) the services require that airplanes roll at velocities larger than critical for many current and planned configurations.

Changing the tail size is the second direct approach to the problem. There is, however, an optimum tail size; smaller or larger tails lead to more violent motions and larger loads. (See ref. 3.) For the case in this paper the optimum tail is somewhat larger than the original tail. The optimum tail size is that for which the pitching and yawing natural frequencies are about the same for the present case. For this situation no roll divergence, as such, is possible. A resonance condition exists, however, when the rolling frequency is about equal to the natural frequencies in pitch and yaw, and the loads increase near this rolling velocity with the optimum tail; thus, relatively large loads also exist and the motions still may be rather violent.

Because of the wide variety of flight conditions, speeds, and altitudes now possible, a solution such as an optimum tail size may not be sufficient or feasible for any specific design. (This is true for normal stability as well as for rolling divergencies.) Thus, the trend towards the extensive use of automatic systems prevails. For the problem of roll coupling, several systems are possible. This report treats briefly five types of systems which are shown in table III.

The first system is a perfect controller which maintains zero sideslip and zero changes in angle of attack (ref. 10). This is a rather complex system requiring the sensing of attitude angles. The next system is a more practical representation of this system (ref. 10). The third system is called a coupling-moment canceler (ref. 5). This canceler in effect balances or cancels the inertia coupling parts of the pitching and yawing moments, which, as indicated in reference 5, are the primary cause for rolling divergences. The last two systems are dampers, a pitch damper and a yaw damper.

The choice of systems presented does not imply that they are the most promising controlling or augmentation systems but is intended only to show the influence of some typical systems on the loads encountered. For the calculations shown, the automatic systems are assumed to have no lags and all proper gains. For any specific design the influence of these factors must, of course, be obtained.

Some typical results of two of these systems (the pitch damper and the perfect controller) are shown. In many investigations of roll coupling, the predominant influence of pitching velocity has been evident (refs. 1, 3, 4, and 9, for example) and the pitch damper has been indicated as a simple and direct way to influence the motions encountered.

Figure 2 shows the effect of a pitch damper on the tail loads. Here are plotted the maximum maneuvering horizontal-tail loads and the maximum vertical-tail loads encountered as functions of average rolling velocity with and without the pitch damper operating. The damping ratio of the airplane with the damper operating was 0.5, and the maximum stabilizer deflection allowed for the damper (the control authority) was 1.8°. These results were obtained from flight tests of a contemporary fighter which except for a larger vertical tail is similar to the hypothetical airplane used in the other rolling calculations. As noted before, these are not measured loads but they have been calculated from motions encountered in actual rolls and aerodynamic loading coefficients measured during other flights.

A considerable improvement in the loads encountered with the damper operating is shown. Rolling velocities much in excess of critical were not obtained, however, and the effects of larger roll rates with the damper operating have not been established in flight. Some calculations of this nature have been made, however, and a summary of such results in comparison with the results for other automatic systems are discussed in this section.

The pitch damper is more effective in reducing the vertical-tail loads than the horizontal-tail loads; this indicates the dominant influence of pitching velocity through inertia coupling. The results shown here for the pitch damper are typical of those obtained for most of the other systems except, of course, the magnitude of reductions varies for each system. These differences are discussed subsequently.

Some results for the most complex of the various systems in table III, the perfect controller, are shown in figure 3. For this controller no variations in normal acceleration or lateral acceleration exist. Plotted are the maximum maneuvering horizontal-tail load and the vertical-tail load as functions of average rolling velocity. The controlled and uncontrolled cases are compared and the results are shown for two initial normal accelerations, 1 g and 2g flights.

These results show that the controller not only eliminates the violence of the maneuver but reduces the tail loads encountered, except at the largest rolling velocities when the controller tends to cause the horizontal-tail loads to be larger than are otherwise encountered. The uncontrolled loads occur primarily from angle of attack and sideslip, whereas the controlled loads occur primarily from control deflections.

These control deflections (ref. 10) are a direct function of the rolling velocity, its square, and its derivative; therefore, increasing rolling velocity requires larger deflections and, as a consequence, larger tail loads. For the uncontrolled case the loads drop off beyond the critical rolling velocity in that the motions eventually become stable again (ref. 1). Thus, loads with the controller tend to become larger than those without at rolling velocities beyond critical.

Another pertinent point regarding the perfect controller is shown in figure 3, that is, the increase in loads both with and without the controller at the higher initial acceleration. The loads are, thus, a function of the initial angle of attack, and even larger initial accelerations will lead to larger loads.

Before the results of all the calculations are summarized, a point of significant interest which exists, particularly with the perfect controller, merits some attention here. Because the automatic systems (particularly the perfect controller) reduce the excursions in angle of attack and sideslip, the airplane with the systems operating tends to roll faster at any aileron deflection than without the system operating. In figure 4 are shown the maximum maneuvering horizontal-tail loads plotted against average rolling velocity and aileron input for 2g flight with and without the perfect controller operating.

For 1 g flight (not shown here) the loads are smaller with the controller operating than without at any aileron deflection as well as any rolling velocity except for the largest rolling velocity as shown in figure 3. For 2g flight, however, the loads, although smaller at a given rolling velocity with the controller, are always larger for any given pilot or aileron input. Thus, there is a tendency in rolls from greater than 1 g flight for the horizontal-tail loads with this type of controller to be larger than without the controller for any amount of applied aileron.

In figure 5 is shown a summary of the maximum maneuvering horizontal-tail loads and the maximum vertical-tail loads calculated in 360° rolls at all average rolling velocities up to about 2.2 radians per second. Each bar represents the magnitude of the maximum load for each of several conditions:

The original tail
The optimum-sized tail
The perfect controller (A)
The coupling-moment canceler (C)
The pitch damper (0.7 critically damped) (D)
The yaw damper (1.246 critically damped) (E).

The practical controller is omitted here because it resulted in loads and motions quite similar to those of the perfect controller.

For 1 g flight, these results show the least horizontal-tail load for the coupling-moment canceler; the pitch damper shows similar results. The yaw damper showed little improvement over the original unaugmented case. For the vertical tail, the perfect controller has the least load with reductions shown for the coupling-moment canceler and the pitch damper, but again little improvement is shown for the yaw damper. The optimum tail shows the improvements previously discussed (fig. 1).

For 2g flight, the horizontal-tail load for the perfect controller has the increase in load that was discussed previously (fig. 4). Sizable reductions in tail load with the coupling-moment canceler and the pitch damper exist, however.

For the vertical-tail load, the least load is encountered with the perfect controller as for the 1 g case, only fair reductions in loads are obtained with the coupling-moment canceler, and a somewhat larger reduction with the pitch damper. No data are available for the optimum tail and the yaw damper for this flight condition.

It is clear, however, that for all systems the loads increase markedly with the initial normal acceleration of the flight.

The tail loads without an automatic system are, of course, caused primarily by the angles of attack and sideslip. With an automatic system, however, the loads are caused by the stabilizer and rudder deflections as well. The amount of control deflection required by any system is therefore of extreme significance.

Figure 6 shows the maximum control deflections required for each of the various systems. Each bar represents the magnitude of the maximum deflection required in rolls of various average rolling velocities up to about 2.2 radians per second. The basic airplanes with the original and optimum tails of course use no controls as noted by the zeros. No data are available for the optimum tail or the yaw damper in 2g flight. The deflections used in 2g flight are appreciably larger than those used in 1 g flight. The largest stabilizer deflection is used by the perfect controller and the least, by the pitch damper. The largest rudder deflection is used by the coupling-moment canceler and the least, by the yaw damper.

Stabilizer deflections of the order of 11°, used by the perfect controller, may be a larger portion of the total available deflection than it is desirable to use. The rudder deflections used by the perfect controller and the coupling-moment canceler are extremely excessive and certainly could not be used. They are larger than the total available deflection of 40°. For specific cases, therefore, the effects of limiting the amount of control deflection used must certainly be investigated.

It is not sufficient to evaluate an automatic system on the basis of the tail loads encountered or the control deflections required alone because, except for the perfect controller, variations in the normal and lateral accelerations also exist. With some automatic systems operating, these accelerations still may be intolerable to the pilot.

In figure 7 are shown the maximum normal and lateral accelerations calculated in 360° rolls at all average rolling velocities up to about 2.2 radians per second. Each bar represents the magnitude of the maximum accelerations calculated for each of the various systems previously discussed. The accelerations shown occurred during rolling maneuvers which were initiated from 1 g and 2g flight.

The results (for both 1 g and 2g flight) show that the variations in normal acceleration below the initial values of 1 g or 2g are only slightly improved by any of the systems except, of course, the perfect controller for which no changes occur. Negative accelerations are experienced for all other systems. The positive variations in normal acceleration are, however, appreciably reduced by all systems but the yaw damper. For the lateral accelerations, improvement is obtained by all systems, although accelerations of $\frac{1}{2}$ g for 1 g flight and 1 g for 2g flight still are experienced.

There is a sizable increase in the accelerations encountered in rolls from 2g flight over those from 1 g flight.

It appears that, in coping with the roll-coupling problem, a considerable compromise must be made between the motions or accelerations that the pilot must tolerate, the tail-loads encountered, and the control deflections required by a system.

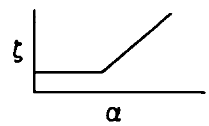
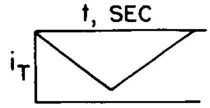
Pitch-Up

The other dominant stability deficiency is the problem of pitch-up. Pitch-up occurs, of course, from nonlinearities in the pitching-moment characteristics of an airplane.

The pitching-moment characteristics for the hypothetical airplane used for the calculations of this paper are typical of those of airplanes with swept wings and high horizontal tails having moderate nonlinearities with angle of attack and are shown in figure 8. The calculations were made from a Mach number of 1, and changes in aerodynamic-center position (fig. 8) with Mach number as well as pitching-moment nonlinearities with angle of attack influence the results.

It is important to realize that the dangers from pitch-up are not only those occurring in the pitch plane, but also those which may occur in the lateral modes of motion when the large angles of attack resulting from pitch-up may cause instabilities in sideslip, violent wing dropping, and spinning. Aerodynamic cures are most desirable, of course, but if not possible, automatic augmentation of some sort appears necessary. For the cases shown herein, the nonlinearities occur in the range of angles of attack and normal acceleration for which it is desirable to operate the airplane. Thus, automatic systems which abort a maneuver rather than allow it to progress reasonably are not desirable.

For the results presented herein, only two automatic systems are treated. These systems are shown in the following table:

SYSTEM	SENSING REQUIRED	DESCRIPTION
VARIABLE-PITCH DAMPER	q AND α OR n_Z	ζ=DAMPING RATIO 
STICK PUSHER	n_Z	t, SEC 

The first system is a rather complex pitch damper, a variable pitch damper. It is representative, however, of systems which do not abort maneuvers. The variable damping system is one which becomes operative beyond some predetermined angle of attack so that the motion is not sluggish in the normal operating range of angles of attack, but also so that the damping increases rapidly as the angle of attack of pitch-up is approached, as shown by the small sketch of the variation in damping ratio.

The second system is a stick pusher which does abort the maneuver. The pusher used, however, is one which senses only angle of attack or normal acceleration and becomes operative only after the desired normal acceleration is reached. For the results considered herein the pusher returned the stabilizer only to the original trim position as shown by the small sketch.

In figure 9 are shown the results for the variable pitch damper. The maximum normal acceleration, the maximum horizontal-tail load (which is negative and increases in magnitude downward on the figure), and the maximum stabilizer deflection required are shown as functions of rate of change of damping ratio with angle of attack. For these cases, the augmenter became active when the angle of attack exceeded the initial trim angle of attack for 1 g. Also shown are the values of the loads for the airplane with a linear pitching-moment curve. The results show an appreciable reduction in the normal-acceleration overshoot (accelerations greater than 4g) with increasing rate of change of damping ratio, the large values leading to less acceleration overshoot than even the linear case. The tail loads are similarly reduced in magnitude and again, at the larger damping ratios, smaller loads are obtained than for the linear case. Rather sizable stabilizer deflections are required by this system; however, values of as much as 5° are required and this is somewhat greater than that used by a moderate authority system. This may be considered an excessive amount of control.

Some results for the stick pusher are shown in figure 10. Here are shown the maximum normal acceleration and the maximum horizontal-tail load as functions of push rate, that is, the rate of change of stabilizer deflection with time. The results are shown for three different stabilizer input rates, or rates of pull-up. The results show little improvement for a stick pusher of this type. The normal acceleration overshoot is reduced only slightly and the tail loads are essentially unchanged. Both the loads and accelerations are appreciably larger than the values for the linear pitching-moment case.

It appears that a pusher of this type, which allows the maneuver to reach its desired acceleration before operating, not only aborts the maneuver but does little good for the maximum loads encountered. A pusher which operates earlier would, of course, produce less loads but would also stop the maneuver much sooner. A pusher with anticipation based on pitching velocity or acceleration in conjunction with a pitch damper undoubtedly would prove useful on all counts.

Compatibility of Systems for Rolling Maneuvers and Pitch-Up

Inasmuch as airplanes may be afflicted by both pitch-up and rolling divergences, the compatibility of an automatic system for one deficiency with the needs of the other deficiency is important. Because of the nature of pitch-up, all systems, used as a cure, require nose-down pitching moments. In addition, all roll-coupling systems require nose-down pitching moments at the onset of the rolling motion, primarily because of the initial positive pitching velocity that exists. As a matter of fact, all systems but the pitch damper require only nose-down moments. Thus, systems for pitch-up would generally not have detrimental effects in rolls and may be helpful. Systems used for roll-coupling which require a sensing of rolling velocity would not operate in a pitching maneuver and thus would have no effect on pitch-up.

It must be pointed out that in rolling maneuvers for which the principal axis is below the flight path, in front of the center of gravity, initial negative pitching velocities are developed rather than positive values which occur for the cases discussed herein. Thus, for such cases nose-up rather than nose-down pitching moments would be required by an automatic system at the onset of a roll. An automatic system for pitch-up such as a pusher might thus be detrimental, whereas a pitch-damper would still be effective for rolling maneuvers.

CONCLUDING REMARKS

In summary, a cursory study has been made of the effects of automatic augmentation and controlling systems on the tail loads and accelerations in rolls and pitch-up. The results of this study are not necessarily of general application but primarily show some of the problems and trends that may be expected. Calculations similar to those presented herein must, of course, be made for any specific design.

The results for rolls indicate the existence of an optimum tail size from the standpoint of the loads encountered, this size being most naturally that which is least likely to cause divergences. Automatic systems ranging from a simple pitch damper to a perfect controller show reductions in the violence of the motions and, in general, a reduction in the tail loads. At average rolling velocities somewhat larger than critical, the horizontal-tail loads obtained with controllers which sense rolling velocity may be larger than are obtained with no controller. In any event, if automatic systems are to be used, they must be considered in the initial design to obtain acceptable motions in rolls and to evaluate properly the loads encountered.

For the pitch-up problem the maximum tail loads are primarily the result of control deflection and thus systems which essentially reduce the input or pull-up deflections will generally improve the acceleration overshoots and reduce the horizontal-tail loads encountered.

Finally, in general, systems used for pitch-up may be compatible with the problems of roll coupling and generally should not be detrimental. On the other hand, of the systems studied for roll coupling, only the pitch damper would be helpful for pitch-up.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 5, 1957.

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TABLE I

MASS CHARACTERISTICS, STABILITY DERIVATIVES, AND OTHER FACTORS

USED IN THE CALCULATIONS OF ROLLING MANEUVERS

[All coefficients and derivatives are based on wing area]

I_X, slug-ft^2	10,976
I_Y, slug-ft^2	57,100
I_Z, slug-ft^2	64,975
I_{XZ}, slug-ft^2	942
q, lb/sq ft	197
S, sq ft	376
b, ft	36.6
$\bar{c}$, ft	11.32
W, lb	23,900
m, slugs	742
V, ft/sec	691
h_p, ft	32,000
ρ, slugs/cu ft	0.000826
M	0.7
$I_{X_e}\omega_e$, ft-lb-sec	17,554
$C_{l_{\delta_a}}$, per radian	-0.0528
C_{l_p}, per radian	-0.255
C_{l_r}, per radian	0.042
$C_{m_{i_T}}$, per radian	-1.0
C_{m_q}, per radian	-3.5
$C_{m_{\dot{\alpha}}}$, per radian	-1.5
C_{m_α}, per radian	-0.36
$C_{n_{\delta_a}}$, per radian	0
$C_{n_{\delta_r}}$, per radian	-0.03
C_{n_r}, per radian	-0.095
C_{n_p}, per radian	0
C_{n_β}, per radian (original tail)	0.057
C_{n_β}, per radian (optimum tail)	0.114
C_{Y_β}, per radian	-0.50
C_{L_α}, per radian	3.85
$C_{L_{\alpha,HT}}$, per radian	0.755
$\frac{d\epsilon}{d\alpha}$	0.43
$C_{Y_{\beta,VT}}$, per radian	-0.23
$C_{Y_{\delta_r,VT}}$, per radian	0.074

$C_{l_\beta}(\alpha)$, per radian (shown in following plot):

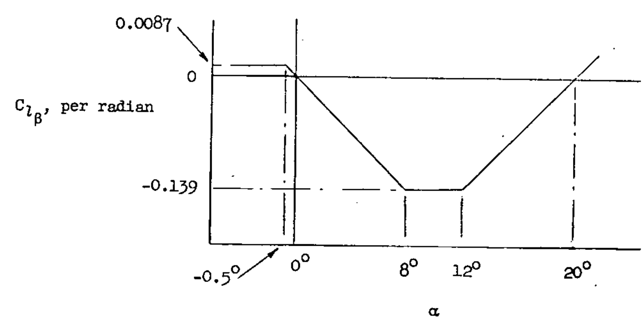

TABLE II

MASS CHARACTERISTICS, STABILITY DERIVATIVES, AND OTHER FACTORS

USED IN THE CALCULATIONS OF PITCH-UP

I_y, slug-ft^2	109,172
$\frac{1}{2}\rho V^2 S$, lb/sq ft	348
S, sq ft	530
$\bar{c}$, ft	16
W, lb	34,450
m, slugs	1,070
V, ft/sec	971
h_p, ft	35,000
ρ, slugs/cu ft	0.000737
Mach number	1.00
$C_{m_{i_T}}$, per radian	-0.773
C_{m_q}, per radian	-2.27
C_{m_α}, per radian	0.867
C_{L_α}, per radian	4.41

TABLE III

SOME TYPES OF ROLL-COUPLING CONTROLLERS AND AUGMENTERS

System		Sensing required	Controls used
A	Perfect controller	α_0, p, $\dot{p}$, and attitude	i_T and δ_r
B	Practical controller	α_0, $\dot{p}$, and p	i_T and δ_r
C	Coupling-moment canceler	p, q, and r or pq and pr	i_T and δ_r
D	Pitch damper	q	i_T
E	Yaw damper	r	δ_r

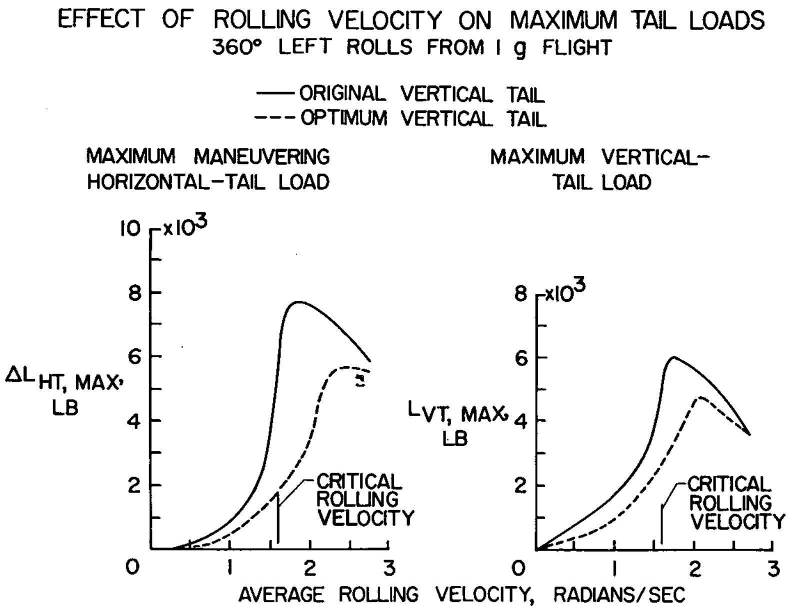

Figure 1

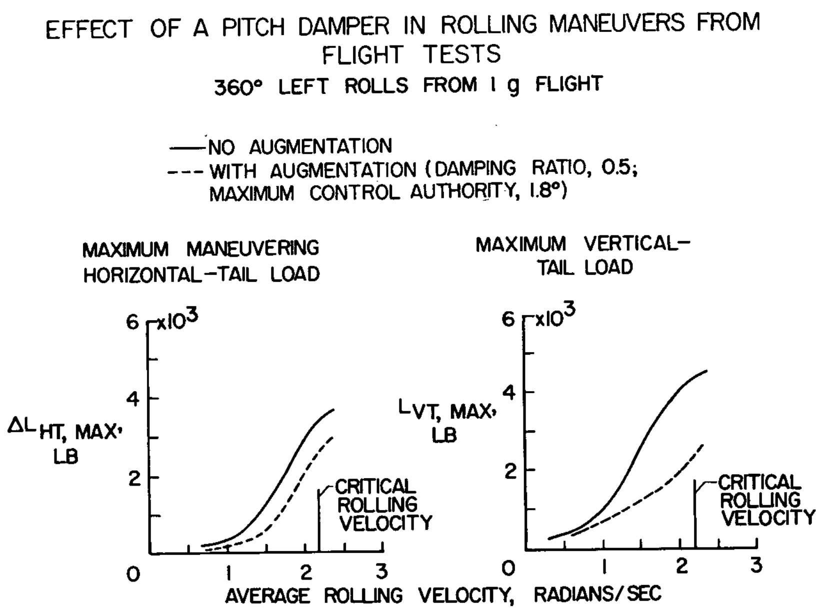

Figure 2

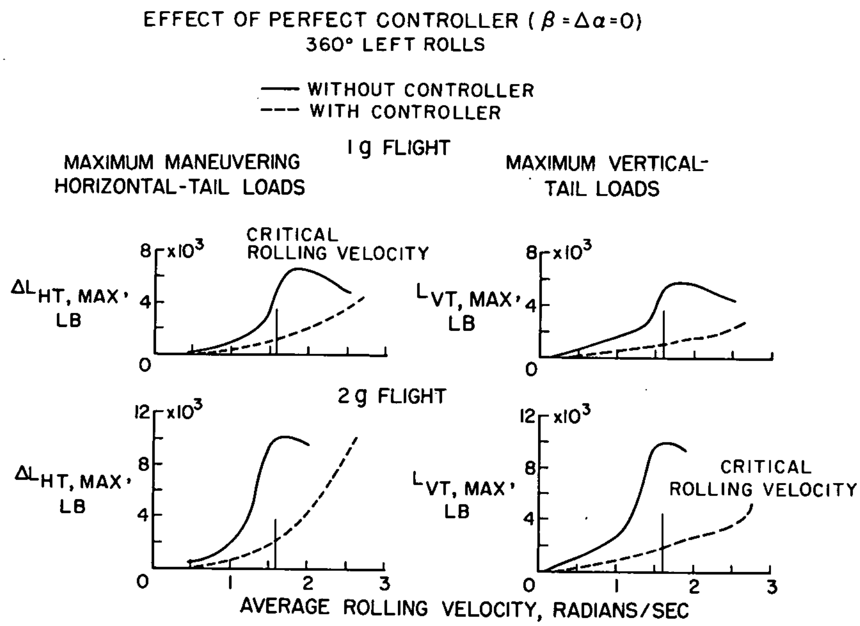

Figure 3

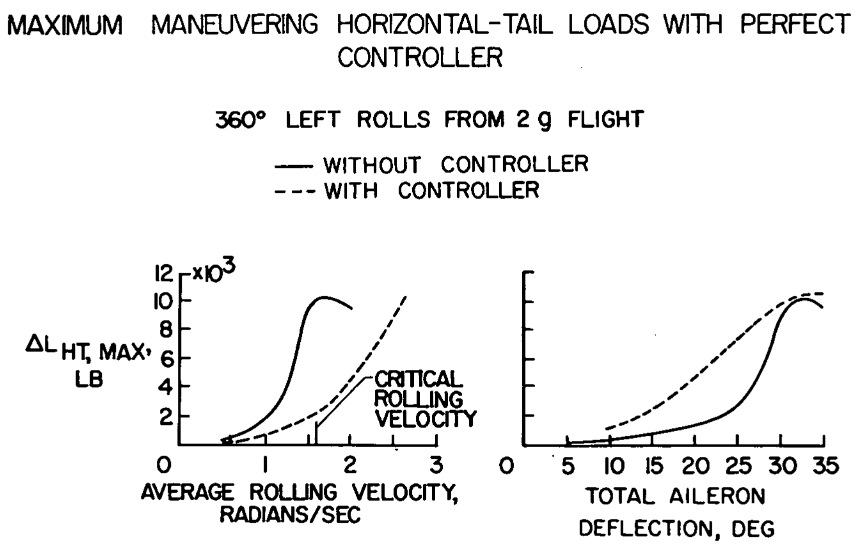

Figure 4

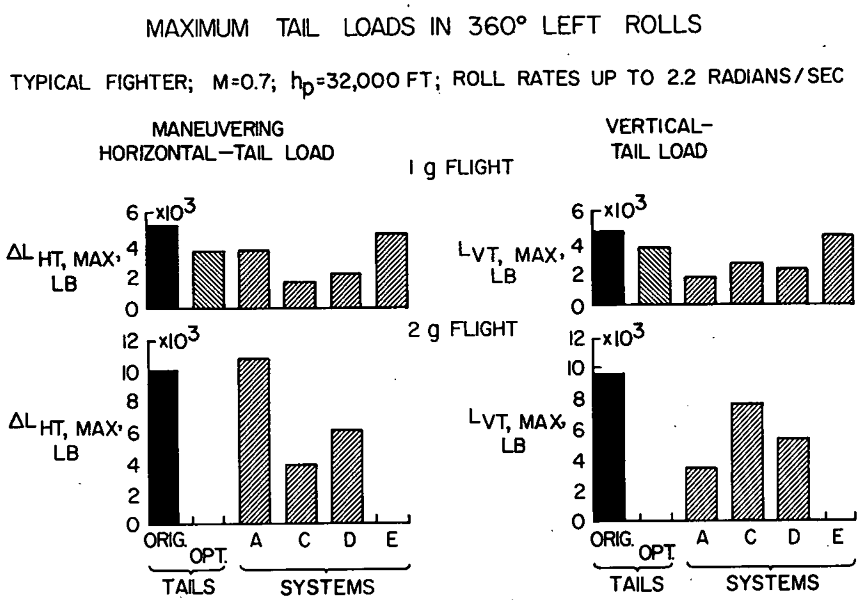

Figure 5

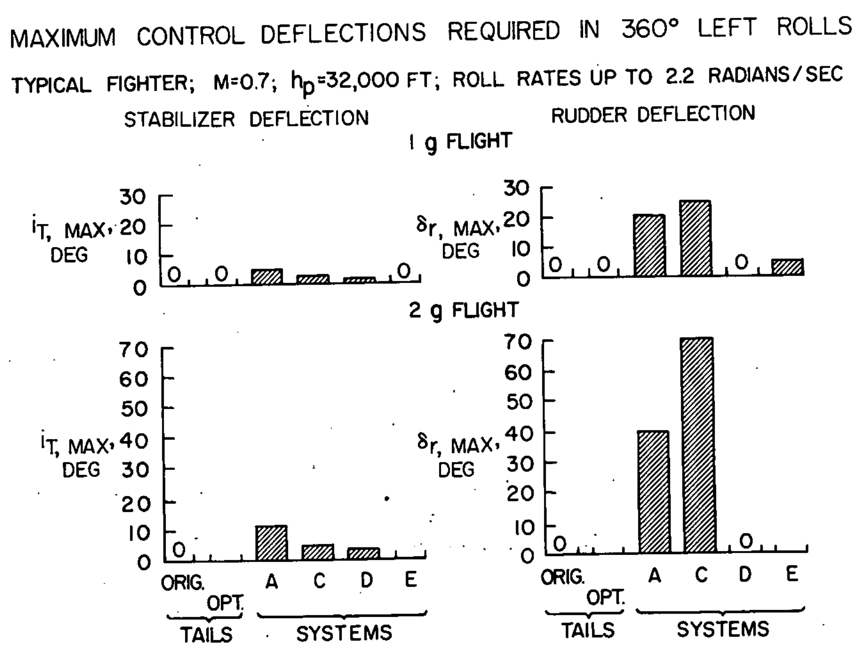

Figure 6

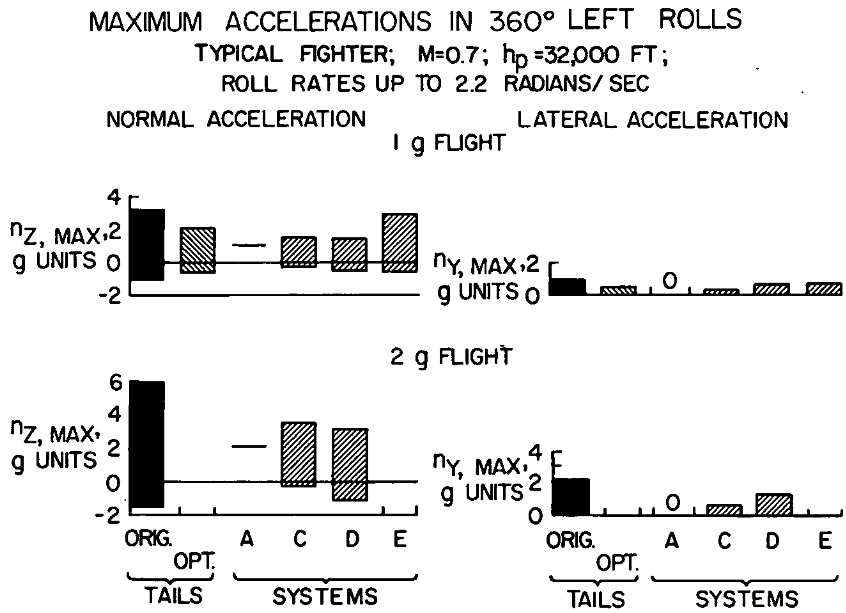

Figure 7

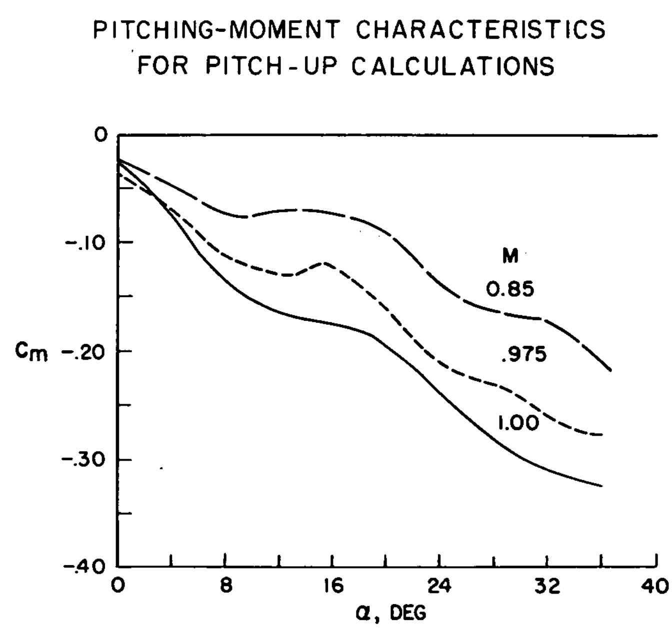

Figure 8

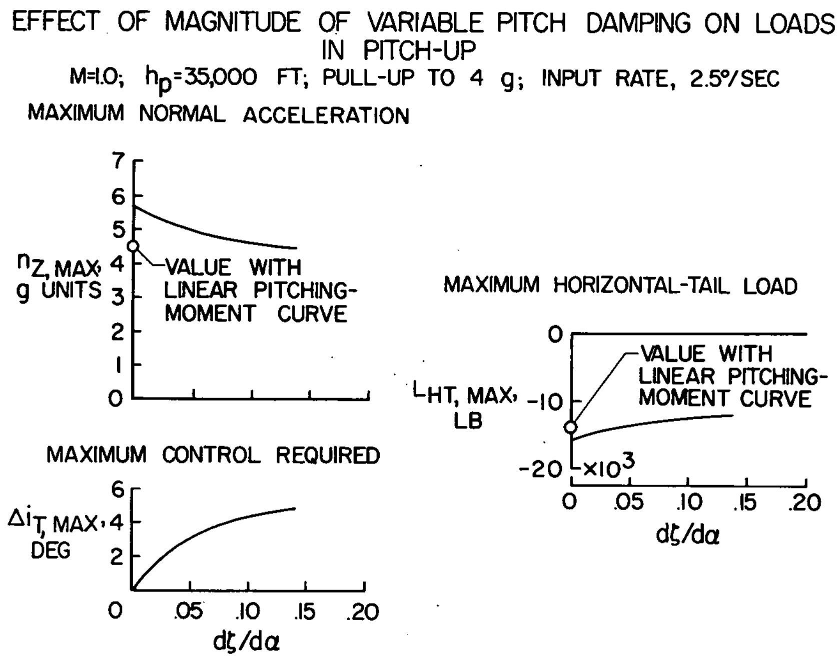

Figure 9

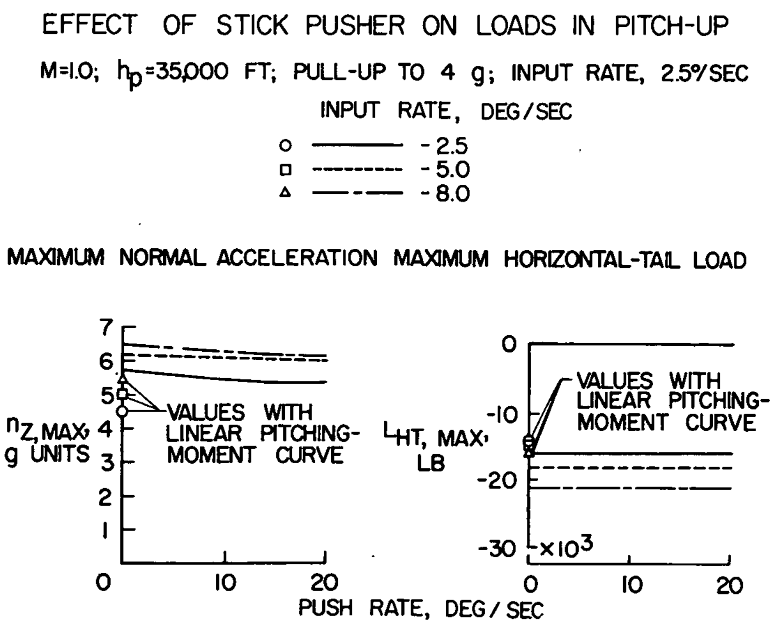

Figure 10

NACA - Langley Field, Va.