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RESEARCH MEMORANDUM

RECENT STABILITY AND AERODYNAMIC PROBLEMS AND THEIR IMPLICATIONS AS TO LOAD ESTIMATION

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NATIONAL ADVISORY COMMITTEE
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RESEARCH MEMORANDUM

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SUMMARY

Certain trends in the design of modern fighter aircraft tend to produce stability deficiencies which may result in large inadvertent structural loads. The deficiencies becoming increasingly important are: (a) loss of directional stability at high angles of attack, (b) loss of directional stability at high Mach numbers, and, probably most important, (c) a tendency to perform whirling divergences in angle of attack and/or sideslip from rolling maneuvers.

It is emphasized that the aerodynamic loads which will be imposed on a modern fighter airplane cannot be predicted without a careful and complete study of both its quasi-static and its dynamic stability characteristics, including time-history analyses of rolling maneuvers using five degrees of freedom. Deficiencies (a) and (b) are aerodynamic and can be remedied by configuration changes based on wind-tunnel investigations. Deficiency (c) is a dynamic phenomenon which requires a great deal more study and may impose limitations on rolling velocities or necessitate the use of automatic stabilization during rolling maneuvers.

INTRODUCTION

Recent flight experiences with research and service airplanes have emphasized the absolute necessity for careful and complete consideration of the stability characteristics when estimating loads. For example, as shown in figure 1, a research airplane went from what was intended to be a normal aileron roll into what the pilot referred to as a "hairy" maneuver in which it reached large angles of attack and sideslip and developed normal accelerations of +7g and -6.7g and a transverse acceleration of 2g, all in the space of about 2 seconds. As would be expected, a large number of items on the airplane were stressed to large percentages of their ultimate loads.

Some of the stability deficiencies which result in advertent high loads have been present for some time. The problem of pitch-up has been discussed previously and the causes of pitch-up and methods for its alleviation are well known (refs. 1 to 7). These include use of a low horizontal tail, wing fences, drooped leading-edge extensions, and leading-edge slats.

The fact that poorly damped airplanes suffer relatively large loadings in turbulent air has been discussed in various published papers (refs. 8 to 10). At present, there are three other types of stability deficiencies which are assuming increasing importance from a loads viewpoint. These deficiencies are as follows:

(1) Loss of directional stability at high angles of attack

(2) Loss of directional stability at high Mach numbers

(3) Tendency to perform whirling divergences from maneuvers involving high rolling velocities.

These will discussed in order.

SYMBOLS

b	wing span, ft
C_L	lift coefficient
C_{n_β}	partial derivative of yawing-moment coefficient with respect to sideslip, per radian
$\left(C_{n_\beta}\right)_{REQ'D}$	partial derivative of yawing-moment coefficient required to avoid resonance in yaw, per radian
$\left(C_{n_\beta}\right)_{RES}$	partial derivative of yawing-moment coefficient corresponding to resonance in yaw, per radian
I_X	moment of inertia about X-axis, slug-ft^2
I_Y	moment of inertia about Y-axis, slug-ft^2
I_Z	moment of inertia about Z-axis, slug-ft^2
k_Z	radius of gyration about Z-axis, ft
M	Mach number

N_β	partial derivative of yawing moment with respect to sideslip, ft-lb/radian
p_{RES}	rolling velocity for resonance in yaw, radians/sec
S	wing area, sq ft
V	flight velocity, fps
W	weight, lb
α	angle of attack, deg
β	angle of sideslip, deg
ρ	density of air, slugs/cu ft

DISCUSSION

Modern fighter configurations tend to have large, long fuselages and low-aspect-ratio wings. They require large angles of attack to develop large lift coefficients. Figure 2 illustrates a stability deficiency which is likely to occur with such a configuration. With the original tail, the static directional stability fell to zero well before maximum lift because of the induced flow field of the fuselage-wing arrangement at high angles of attack. An airplane having such a loss in directional stability will tend to diverge in sideslip with a resulting high tail load if the divergence should take place at large values of dynamic pressure. This has been demonstrated by the X-5 airplane and was discussed in reference 11. For the configuration of figure 2 a larger vertical tail greatly increased the static stability and correspondingly lessened the likelihood of divergences in sideslip.

The second stability deficiency arising from aerodynamics which is currently an increasing problem is shown in figure 3. This figure is a plot of some data on the X-1A from the Langley 9-inch supersonic tunnel which illustrates a typical tendency for airplanes to lose static directional stability with increasing Mach number at supersonic speeds. Violent maneuvers have been experienced with the X-1A airplane in this Mach number range. This loss in stability is due to loss in tail effectiveness with Mach number. Notice, however, that the tail is still capable of developing high loads in sideslip even though its effectiveness has been reduced enough to destroy the directional stability of the airplane. A supersonic airplane recently suffered a structural failure because of directional divergence at a Mach number of 1.5 for which a similar loss in C_{n_β} with Mach number was probably primarily responsible.

The third major stability deficiency which is going to be of great concern to the structural designer is a dynamic problem and was predicted by Phillips in reference 12. This type of instability is encountered in rolling maneuvers. Essentially, it tends to occur when the rate of roll approaches the natural circular frequency in pitch or yaw on an aircraft having its weight concentrated in the fuselage. The resonance between rolling and pitching, or yawing, causes what is perhaps best described as a whirling motion in which the fuselage attempts to set itself at right angles to the flight path. Large angles of sideslip and/or angles of attack are generated. It was this type of maneuver which gave rise to the extreme loadings on the research airplane mentioned earlier.

In order to understand why modern high-performance airplanes are prone to such motions, compare a modern fighter with a 1935 fighter (fig. 4). The modern fighter has the same span but is nearly twice as long. It has about three times the wing loading. It flies at twice the altitude. The radius of gyration in yaw is two-thirds larger. Its weight is concentrated in the fuselage. It will be shown that these factors combine in a way which indicates that the modern airplane will tend to be much more prone to become uncontrollable in rolling motions than the 1935 airplane.

The analysis in reference 12 indicated that the value of rolling velocity at which resonance with the natural frequency in yaw occurred could be given by

$$p_{RES} = \sqrt{\frac{N_\beta/I_Z}{\frac{I_Y - I_X}{I_Z}}} \qquad (1)$$

Nondimensionalizing and rearranging this expression gives the directional stability required to avoid resonance in yaw as

$$\left(C_{n_\beta}\right)_{REQ'D} > \left(\frac{pb}{2V}\right)^2 \frac{\frac{I_Y - I_X}{I_Z}}{4.03b\left(\frac{\rho}{W/S}\frac{b^2}{{k_Z}^2}\right)} \qquad (2)$$

A similar expression can be developed for resonance in pitch but will not be presented since the points of interest are illustrated by the yawing equation. Notice that the value of C_{n_β} required depends on the square of the rolling velocity, a wing-loading inertia parameter, and a gyroscopic inertia coupling parameter.

In figure 5 is presented the variation of the gyroscopic inertia coupling parameter for fighter and research airplanes studied in the Langley 15-foot and 20-foot free-spinning tunnels over the 20-year period from 1935 to 1955. This parameter stayed substantially constant at a value of approximately 0.3 from 1935 to 1945 but has risen to a mean value of 0.7 at the present time. This increase tends to increase the directional stability required to avoid resonance.

Figure 6 gives the variation of the mass inertia parameter over that same period. This parameter has been normalized at the value in 1935. Notice that its value in 1955 has fallen to about one-sixteenth its value in 1935. This decrease corresponds to a large increase in the required directional stability.

Now it can be seen how the value of C_{n_β} corresponding to resonance in yaw $\left(C_{n_\beta}\right)_{RES}$ at $pb/2V = 0.09$ has varied over the 20-year period (fig. 7). This value from 1935 to 1945 was about 0.00015, considerably less than the typical value of 0.0005 to 0.001 used in World War II airplanes. Beginning with the advent of jet engines, the value of $\left(C_{n_\beta}\right)_{RES}$ has risen rapidly since 1945 until the value of $\left(C_{n_\beta}\right)_{RES}$ in the typical fighter airplane of 1955 is of the order of 0.006, 40 times the value in the World War II airplane and considerably larger than the typical range of values of $\left(C_{n_\beta}\right)_{RES}$, 0.001 to 0.002, provided for these airplanes.

The analysis of the trend of directional stability required presented in figure 7 was based on the assumption that the reduced rolling velocity $pb/2V$ remained constant at a value of 0.09. This is not true, however, for transonic and supersonic speeds. Figure 8 indicates the variation of $pb/2V$ with Mach number. In general, the ability of lateral controls to produce $pb/2V$ falls off with increases in Mach number at transonic and supersonic speeds somewhat as indicated by the "typical" curve. This is an alleviating effect upon the trend toward increasing troubles with divergent whirls. Equation (2) indicates that $\left(C_{n_\beta}\right)_{RES}$ decreases as $(pb/2V)^2$. It may be necessary for the designer to take steps to insure that the specified rolling velocities cannot be exceeded in order to avoid unnecessary troubles with whirling divergences.

Analog-computer studies have indicated that, although the analysis of reference 12 gives an excellent picture of the nature of this phenomenon and is an excellent indicator that a dangerous condition exists, it does not take sufficient factors into account to permit it to be used as criterion of the amount of sideslip to be expected in a rolling maneuver. In the light of present knowledge, it appears that the sideslip response to rolling excitation is of the nature of a frequency-response curve in which both the amplification factor and the forcing function are dependent on such things as the timing, rate, and magnitude of control applications, the angle between the airplane principal axis and the zero-lift line, the initial angle of attack, and the aerodynamic characteristics of the configuration. The main point that has emerged is that, in order to predict the angle of sideslip or angle of attack which will be generated in rapid rolling motions of modern fighters, it is necessary to make a careful and thorough study of possible maneuvers by means of a simulator or analog computer, using five degrees of freedom including the nonlinear inertia terms and the engine gyroscopic couples. The aerodynamic characteristics of the configuration must be carefully represented and factors such as the pitching moment due to ailerons when sideslipping, for example, must in general be included. Cross-coupling effects may be very important. For example, a large increase in damping of the pitching motion, such as might be achieved by artificial means, was indicated to be very effective in reducing the sideslip angle.

CONCLUDING REMARKS

It should be emphasized that the aerodynamic loads which will be imposed on a modern fighter airplane cannot be predicted without a careful and complete study of both its quasi-static and its dynamic stability characteristics. The well-known problems of pitch-up and poor damping of oscillations in turbulent air have been present for some time. Three more must be added - divergence in sideslip at high angles of attack, divergence in sideslip at high Mach numbers, and, probably most difficult of all, a tendency for modern fighters to enter a whirling divergence from rolling maneuvers. The first two of these are aerodynamic deficiencies which can be remedied by configuration changes based on wind-tunnel investigations. The third is a dynamic condition which requires a great deal more study and may impose limitations on rolling velocities or necessitate the use of automatic stabilization during rolling maneuvers.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 25, 1955.

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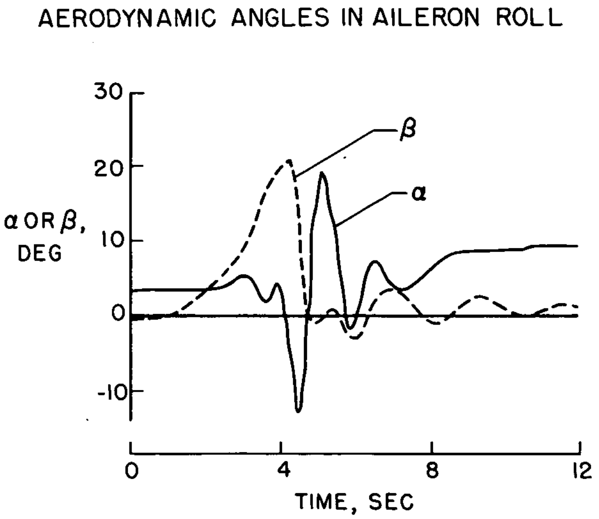


Figure 1

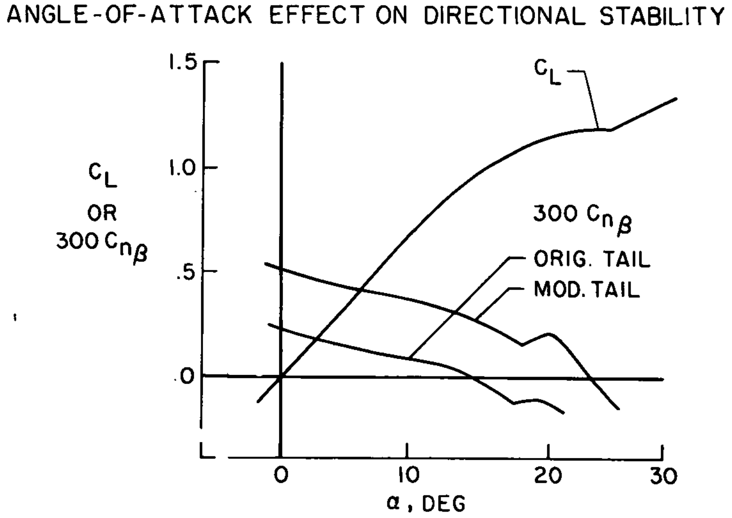


Figure 2

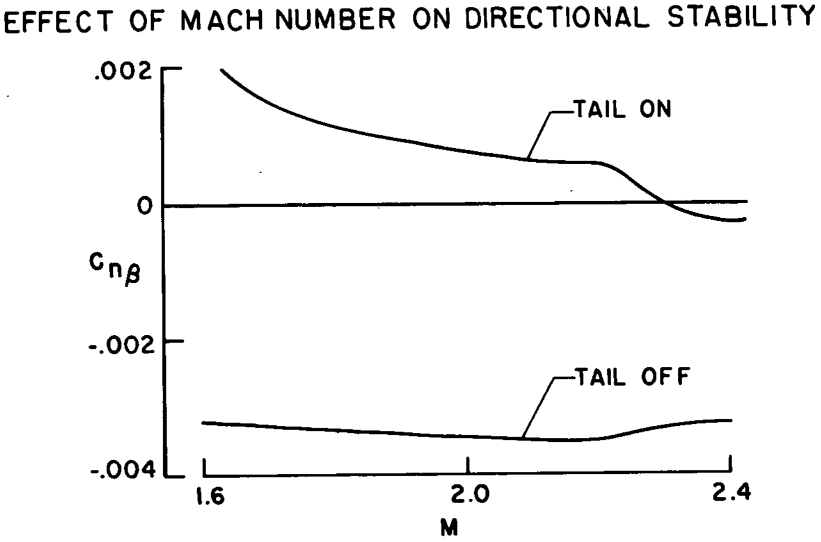
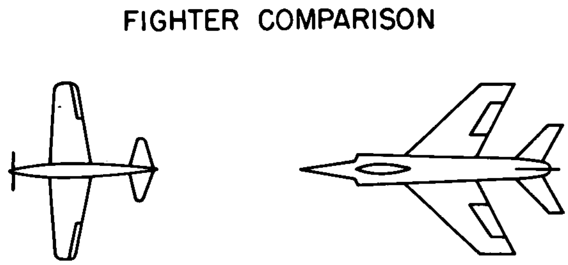


Figure 3



35	b, FT	35
20	$\frac{W}{S}$, LB/SQ FT	60
20,000	ALT., FT	40,000
6	k_Z, FT	10
0.3	$\frac{I_Y - I_X}{I_Z}$	0.72

Figure 4

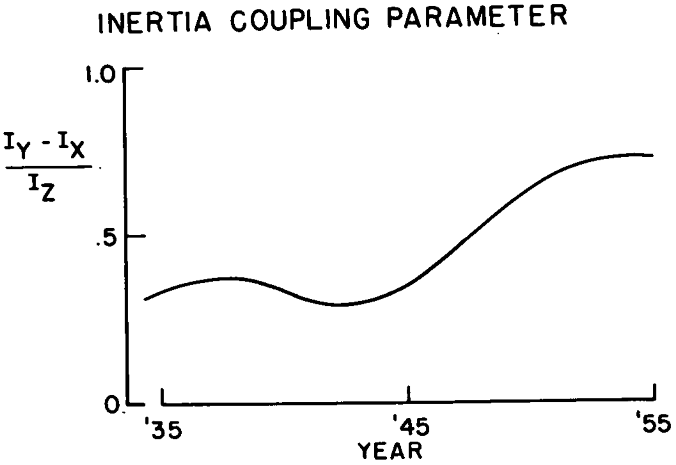


Figure 5

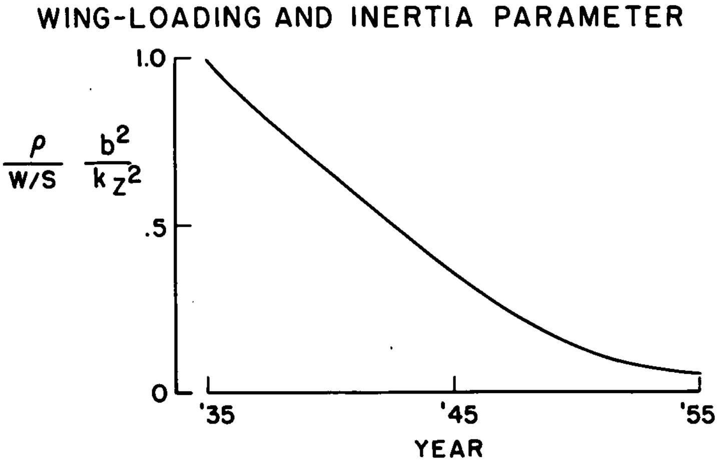


Figure 6

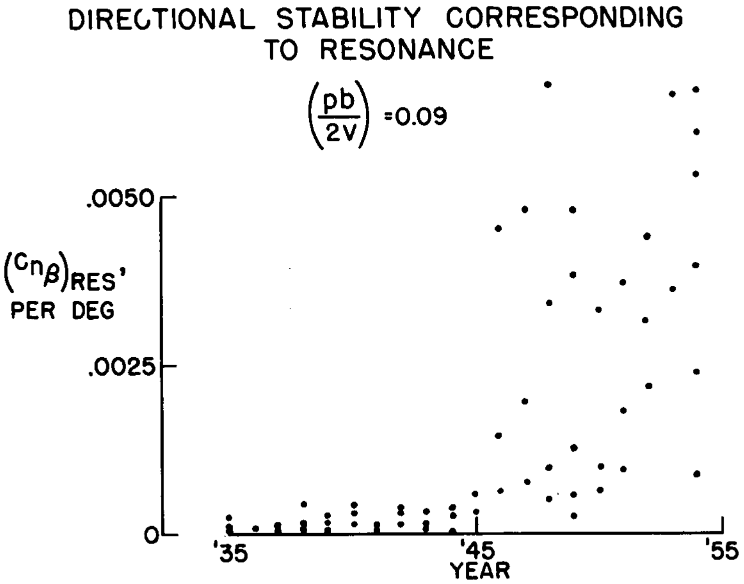


Figure 7

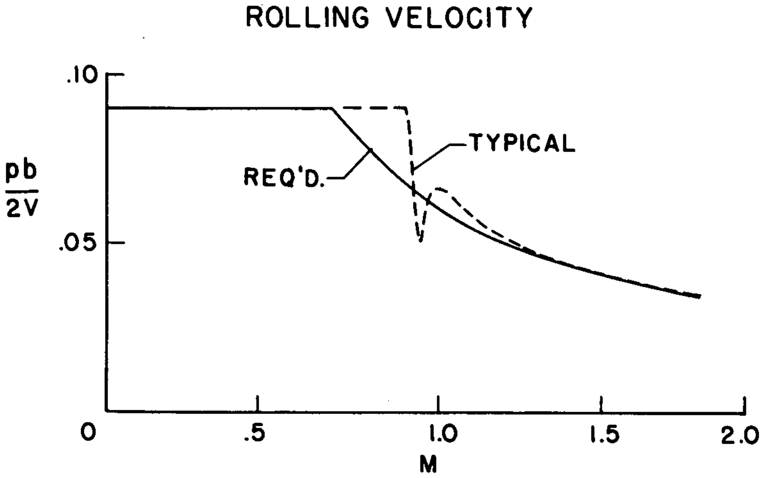


Figure 8