RESEARCH MEMORANDUM

DYNAMIC LATERAL BEHAVIOR OF HIGH-PERFORMANCE AIRCRAFT

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SUMMARY

Several proposed high-performance aircraft have been studied analytically and by model flight tests to define some problem areas in dynamic lateral behavior of high-speed aircraft which require specific attention. In particular, aileron control problems and Dutch roll characteristics with and without artificial damping were considered. The results indicate that effective dihedral and cross-control derivatives can have gross effects on the lateral stability and controllability of hypersonic gliders.

INTRODUCTION

Hypersonic gliders have been proposed which would extend regions of manned flight to speeds of 20,000 feet per second and altitudes above 200,000 feet. These airplanes, although they would fly to much higher altitudes than current aircraft, experience dynamic motions and control responses similar to those of current aircraft. This is so because the dynamic pressures encountered throughout the flight regime are appreciable; thus, significant aerodynamic forces and moments and airplane natural frequencies comparable to those of today's aircraft are obtained. As a result, dynamic stability and response characteristics remain important. In this paper several possible problem areas related to the lateral behavior of high-performance aircraft are examined.

SYMBOLS

b wing span

S wing area

M Mach number

*Title, Unclassified.

[redacted]

q	dynamic pressure
h	altitude, ft
k_1	autopilot gain, $-\delta_r/\beta$
k_2	autopilot gain, δ_r/δ_a
k_3	autopilot gain, $\delta_a/\dot{\varphi}$
I_X	moment of inertia about x-axis, slug-ft^2
I_Z	moment of inertia about z-axis, slug-ft^2
$t_{1/2}$	time to damp to 1/2 amplitude, sec

$$C_l = \frac{\text{Rolling moment}}{qSb}$$

$$C_n = \frac{\text{Yawing moment}}{qSb}$$

α	angle of attack
β	angle of sideslip
$\dot{\varphi}$	rolling velocity
δ_a	aileron deflection
δ_r	rudder deflection

$C_{n_\beta} = \partial C_n/\partial\beta$

$C_{l_\beta} = \partial C_l/\partial\beta$

$C_{n_{\delta_a}} = \partial C_n/\partial\delta_a$

$C_{l_{\delta_a}} = \partial C_l/\partial\delta_a$

$C_{n_{\delta_r}} = \partial C_n / \partial \delta_r$

$C_{l_{\delta_r}} = \partial C_l / \partial \delta_r$

DISCUSSION

Several stability and controllability problems related to lateral behavior of high-speed aircraft, such as effects of static lateral derivatives C_{n_β} and C_{l_β} on Dutch roll stability, aileron divergence criteria, and effects of C_{l_β} and cross-control derivatives on damper design, are considered.

In reference to the Dutch roll stability the following expression defines a parameter which is generally a primary factor in determining the undamped natural frequency of the Dutch roll mode. Negative values of this parameter

$$C_{n_{\beta,DYN}} = C_{n_\beta} - \frac{I_Z}{I_X} \alpha C_{l_\beta} \tag{1}$$

may lead to a divergence. Although the exact expression for the Dutch roll spring constant includes rotary derivative effects, this approximation which depends only on the static lateral derivatives C_{n_β} and C_{l_β} is adequate for most cases. For flight conditions in which rotary derivatives are large, these effects must be considered.

The contributing factors in $C_{n_{\beta,DYN}}$ are now considered. In addition to the directional stability, there is a contribution of effective dihedral which is proportional to the inertia ratio I_Z/I_X and angle of attack. For long, slender, high-speed aircraft, inertia ratios I_Z/I_X of 10 or more are common. Thus the term involving C_{l_β} can have a predominant effect even at moderate angles of attack. For example, if the aircraft has negative effective dihedral, this term can overcome directional stability and lead to a divergence. In an effort to obtain positive directional stability at high Mach numbers and angles of attack, designers are considering configurations, for example, ventral fins, which may lead to negative effective dihedral. Thus, although C_{n_β} is improved, $C_{n_{\beta,DYN}}$ may be decreased, and a marginally stable or unstable airplane will result.

Now consider the other condition of positive effective dihedral. With positive effective dihedral this term can compensate for negative directional stability and produce a stable airplane. An illustration of this favorable effect of positive effective dihedral and the importance of $C_{n_{\beta,DYN}}$ will now be presented.

Figure 1 shows plots of C_{n_β} and $C_{n_{\beta,DYN}}$ for a canard configuration discussed in reference 1. These parameters are plotted against angle of attack.

For this particular configuration having twin inboard vertical tails, C_{n_β} decreased with increasing angle of attack and reached large negative values in the high-angle-of-attack range, where negative values of C_{n_β} are normally associated with a directional divergence. The loss of C_{n_β} is attributed to an effective change in the angle of sideslip of the vertical tail associated with the vortex flow from the canard surfaces. However, the $C_{n_{\beta,DYN}}$ criterion indicates the airplane to be stable up to an angle of attack of 34°.

A model of this configuration was tested in the Langley full-scale tunnel by the free-flying-model technique at angles of attack of 28° to 35°. The model flew smoothly and was easy to control, but at the higher angles of attack where $C_{n_{\beta,DYN}}$ goes to zero, the pilot observed that the model was becoming difficult to control as expected.

The following expressions are criteria that should be satisfied when using rudder and aileron controls to maintain zero bank angle:

For the aileron alone:

$$C_{n_\beta} - C_{l_\beta} \frac{C_{n_{\delta_a}}}{C_{l_{\delta_a}}} > 0 \tag{2}$$

For the aileron plus rudder proportional to sideslip $\left(\delta_r = -k_1\beta\right)$:

$$C_{n_\beta} - C_{l_\beta} \frac{C_{n_{\delta_a}}}{C_{l_{\delta_a}}} + k_1\left(\frac{C_{n_{\delta_a}}}{C_{l_{\delta_a}}} C_{l_{\delta_r}} - C_{n_{\delta_r}}\right) > 0 \tag{3}$$

For the aileron plus rudder proportional to aileron $\left(\delta_r = k_2\delta_a\right)$:

$$C_{n_\beta} - C_{l_\beta}\left(\frac{C_{n_{\delta_a}} + k_2 C_{n_{\delta_r}}}{C_{l_{\delta_a}} + k_2 C_{l_{\delta_r}}}\right) > 0 \tag{4}$$

The first expression (eq. (2)) is a divergence criterion when aileron alone is used. This expression must be positive to avoid a lateral divergence. Divergence can result for combinations of (1) positive effective dihedral $\left(-C_{l_\beta}\right)$ and adverse yaw, since $C_{n_{\delta_a}}/C_{l_{\delta_a}}$ would be negative, and (2) negative effective dihedral and favorable yaw with $C_{n_{\delta_a}}/C_{l_{\delta_a}}$ being positive. The importance of this criterion has been demonstrated in flight tests of airplanes having positive effective dihedral and adverse aileron yaw.

Some unconventional controls proposed for preliminary hypersonic configurations have actually produced cross-control derivatives of the same order of magnitude as the basic control derivatives and results have been obtained recently at low speeds with free-flying models of such configurations. Figure 2 shows the ratio of aileron effectiveness parameters (yawing moment to rolling moment) of three hypersonic glider configurations (a flat-top, a flat-bottom, and an all-wing configuration) plotted against angle of attack. Positive direction corresponds to favorable aileron yaw.

Notice that the flat-top and all-wing configurations have aileron yawing moments twice as large as the rolling moments, whereas the flat-bottom configuration has relatively small aileron yaw. All three configurations have positive effective dihedral and in terms of the aileron-alone divergence criterion, the all-wing configuration with large adverse yaw is predicted to be divergent.

Models of these three configurations were flown at angles of attack of 10° to 20° using aileron control only. The flat-bottom model flew smoothly and was easy to control. The flat-top model experienced considerable yawing motion because of the low level of $C_{n_{\beta,DYN}}$ and the large aileron yaw. The all-wing model was rapidly divergent, as expected, and could not be controlled. After this test, the rudder of the all-wing model was linked to the aileron to reduce the aileron yaw effectively and the model became controllable. In general, when both rudder and aileron are used for control, the two cross-control derivatives, yaw due to aileron and roll due to rudder, are important in determining the divergence characteristics. Two automatic-control schemes for introducing deflections to alleviate this divergence condition have been examined.

The divergence criterion (eq. (3)) when the rudder is used proportional to sideslip angle in order to reduce sideslip has been given. The first part of this equation is identical to that of equation (2) and the second part is a function of the aileron and rudder effectiveness derivatives. For configurations which would be divergent with aileron-alone control, the possibility exists for stabilizing the system by the effect of the second term. Of course, the second term can be destabilizing too for values of cross-control derivatives having like algebraic signs and exceeding the primary derivatives $C_{l_{\delta_a}}$ and $C_{n_{\delta_r}}$.

The divergence criterion when the rudder is deflected proportional to the aileron in order to counter aileron yaw is given in equation (4). The aileron-alone criterion (eq. (2)) is modified by a $k_2C_{n_{\delta_r}}$ term in the numerator and a $k_2C_{l_{\delta_r}}$ term in the denominator. If k_2 is set equal to $-\frac{C_{n_{\delta_a}}}{C_{n_{\delta_r}}}$, this destabilizing term becomes zero. Thus, feedbacks in the form of rudder deflections proportional to sideslip angle and aileron deflection may be effective in alleviating divergence conditions.

These cross-control derivatives can also have an important effect on damper design. Both yaw and roll dampers may be required to provide satisfactory lateral characteristics at high altitudes. Next, a stability problem arising from the use of dampers with a hypersonic glider configuration is considered.

Figure 3 shows the effects of large variations of the cross-control derivatives on Dutch roll damping for a flat-bottom hypersonic glider configuration for a flight condition of $M = 6.86$ and an altitude of 130,000 feet. The ratio of $C_{n_{\delta_a}}$ to $C_{l_{\delta_a}}$ is plotted as the ordinate. The ratio $C_{l_{\delta_r}}/C_{n_{\delta_r}}$ is plotted as the abscissa. Curves of constant time to damp to 1/2 amplitude of 1, 2, and 5 seconds, and infinity are shown. This figure indicates the variations in the Dutch roll damping for combinations of cross-control derivatives up to ±2 after roll and yaw damper gains were selected to provide a Dutch roll damping just under 2 seconds. Generally large changes in damping can result from variation in these parameters. In particular for the range of cross-control derivatives shown for this airplane, large losses in Dutch roll damping can result for favorable aileron yaw and negative rolling moment due to rudder deflection (first quadrant). In fact, for some combinations of the ratios (1:1, for example) the damping is actually reduced to zero. This is by no means a general result. Other airplanes might experience damping losses for different combinations of these parameters.

In recent designs of damper systems, such problems have already arisen and in one case, for example, the problem was solved by feeding a yaw-rate signal into the roll channel to offset the rolling moment due to the rudder. Also interconnections between rudder and aileron have been used to alleviate the effect of large cross-control derivatives. Since airplanes are being designed to fly through a wider range of flight conditions, it is becoming increasingly difficult to avoid large values of cross-control derivatives, and this problem may become more critical.

In addition to the cross-control derivatives, dihedral effect C_{l_β} may also have an important effect on damper design. The effect of positive and negative effective dihedral on Dutch roll frequency has been discussed, and in figure 4 the results of a study to investigate damper-gain requirements for values of C_{l_β} of 0.027 and -0.027, are presented. Damping as $\frac{1}{t_{1/2}}$ is shown for the two lateral modes of primary concern, the Dutch roll oscillation and the damping-in-roll mode, as a function of roll-damper gain k_3 for a flight condition of $M = 6.86$ and an altitude of 130,000 feet. The cross-control derivatives were considered to be zero. The solid lines on the figure correspond to the case of $C_{l_\beta} = 0.027$ or negative effective dihedral. A yaw-damper gain was selected for which the Dutch roll oscillation would damp to 1/2 amplitude in 2.5 seconds, based on a one degree of freedom in yaw response. With this yaw damper and zero k_3, no roll damper, the damping-in-roll mode is unstable and indicated a rapid roll divergence. The Dutch roll oscillation has good damping at this point. As k_3 is increased, the damping-in-roll mode is made stable but the damping of the Dutch roll oscillation decreases markedly.

For the case of $C_{l_\beta} = -0.027$, positive effective dihedral, two important differences should be noted. First, the damping-in-roll mode is stable even for $k_1 = 0$, and, secondly, as k_1 is increased, the Dutch-roll damping is higher. A comparison of both sets of curves clearly indicates the importance of C_{l_β} in determining roll- and yaw-damper gains and the poor damping which may result with negative effective dihedral.

CONCLUSIONS

In conclusion, some studies of high-performance aircraft have indicated that:

1. For recently proposed high-performance aircraft having high inertia ratio I_Z/I_X, the effective dihedral parameter C_{l_β} assumes greater importance in affecting the lateral stability characteristics of the airplane. In particular, negative effective dihedral may lead to a divergence.

2. Attention must be given to the cross-control derivatives of hypersonic aircraft in avoiding divergence conditions and adverse effects of dampers.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 18, 1958.

REFERENCE

1. Baals, Donald D., Toll, Thomas A., and Morris, Owen G.: Airplane Configurations for Cruise at a Mach Number of 3. NACA RM L58E14a, 1958.

DIRECTIONAL STABILITY PARAMETERS OF CANARD CONFIGURATION

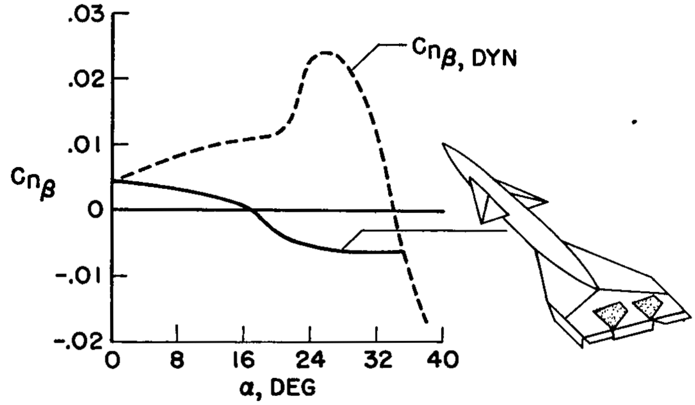

Figure 1

LOW - SUBSONIC - SPEED LATERAL CONTROL

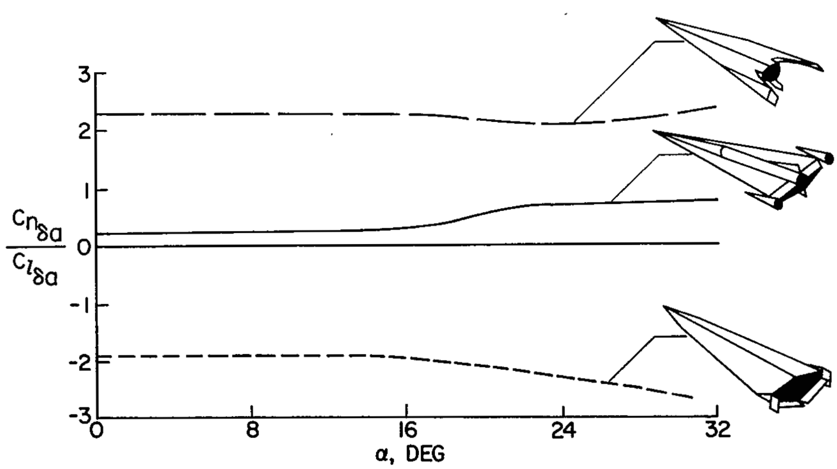

Figure 2

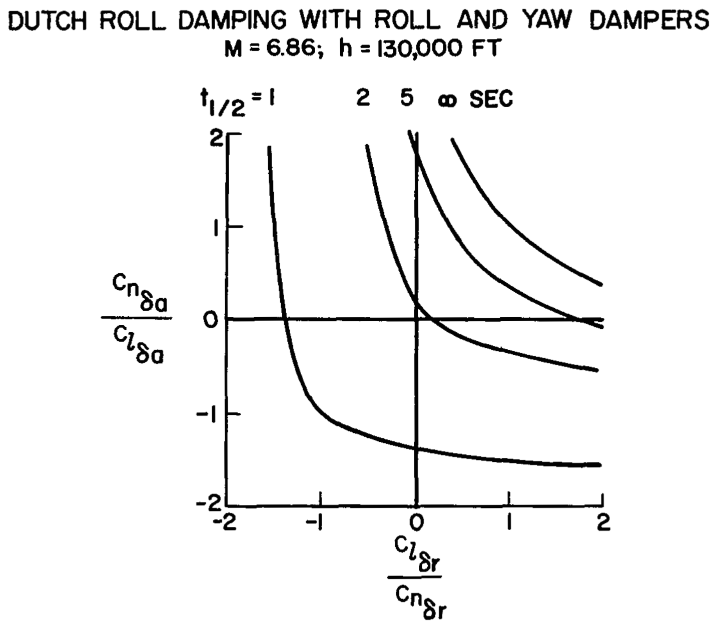

Figure 3

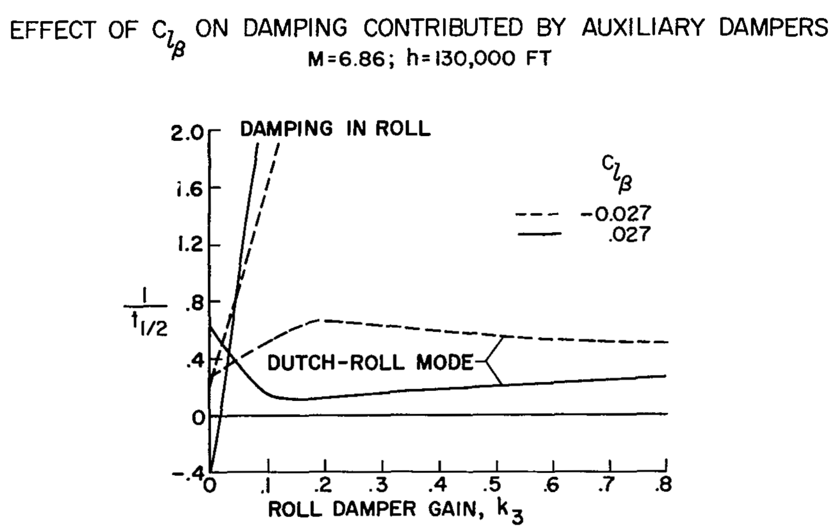

Figure 4

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