7. RECENT AERODYNAMIC STUDIES APPLICABLE TO HIGH PERFORMANCE MANEUVERING AIRCRAFT

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SUMMARY

Recent emphasis on air-to-air combat has led the NASA to intensify the research of methods for improving the maneuvering normal load factor while retaining a high degree of performance for other combat missions.

The results of recent wing buffeting tests at high subsonic speeds have shown that the use of trailing-edge flaps delays buffeting onset by delaying separation. The static margin at supersonic speeds can be reduced and the normal load factor increased with the use of either retractable canards or variable sweep aft horizontal tails. Positioning the horizontal tail low on the fuselage was shown to be superior on two counts: (1) At supersonic speeds the lower tail experiences an increase in control effectiveness with increasing lift, and (2) the complete configuration aerodynamic center shift with Mach number is smaller with the low tail.

INTRODUCTION

The trend to design one aircraft to accomplish a variety of missions leads to compromises which limit the maneuverability of the aircraft. As an example of the conflicting requirements, the high wing loading dictated by gust alleviation in the low level supersonic interdiction mission tends to produce limits on the maneuvering normal load factor at moderate dynamic pressures. Recent emphasis on maneuverability in air-to-air combat has led NASA to intensify research into the methods by which improvements in load factor may be realized while retaining a high level of performance for other missions.

Figure 1 will serve to illustrate the subjects chosen for discussion in this paper. The typical load factors are shown as a function of Mach number at a wing loading of 100 pounds per square foot at 36 000 and 60 000 feet. The structural limit of fighter aircraft is shown at a load factor of 7.33. Normally, below the structural line, the load factor is restrained by aerodynamic considerations; note that the maximum lift coefficient $C_{L,max}$ limits the load factor at low speed. At Mach numbers between 0.60 and 1.0, buffeting limits the load factor rather than $C_{L,max}$. At supersonic speeds aerodynamic longitudinal control power usually curtails the load factor as shown by the position of the control boundary below the $C_{L,max}$ curve. The effect of increasing altitude is shown by comparison of the supersonic load factors at altitudes of 36 000 and 60 000 feet. The obvious result is a decreased load factor at all Mach numbers due to the reduced dynamic pressure. For a typical engine size it would be possible to maintain speed at the load factors indicated along the dashed line. At load factors higher than this line, the aircraft will decelerate, but it is still useful to study ways to increase load factor in the direction of $C_{L,max}$ or the structural limit especially at the higher altitudes in order to improve maneuverability.

The maneuverability considerations given in this paper are as follows: Results of some recent buffet tests, made in an attempt to raise the buffet limit at subsonic speeds, are presented. The effect of static margin changes at supersonic speeds, investigated in an attempt to raise the control limit, is discussed in terms of instantaneous load factor. Also, some methods of increasing longitudinal control power at supersonic speeds are presented.

COEFFICIENTS AND SYMBOLS

b	wing span
C_L	lift coefficient
$C_{L,max}$	maximum lift coefficient
C_m	pitching-moment coefficient
$\bar{c}$	mean aerodynamic chord
F	net thrust
h	altitude
i_t	tail incidence
M	Mach number
$\dot{m}_1$	primary flow rate
$\dot{m}_2$	secondary flow rate
n	load factor, $\frac{\text{Lift}}{\text{Weight}}$
S	reference area
S_{basic}	basic reference area
S_t	exposed tail area
W	weight

y_f	lateral extent of trailing-edge flap
y_p	lateral distance to wing pivot
z_t	tail height
δ_f	flap deflection
δ_j	jet deflection
Λ_t	tail leading-edge sweep angle
Λ_w	wing leading-edge sweep angle
λ	taper ratio
σ	root-mean-square bending moment

Subscripts:

max	maximum
T	take-off conditions

RESULTS AND DISCUSSION

Buffeting at High Subsonic Speeds

Aerodynamic buffeting at high subsonic speeds has been defined as a structural response to separated flow caused by shock—boundary-layer interaction. The aircraft designer has control of a number of parameters such as wing airfoil section, sweepback, aspect ratio, and, at the higher subsonic speeds, variations in the vehicle area diagram (ref. 1), all of which have an influence on buffeting. The compromises in a given design, however, usually are made in a direction to improve performance rather than buffeting.

The wind tunnel is a powerful experimental tool for assessing wing buffeting onset. This fact has been shown by comparison of a number of model and full-scale airplane tests. (See refs. 2, 3, and 4.) Tests of a general research nature have been undertaken recently at Langley Research Center and are intended to explore means of raising the lift at which buffeting first occurs. Figure 2 illustrates some of these results. The root-mean-square value of the oscillating bending strain σ is plotted as a function of C_L for three wing sweeps of the model shown. An NACA 2408 wing section, parallel to free stream, was used on the outer panel in the 25° sweep position. The values of σ were obtained by monitoring the output of a strain gage mounted in the root section of the wing as indicated in the sketch. These data were acquired at a Mach number of 0.86. The rapid increase in σ at about

$C_L = 0.50$ is taken as the onset of buffeting. For the flight conditions listed in the figure, a wing loading of 100 pounds per square foot and an altitude of 36 000 feet, the maximum load factor before buffeting onset in only 1.25. Changing wing sweep angle from 25° through 45° is seen to have only a minor effect on the initial buffeting. However, past onset at $C_L = 0.80$, the effect of increasing sweep angle is a marked reduction in buffeting intensity.

Whereas the sweep effect shown is beneficial, the objective of the program is to delay the buffeting onset to a higher lift. One possible method of alleviating buffeting onset is through the use of trailing-edge flaps, which allow the high loads to develop at low angles of attack. The physical effect on the wing is a smoothing of the chordwise loading and the delay of separation. Some buffeting measurements are shown for a configuration with trailing-edge flaps in figure 3.

The root-mean-square bending moment σ is shown in figure 3 as a function of C_L for a wing sweep of 35° at a Mach number of 0.86. The flaps-retracted (dashed) curve is repeated for reference. Other curves represent data for flaps extended 1/3 of the local chord from about 1/4 to 3/4 of the wing semispan. A comparison of the flaps-retracted curve with that for the flaps extended at zero deflection reveals that the additional wing area simply reduces the buffeting intensity, having a negligible effect on buffet onset. As the flap is deflected, however, the onset point moves to a value of C_L of about 0.67. With the assumptions of the previous figure, the maximum load factor before buffet onset is approximately 1.7.

The flap span and flap chord were selected arbitrarily for these tests. It was assumed that some span at the tip of the wing would be required for an aileron roll control, and therefore the flap span was limited. It is of interest to assess the effect of flap span. Figure 4 shows similar results obtained with a plain flap on which the span was varied. The root-mean-square fluctuating moment is plotted as a function of the lift coefficient at a Mach number of 0.86. The flap deflection for the solid and broken curves is $\delta_f = 10^\circ$. The dashed curve is repeated once more for reference. The broken curve represents data for a flap extended from about 1/4 to 3/4 of the wing semispan. The solid curve shows data taken when the flap is deflected 10° from 1/4 of the wing semispan to the wing tip. These data indicate that the improvement in lift at which buffeting occurs is not sensitive to the span of the plain flap tested.

These data do not represent any attempt to optimize the flap configuration or flap deflections but are presented to indicate some early results of a program recently undertaken by the NASA to improve buffeting.

Supersonic Considerations

As mentioned earlier the supersonic maneuverability is usually limited by the control power available. In order to move the control boundary toward the structural limit or the lift limit, two different approaches may be considered. First, reducing the supersonic longitudinal stability level will increase the amount of instantaneous load factor for a given control and, second, the control power itself could be improved, thus increasing the load factor.

Longitudinal Stability

Various wing geometry effects are shown in figure 5. The first effect to be noted in this figure is the effect of planform noted in paper no. 6 by Lamar and Alford where it was indicated that the clipped arrow wing had less aerodynamic center shift than did the delta wing. On the left is a comparison of an arrow and two delta wings, all clipped to a taper ratio of 0.125. All wings had a leading-edge sweep angle of 60°. Similar planforms were shown in paper no. 6. The effect of this reduced aerodynamic center shift on the trimmed normal load factor plotted against altitude is shown for $M = 3.0$. The assumed conditions are $W/S = 100$ pounds per square foot for the basic wing and a constant tail load available for trim at the maximum load factor. A comparison of the load factors at a 70 000-foot altitude indicates that the arrow wing (dashed curve) gives 4.0g, whereas the delta (dot-dash curve) at the same wing area has 2.3g. This difference in load factor is due to the difference in aerodynamic center shift between these two planforms.

The second effect depends on the size of the wing. An examination of the lift-curve slopes of the two wing shapes at subsonic speeds showed the arrow wing to have the lower landing speed at a given angle of attack. Increasing the size of the delta by a factor of 1.3 to give comparable landing performance and locating the wing to give the same subsonic static margin appeared logical. The results of these changes in the wing are indicated by the solid curve which shows an even lower trimmed load factor at Mach 3.0 ($n = 2.0$). This result, even though surprising at first, is easily understood when the assumption of a constant tail load is recalled. The larger wing has a larger load shift measured in feet at the higher Mach numbers; the constant tail power then cannot balance as high a value of wing lift and if the airplane weight is constant the trimmed load factor decreases. Increasing the wing size decreases the supersonic maximum trimmed load factor when the aerodynamic control power is limited. If, on the other hand, the configuration is limited in lift and not limited in control, increasing the wing size increases the available load factor; therefore, wing loading, for the conditions considered, is not a unique parameter for the determination of maximum load factor at supersonic speeds.

Figure 6 illustrates the effect of pivot location for the variable sweep wing. The wing pivot location is given in terms of the semispan of the high sweep wing. Paper no. 6 discussed the aerodynamic center shift with sweep and its sensitivity to the location of the wing pivot. The reduction in static margin afforded by the pivot change accounts for the increase in load factor shown in the figure. At 60 000 feet, the pivot at 42 percent of the semispan gives a load factor of 1.5 whereas the pivot at 56 percent of the semispan gives about 2.2.

Although the Mach effect on the wing is the primary cause of the increase in stability in going from subsonic to supersonic speeds, application of variable geometry to other components of the aircraft could be utilized to offset the effect of the undesirable supersonic loading. Two possible methods which have been studied are shown in figure 7.

The retractable canard concept illustrated on the left of figure 7 (refs. 5, 6, and 7) had a highly swept wing and a low aft horizontal tail for control. With the canard retracted, the subsonic conditions fix the center of gravity. At a supersonic speed of about $M = 2.0$ with $W/S = 100$ pounds per square foot, the available load factor is about 2.6 at an altitude of 60 000 feet. As the canard is extended at supersonic speeds, the reduction in static margin allows trim to a load factor of 4.6 with the same control deflection. If the canard can be unfolded with some positive incidence, the gain in load factor can be even higher.

Another concept for the reduction of the supersonic static margin is the variable sweep horizontal tail, illustrated on the right of figure 7. This concept assumes that, to reduce the wave drag, the tail must be swept back during supersonic flight (ref. 8). At subsonic speed, however, the tail may be unswept to furnish a greater span and increased effectiveness, thereby allowing a more aft center of gravity. The lower supersonic static margin due to this more aft center of gravity improves the load factor to about 6.5 with the variable sweep tail as contrasted with about 2.2 for the forward center of gravity associated with the fixed tail. The effectiveness of the concept is sensitive to the tail arm however, as it is possible for the tail arm to decrease faster than effectiveness increases on short coupled configurations.

Longitudinal Control

The replacement of the elevator control with the all-movable horizontal tail was probably the first step toward improved supersonic longitudinal control effectiveness; all-movable tails have been widely accepted for many years. The advantages of tail length, size, and efficient planform with regard to control effectiveness are obvious, but quite often compromises must be made because of considerations such as aircraft length or weight. One approach which may be open to the designer, however, is to locate the horizontal tail in the most advantageous flow field. At subsonic speeds the importance of the vertical location of the horizontal tail is well documented and the desirability of a low tail position for stability is generally accepted. In order to determine the effect of the vertical location of the horizontal tail on supersonic maneuverability, a systematic investigation was recently undertaken by the NASA. The configuration studied is shown in figure 8.

Two sizes of the horizontal tail were tested. The sizes and locations were selected to keep the horizontal-tail volume coefficient a constant. Each tail then was tested in two vertical locations, in the chord plane of the wing and $0.06\bar{c}$ below the wing. Control effectiveness as well as the stability contribution of each tail was measured. The effect of vertical position for the small tail is shown in figure 9.

Presented in figure 9, for a Mach number of 2.16, is pitching-moment coefficient as a function of lift coefficient for the chord-plane tail (shown dashed) and for the low tail (shown solid). Note that both tails show the same stability level and essentially the same level of control effectiveness at zero lift. As lift increases the chord-plane tail loses effectiveness and the low tail gains effectiveness with the result that the low tail trims at a lift coefficient which is 40 percent higher than that associated with the chord-plane tail, both having -20° incidence.

Essentially the same result was found when the large closely coupled tails were tested as shown in figure 10. The pitching-moment coefficient is plotted as a function of lift coefficient at a Mach number of 2.16 for the chord-plane tail (dashed) and the low tail (solid). Compared as before with the same moment reference (or center of gravity), the low tail shows about a 50-percent increase in trimmed C_L with -20° of incidence.

Further tests on this model showed that the low tail has, as might be expected, a higher stability contribution at subsonic speeds due to its position below the high downwash field of the wing and, therefore, less stability increase with Mach number. If the results are compared on the basis of both the low tail and the chord-plane tail having the same static margin at $M = 0.90$, the low tail result is even more dramatic. These data, adjusted, are shown as the dotted curve (extrapolated to trim as the supersonic tests were not carried to sufficiently high lift). These effects for the large closely coupled tail are shown in figure 11 in which load factors as a function of altitude are compared. At 60 000 feet the chord-plane tail gives a load factor of 2.6. At the same center of gravity the low tail gives 3.8. At a static margin equal to that of the configuration with the chord-plane tail at $M = 0.90$, the value (extrapolated) for the low tail is 5.8.

Another method, which appears to offer a great deal of promise for enhancing load factor at supersonic speeds, involved deflecting the thrust of the jet engine. A possible method of deflecting the thrust is illustrated in figure 12. On the right of the figure a duct is shown schematically. Hot gas is taken from the convergent section and bypassed around the throat and re-injected in the divergent section where it separates the main flow in a controlled manner proportional to the injected flow. The effect of deflection of the gross thrust at $M = 2.16$ on load factor is a function of altitude. The solid curve shows the available load factor with -25° incidence of the horizontal tail (data from ref. 9). The dashed curve shows the calculated load factor as the exhaust of the engine is deflected -5° in combination with deflection of the horizontal tail. The engine is assumed to be sized to give a thrust-weight ratio of 0.80 at take-off conditions. Once again at 60 000 feet the load factor has improved from about 2.2 to about 5.6 as a result of deflection of the thrust.

Data obtained on a similar nozzle configuration indicate that to deflect the jet -5°, about 6 percent of the primary nozzle flow is required for re-injection.

CONCLUDING REMARKS

In conclusion, some results of recent wing buffeting tests have shown that the moderate increases in wing sweep for variable sweep wings provide a significant reduction in the buffeting intensity at high subsonic speed. The use of trailing-edge flaps delays buffeting onset by redistributing the chord load and delaying separation.

A number of methods were shown whereby the static margin at supersonic speeds can be reduced with a consequent improvement in the normal load factor. These methods included retractable canards and variable sweep aft horizontal tails.

Positioning the horizontal tail low on the fuselage as opposed to positioning on the chord plane of the wing was shown to be superior on two counts: (1) the lower tail experiences an increase in control effectiveness with lift whereas the effectiveness of the chord-plane tail decreases as lift increases, and (2) the aerodynamic center shift with Mach number appears to be much smaller when the tail is mounted low on the fuselage. An alternate system for aerodynamic control is discussed, which involves deflection of the main flow of the jet engines; approximately 6 percent of the main nozzle flow is required to deflect the jet -5°.

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ILLUSTRATIVE LOAD FACTOR DIAGRAMS

W/S = 100 LB/SQ FT

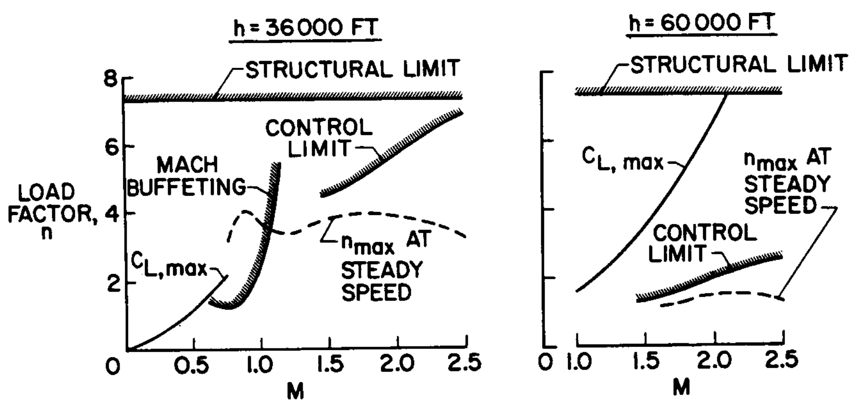

Figure 1

EFFECT OF WING SWEEP ON BUFFETING MOMENT

M = 0.86

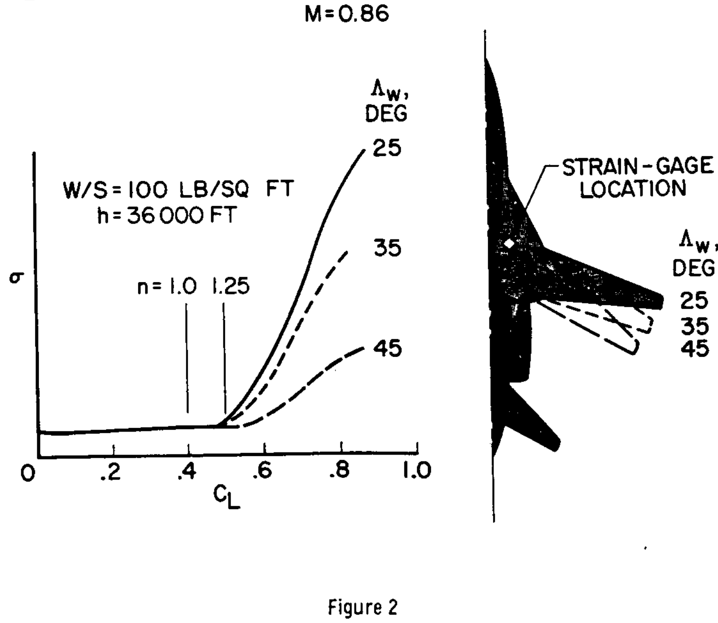

Figure 2

EFFECT OF FLAP DEFLECTION ON BUFFETING MOMENT

M=0.86; Λ_w=35°

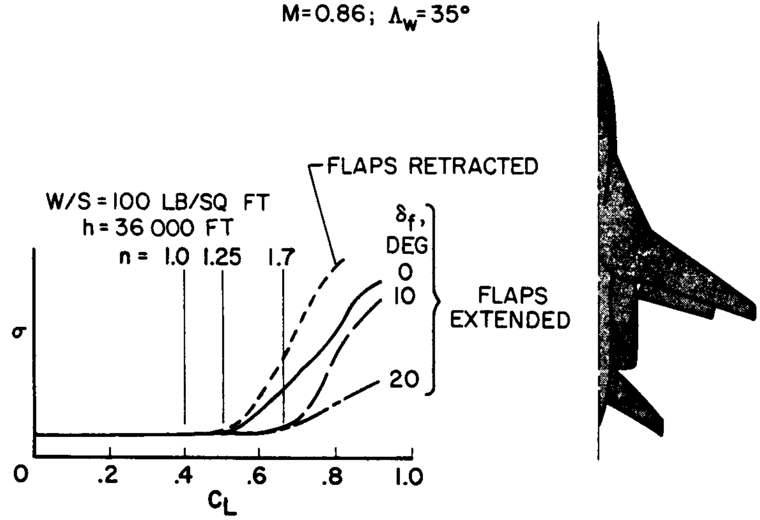

Figure 3

EFFECT OF FLAP SPAN ON BUFFETING MOMENT

M=0.86; PLAIN FLAPS; Λ_w = 35°

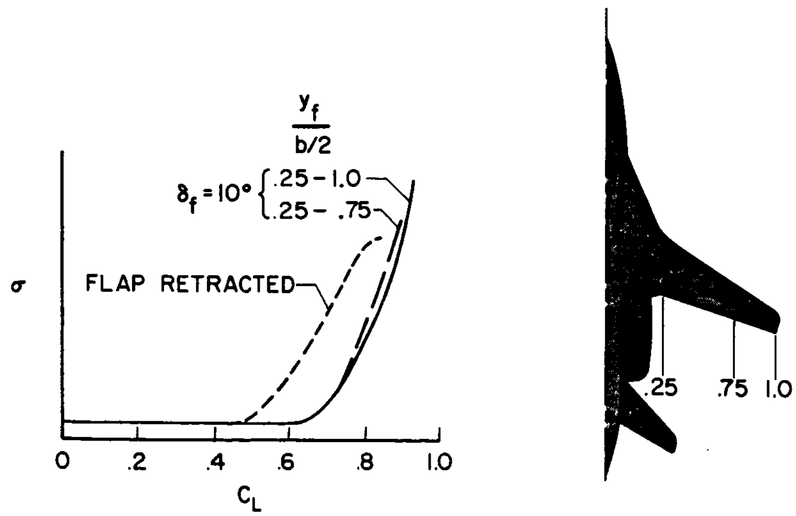

Figure 4

EFFECT OF WING GEOMETRY

CONSTANT TAIL LOAD, W/S_{basic} = 100 LB/SQ FT

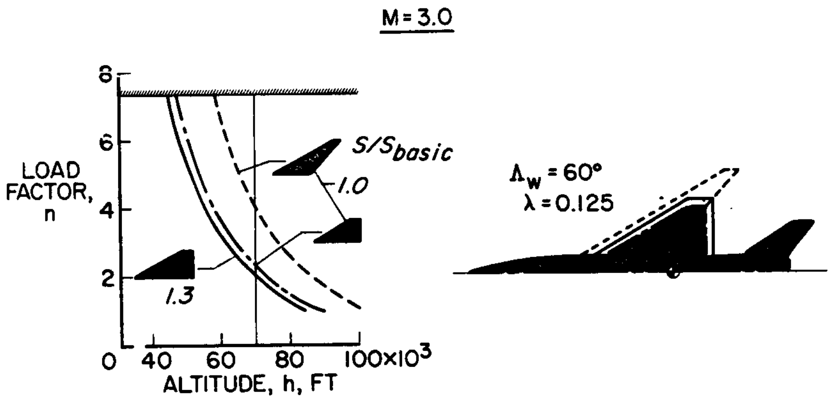

Figure 5

EFFECT OF PIVOT LOCATION

W/S = 100 LB/SQ FT

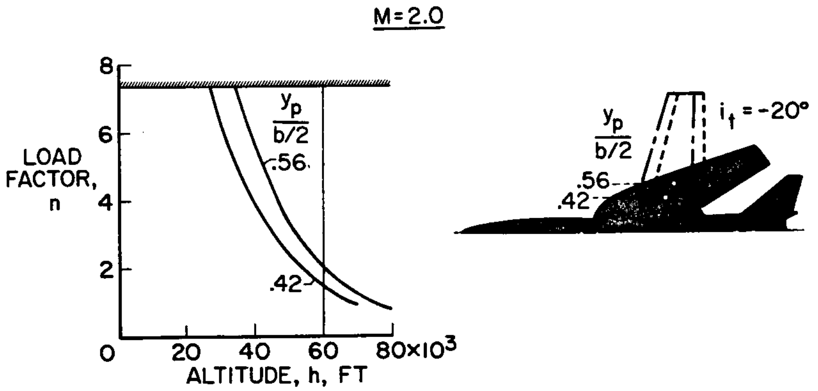

Figure 6

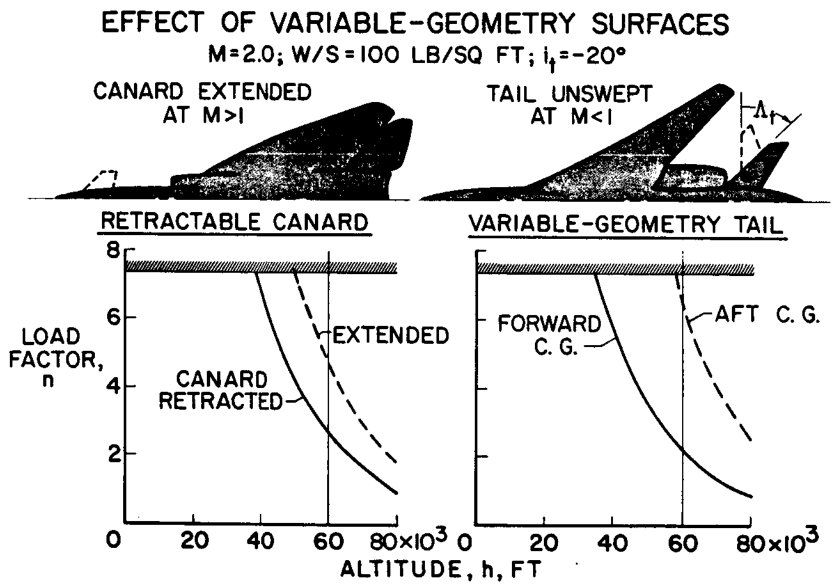

Figure 7

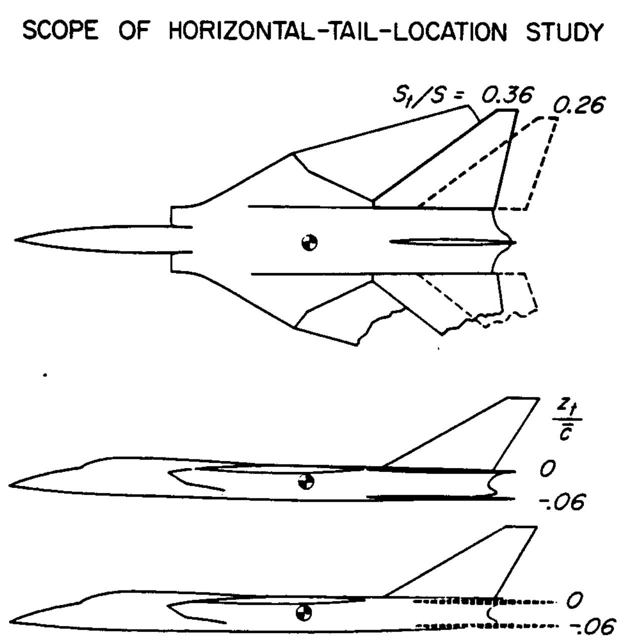

Figure 8

EFFECT OF HORIZONTAL-TAIL LOCATION

M = 2.16; $S_t/S = 0.26$

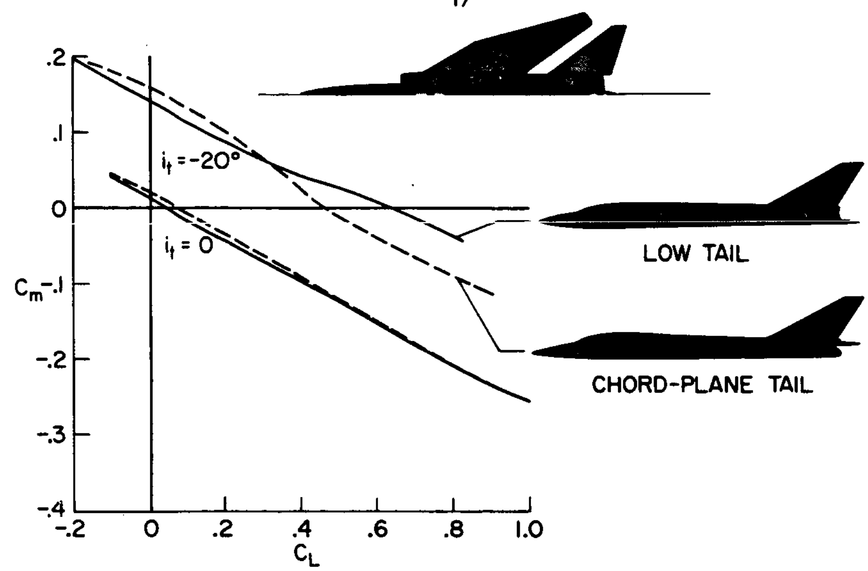

Figure 9

EFFECT OF HORIZONTAL-TAIL LOCATION

M = 2.16; $S_t/S = 0.36$

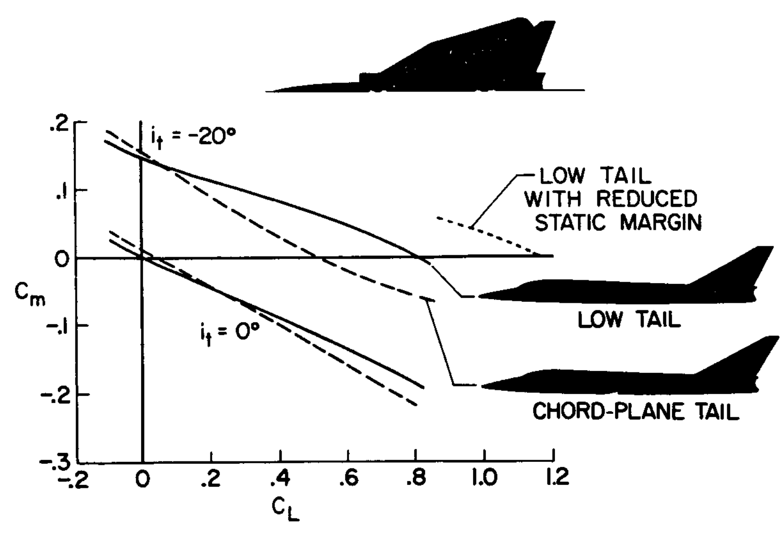

Figure 10

VARIATION OF LOAD FACTOR WITH ALTITUDE
$M = 2.16$; $W/S = 100$ LB/SQ FT; $S_t/S = 0.36$

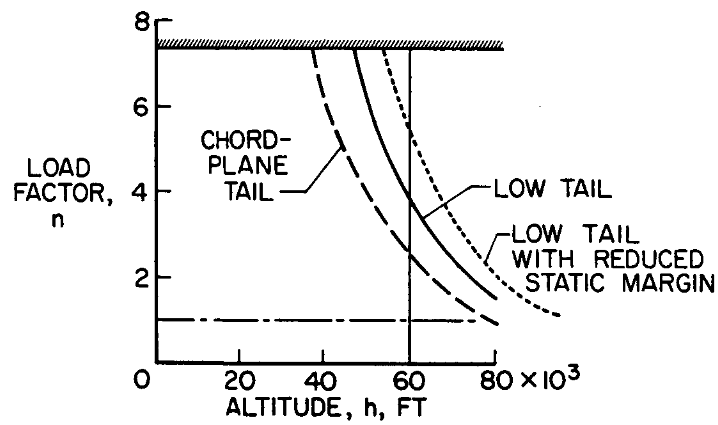

Figure 11

CALCULATED EFFECT OF THRUST DEFLECTION
$M = 2.16$; $(F/W)_T = 0.80$; $W/S = 100$ LB/SQ FT

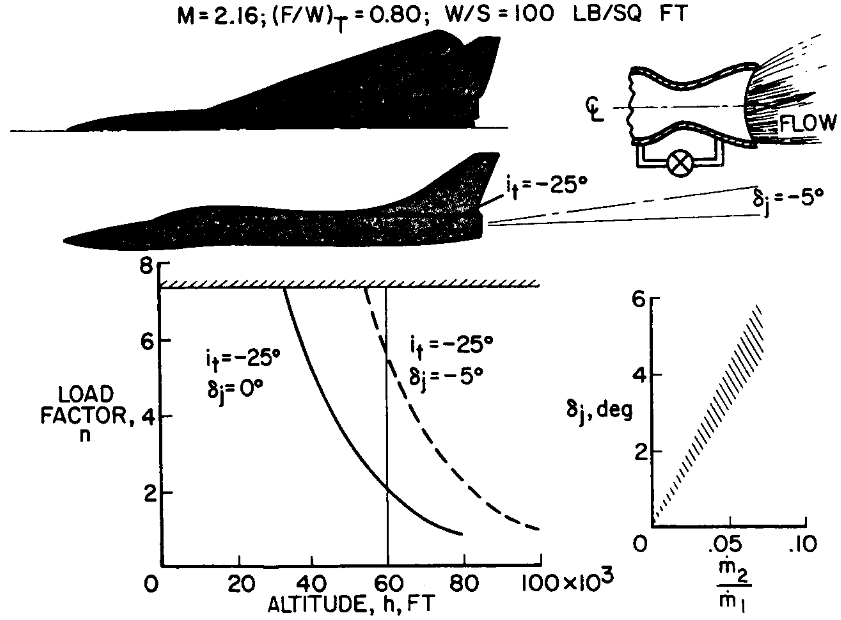

Figure 12