6. AERODYNAMIC-CENTER CONSIDERATIONS OF WINGS AND WING-BODY COMBINATIONS

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SUMMARY

Aerodynamic-center variations with Mach number are considered for wings of different planform. The normalizing parameter used is the square root of the wing area, which provides a more meaningful basis for comparing the aerodynamic-center shifts than does the mean geometric chord. The theoretical methods used are shown to be adequate for predicting typical aerodynamic-center shifts, and ways of minimizing the shifts for both fixed and variable-sweep wings are presented.

INTRODUCTION

In the design of supersonic aircraft, a detailed knowledge of the aerodynamic-center position is important in order to minimize trim drag, maximize load-factor capability, and provide acceptable handling qualities. One of the principal contributions to the aerodynamic-center movement is the well-known change in load distribution with Mach number in going from subsonic to supersonic speeds. In addition, large aerodynamic-center variations are quite often associated with variable-geometry features such as variable wing sweep.

The purpose of this paper is to review the choice of normalizing parameters and the effects of Mach number on the aerodynamic-center movement of rigid wing-body combinations at low lift. For fixed wings the effects of both conventional and composite planforms on the aerodynamic-center shift are presented, and for variable-sweep wings the characteristic movements of aerodynamic-center position with pivot location and with variable-geometry apex are discussed.

Since systematic experimental investigations of the effects of planform on the aerodynamic-center movement with Mach number are still limited, the approach followed herein is to establish the validity of the computative processes by illustrative comparison with experiment and then to rely on theory to show the systematic variations. The two theories used in this paper are for the wing alone in unseparated flow. One is a modified Multhopp subsonic lifting-surface theory developed by the senior author (unpublished), and the other is a supersonic lifting-surface theory (ref. 1). For wings experiencing separated flow these theories are not adequate for predicting the aerodynamic-center movement.

SYMBOLS

A aspect ratio

a distance from apex of high-sweep wing to apex of low-sweep wing (see fig. 10)

b span

C_L lift coefficient

C_p pressure coefficient, $\dfrac{p_{local} - p_{free\ stream}}{q}$

ΔC_p incremental pressure coefficient, $C_{p,upper} - C_{p,lower}$

$\bar{c}$ mean geometric chord

c_r root chord of basic planform

c_t tip chord of basic planform

d longitudinal distance from root trailing edge to tip trailing edge

K constant

l longitudinal distance from apex to tip trailing edge

M Mach number

p static pressure

q free-stream dynamic pressure

S wing area

x chordwise distance from apex of high-sweep wing to plane-of-symmetry intercept with trailing edge of free-floating apex

$\bar{x}_M$ chordwise distance from a reference point to aerodynamic center at any Mach number

$\left.\begin{matrix}\bar{x}_{M=0}, \bar{x}_{M=0.2}, \bar{x}_{M=0.25} \\ \bar{x}_{M=2}, \bar{x}_{M=3}\end{matrix}\right\}$ chordwise distance from a reference point to aerodynamic center at specific Mach number indicated by subscript

$\Delta\bar{x}$ incremental change in aerodynamic-center location

y_b spanwise distance from plane of symmetry to leading-edge break

y_p spanwise distance from plane of symmetry to pivot

α angle of attack

Λ leading-edge sweep of wing

Λ_o leading-edge sweep of outer panel

Λ_t leading-edge sweep of cranked wing tip

λ taper ratio

REQUIREMENT OF A NORMALIZING PARAMETER

A knowledge of the actual dimensional movement of the aerodynamic center is required in order to determine the out-of-trim moments which must be balanced by the control surface. Thus, in the selection of a normalizing parameter the need for a reference length which, for a given wing area, is independent of planform is considered to be of primary importance. The reference length selected is the square root of the wing area $\sqrt{S}$, which, of course, is independent of planform and therefore provides fractional aerodynamic-center movements that are proportional to the actual dimensional shifts.

The customary use of the mean geometric chord $\bar{c}$, although adequate for normalizing the aerodynamic-center shift for a given planform, is not convenient when comparing planforms, since the magnitude of $\bar{c}$ is dependent upon planform. The relationship between $\bar{c}$ and $\sqrt{S}$ is given both algebraically and graphically in figure 1 for wings which fit within the geometry limitations shown and may be of help in transferring aerodynamic-center shifts from one normalizing parameter to another.

DISCUSSION

Comparison of Theory and Experiment

Some typical experimentally determined aerodynamic-center shifts with Mach number (ref. 2), which are useful in evaluating the theories and the previously mentioned normalizing parameters, are presented in figures 2 and 3.

The experimental shifts, together with theoretical predictions, are shown in figure 2 for a series of delta wings with aspect ratios ranging from 2 to 4. In this figure $\Delta\bar{x}$ is the distance between the aerodynamic-center location at a Mach number of 0.25 and the aerodynamic-center location at any Mach number. The mean geometric chord $\bar{c}$ and the square root of the wing area $\sqrt{S}$ are used as normalizing parameters, and both $\Delta\bar{x}/c$ and $\Delta\bar{x}/\sqrt{S}$ are plotted as functions of Mach number. When the aerodynamic-center shift is based on the respective $\bar{c}$, the delta wing with the lowest aspect ratio has the smallest incremental change in aerodynamic-center location at the supersonic Mach numbers. However, when the aerodynamic-center shift is based on the respective $\sqrt{S}$, all three wings exhibit essentially the same fractional change in aerodynamic-center location throughout the Mach number range. The theories predict reasonably well the aerodynamic-center shifts for these delta-wing—bodies.

Figure 3 presents three wing-body combinations and illustrates the effect of wing sweep and taper ratio on the aerodynamic-center shift with Mach number. The wings are of aspect ratio 3 and have planforms ranging from a trapezoidal shape to a delta shape. Of the three wing-body combinations shown, the delta-wing—body configuration is seen to exhibit the smallest change in aerodynamic-center location for Mach numbers greater than 1 when $\bar{c}$ is used as the normalizing parameter. However, when $\sqrt{S}$ is used as the normalizing parameter, the aerodynamic-center shift for the sweptback-wing—body configuration is almost as small. Again the agreement between theory and experiment is reasonable.

When the trapezoidal, sweptback, and delta planforms are sized for take-off and landing conditions at $\alpha = 12^{\circ}$, the lift developed on each planform is taken into account, as shown in figure 4. The delta wing no longer exhibits the smallest aerodynamic-center shift since its value of lift-curve slope is the lowest.

Fixed-Wing Studies

In figures discussed subsequently, the aerodynamic-center shifts have been computed by the theoretical methods. For wings which have fixed planforms, the reference length is the $\sqrt{S}$ of each planform.

The results of one such aerodynamic-center study for a series of conventional fixed wings with planform variation in sweep and in taper and notch ratios are presented in figure 5. For a delta wing, $d/l = 0$ and for an arrow wing, $d/l > 0$. For illustrative purposes both the effect of changing the leading-edge sweep and the notch ratio when the taper ratio is zero and the effect of changing the taper and notch ratios when the leading-edge sweep angle is 60° are presented.

When the taper ratio is zero, a decrease in $\Delta\bar{x}/\sqrt{S}$ of about 0.05 occurs as the notch ratio is increased from 0 to 0.5 for leading-edge sweep angles of 45° and 60°. For a sweep angle of 70°, $\Delta\bar{x}/\sqrt{S}$ at first decreases approximately 0.01 and then increases about 0.01 above its value at $d/l = 0$. At any particular notch ratio, the wing with the lowest sweep shows the smallest aerodynamic-center shift.

When the wing leading-edge sweep angle is 60°, decreases in $\Delta\bar{x}/\sqrt{S}$ of 0.05, 0.09, and 0.12 occur over the range of notch ratios considered for taper ratios of 0, 0.25, and 0.50, respectively. At any particular notch ratio, the wing with the lowest taper ratio exhibits the smallest aerodynamic-center shift. When the supersonic Mach number is other than 3, different trends in the aerodynamic-center movement may occur with increasing notch ratio.

One method of minimizing the aerodynamic-center shift of an arrow wing is to reduce the sweep of the wing tip by shearing it forward. Some calculated results illustrating this technique are presented in figure 6. The basic arrow wing has a sweep of 74°, and $\Delta\bar{x}/\sqrt{S}$ is reduced to about half its original value by shearing the tip forward from 74° to 55°. The reason for this reduction is that wings with cranked tips carry more of the loading inboard where the sweep is higher and where the value of lift-curve slope is less influenced by Mach number. Thus, the inner panel tends to pull the aerodynamic center forward with increasing supersonic Mach number.

One method of reducing the aerodynamic-center shift of a delta wing is the addition of a forewing inboard. In figure 7 the effect of such an addition is presented as a function of the leading-edge-break location and apex extension. A reduction in the aerodynamic-center shift is obtained for each apex location as $\frac{y_b}{b/2}$ is increased from 0 to 0.5. At any particular value of leading-edge-break ratio within the range examined, the wing with the most forward apex or the longest root chord has the smallest aerodynamic-center shift, because the inboard sweeps are higher and therefore the inner panel has a lower aspect ratio which gives it an essentially invariant value of lift-curve slope with Mach number. However, the outer panel has a higher aspect ratio and lower sweep, and the value of lift-curve slope decreases with increasing supersonic Mach number. Thus, the inner panel carries proportionally more of the loading. The aerodynamic center is forced forward with increasing values of leading-edge-break ratio because of the area added inboard. Experimental substantiation of this low level of aerodynamic-center shift, with a model that had a wing which covered most of the body, was provided by Hopkins, Hicks, and Carmichael in paper no. 32 of this conference. (See also ref. 3.)

In addition, wing-body combinations exhibit smaller aerodynamic-center shifts than does the wing alone because the body acts as a forewing with a very low value of leading-edge-break ratio.

Variable-Sweep-Wing Studies

For wings with variable sweep, a problem in aerodynamic-center variation, in addition to that caused by the Mach number effect, results from changes in the wing sweep. The shift resulting from wing-sweep changes must be minimized in order to make variable-sweep wings competitive, from aerodynamic-center considerations, with fixed wings. To illustrate this problem, the theoretical loading distributions of a variable-sweep wing with an outboard pivot (ref. 4) at a Mach number of 0.23 and at low lift is presented in figure 8. At the top of this figure the variable-sweep wing is shown in its low-sweep and high-sweep positions, and superimposed on the low-sweep planform are its theoretical and experimental chordwise pressure loadings which are seen to be in good agreement. At the bottom of the figure the theoretical longitudinal loading distributions for both sweeps have been computed at $C_L = 0.12$ and projected onto the plane of symmetry. As the outer panel is swept back, the inner panel carries more of the loading and thus tends to balance out the additional moments created by the reduced outer-panel loadings acting through longer moment arms. In this example, because of the outboard location of the pivot, the aerodynamic center, as given by the chordwise location of the lift vector, actually shifts slightly forward.

A study was undertaken to determine the effect that the pivot location has on the aerodynamic-center shift, and the results are presented in figure 9. In this figure and in figure 10, the reference planform area is taken for the wing in its high-sweep position.

Each pivot lies on the loci of points from which the outer panel can be swept from its high-sweep position to a low-sweep position. The relative chordwise location of the pivot determines the chordwise position of the outer panel at low sweep without changing the sweep angle or the semispan.

The results of the theoretical study show that the total aerodynamic-center shift $\Delta\bar{x}/\sqrt{S}$ (see fig. 9) can be reduced from 0.2 to 0.1 by moving the pivot outboard. The dashed line is used as a reference to indicate that portion of the total shift caused by the change in Mach number from 0.2 to 2 at $\Lambda_o = 70^\circ$. The remaining shift is attributed to the change in sweep from 15° to 70° at $M = 0.2$. The movement of the pivot outboard changes only the part of the shift dependent on sweep. By proper positioning of the pivot, this part of the shift can be eliminated. When the sweep effect causes the aerodynamic center to move ahead of its low-speed high-sweep position, the Mach number effect is reduced.

These results are supported by experimental data for a similar wing-body combination. Figure 9 shows that a reduction in the total aerodynamic-center shift of 0.07 occurs as the spanwise location of the pivot is moved from one extreme to the other. The characteristics of this combination and how the pivot location affects maneuverability considerations are discussed by Taylor in paper no. 7 of this conference.

In paper no. 5, Ray, Lockwood, and Henderson note that if a high inboard sweep is required for supersonic flight, then at subsonic speeds and low outer-panel sweep, devices such as the double inboard pivot (ref. 5) and the free-floating apex (ref. 6) can be used to eliminate the resulting pitch-up. These devices also provide a means of controlling the aerodynamic-center movement, as illustrated in figure 10, where they are shown to have the following two features in common: (1) When the outer panel is in its low-sweep position, the forewing or apex is either pivoted inside the fuselage or allowed to free-float carrying no load; and (2) when the outer panel is swept back, the apex is affixed to the front of the outer panel and forms a continuous leading edge.

Lifting-surface calculations have been made to illustrate the effect of the amount of the apex which is folded or free-floated. Varying amounts of the apex have been removed to represent the aerodynamic effect of both concepts. With the removal, subsonically, of an increasingly large amount of the apex (correlated with the chordwise distance x), the total aerodynamic-center shift decreases from about 0.18 to 0. Again the dashed line represents that portion of the shift due to changing the Mach number from 0 to 3 when $\Lambda_o = 71.5^\circ$. The effect of changing the sweep Λ_o from 71.5° to 25° at $M = 0$ makes up the remainder of the shift.

When $x/a = 0$, the change in wing sweep has essentially no effe[illegible]: consequently, almost all the aerodynamic-center shift is due to the change i[illegible] number. However, when $x/a = 1.0$, the sweep effect is large enough to ca[illegible] all the Mach number effect.

It should be noted that the aerodynamic-center shift may also be minimized by changing the supersonic Mach number or by changing the center-of-gravity location at the different sweeps and Mach numbers.

CONCLUSIONS

A general conclusion of this study is that, when comparing aerodynamic-center movements of wings of different planform, a normalizing parameter independent of planform, such as the square root of the wing area, is more appropriate than the customarily used mean geometric chord, which is dependent on planform. The following specific conclusions were reached:

1. The theoretical methods have been demonstrated to be adequate for predicting the aerodynamic-center shift with Mach number for a variety of wing planforms, but are not suitable for determining the absolute aerodynamic-center location at any Mach number since body and interference effects are not included.

2. For fixed wings, the aerodynamic-center shift can be controlled by proper selection of sweep and of taper and notch ratios and by inboard and outboard area proportioning with different degrees of sweep.

3. For variable-sweep wings the aerodynamic-center shift can be controlled by pivot location and by apex devices, such as the double inboard pivot and the free-floating apex.

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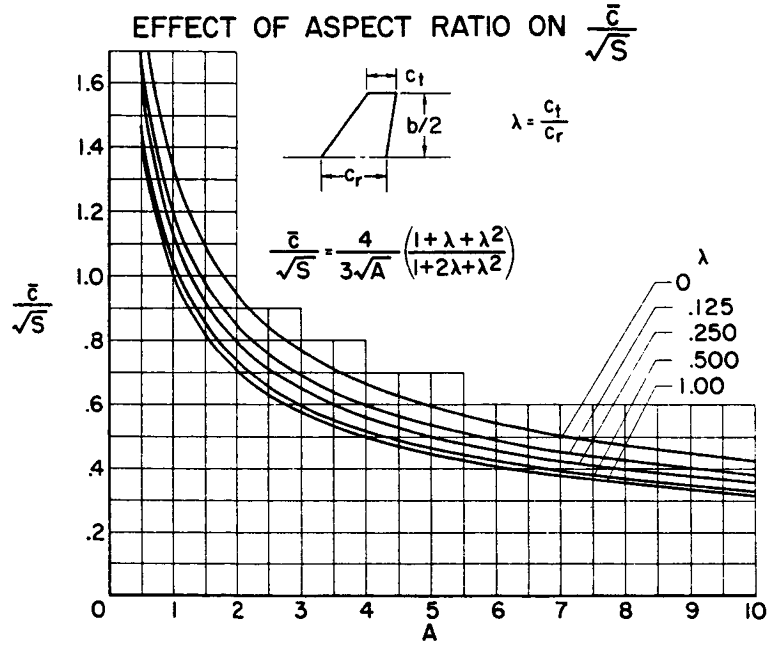


Figure 1

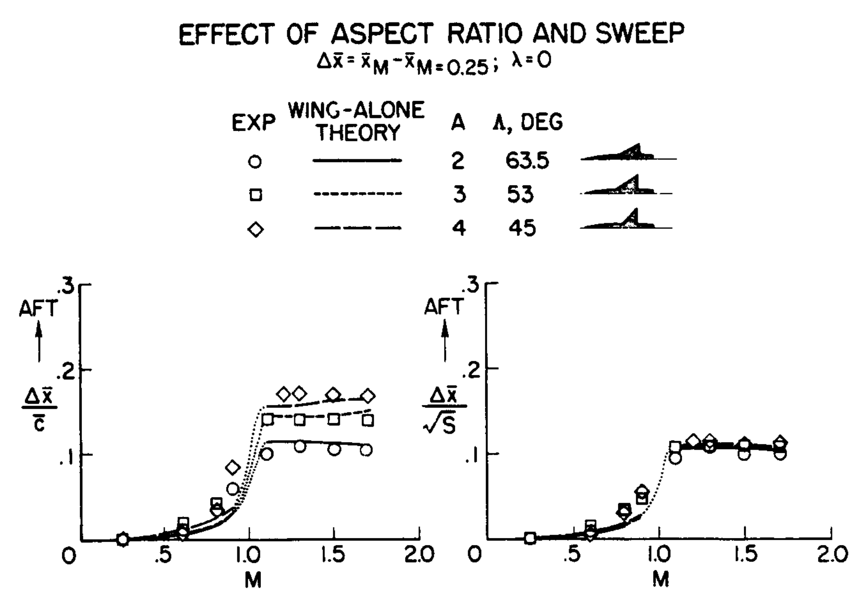


Figure 2

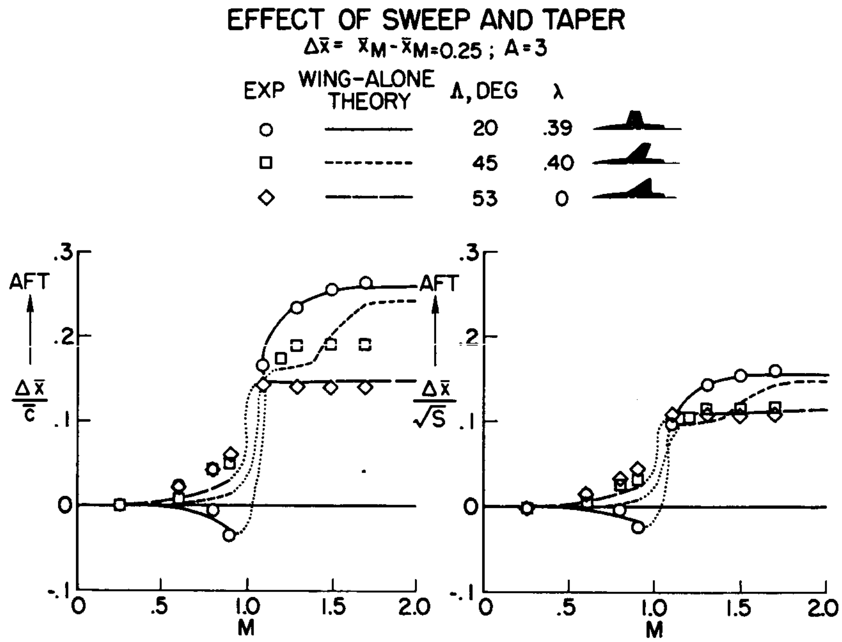


Figure 3

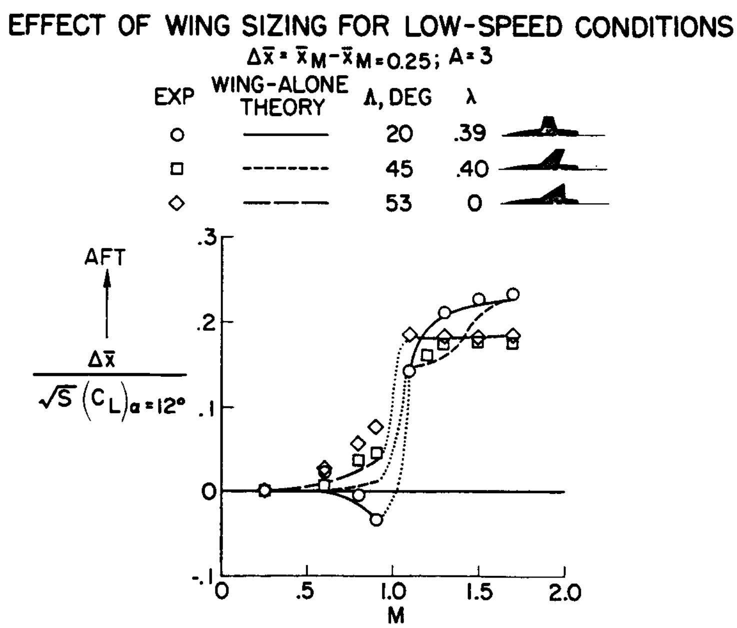
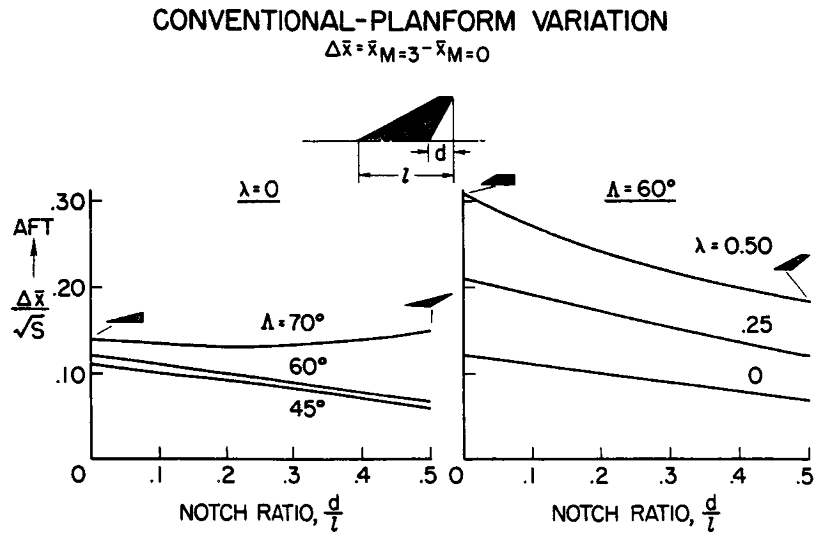


Figure 4



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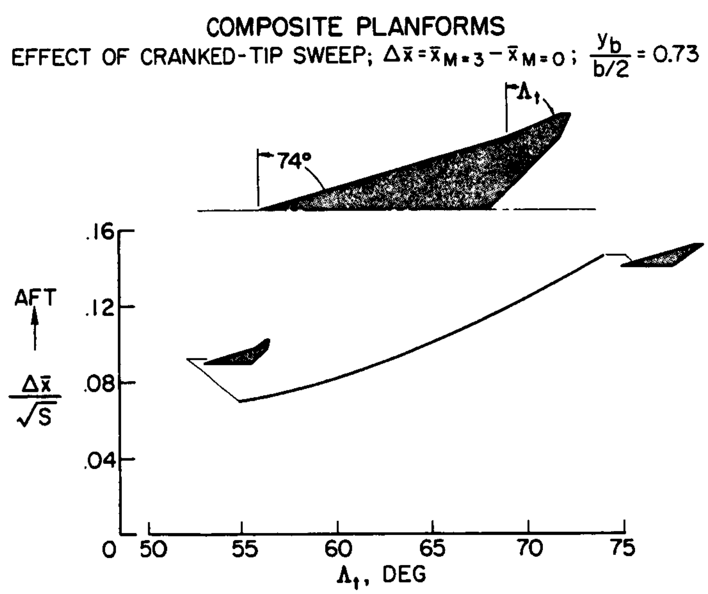

Figure 6

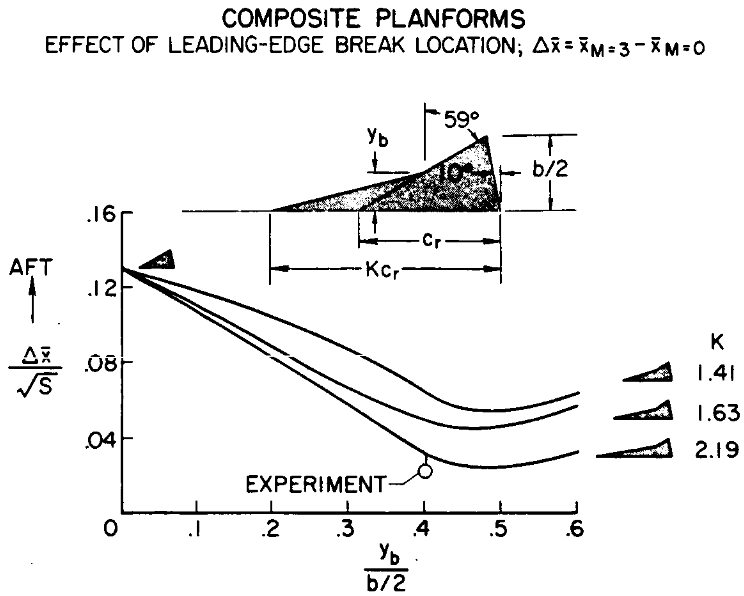

Figure 7

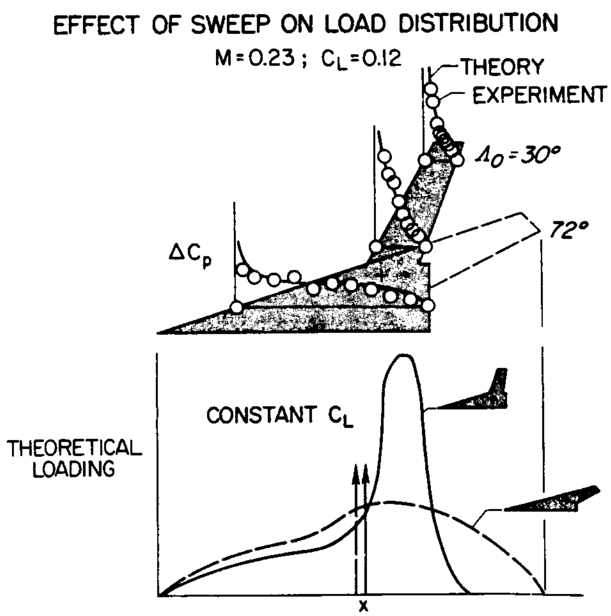

Figure 8

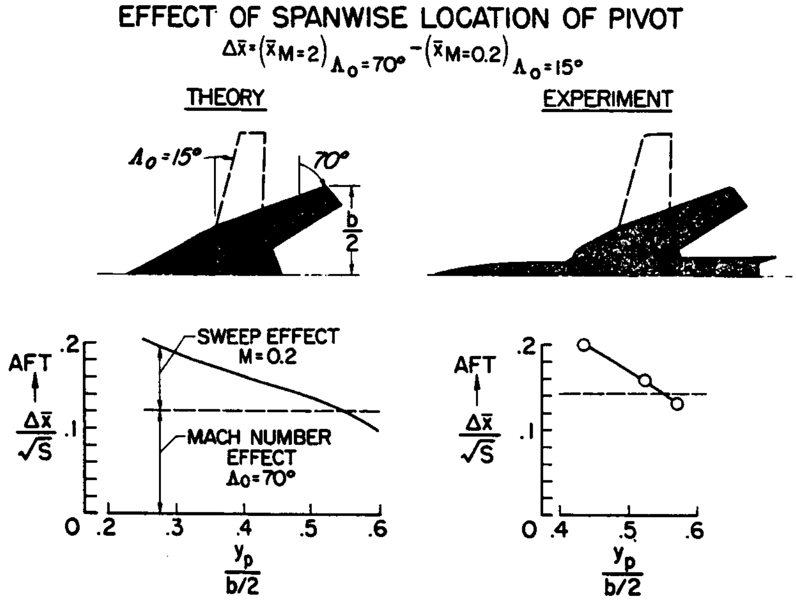

Figure 9

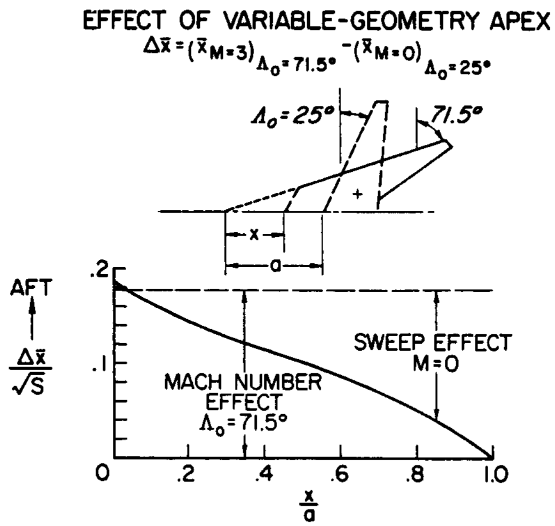

Figure 10