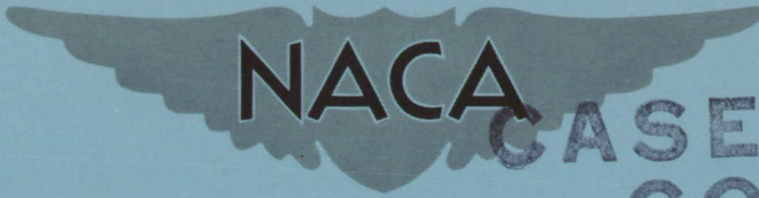


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RESEARCH MEMORANDUM

FLUTTER CHARACTERISTICS OF SWEEP WINGS

AT TRANSONIC SPEEDS

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RESEARCH MEMORANDUM

FLUTTER CHARACTERISTICS OF SWEEPED WINGS

AT TRANSONIC SPEEDS

By Laurence K. Loftin, Jr.

SUMMARY

An experimental study of the flutter characteristics of swept wings is being made in the Langley transonic blowdown tunnel. The purpose of this work is to determine the important effects of some of the plan-form variables and to provide the basis for a means of flutter prediction at transonic speeds. The investigations have consisted of studies of the effects of variations in sweepback angle, aspect ratio, and taper ratio through a Mach number range extending from about 0.8 to 1.35. The investigations have shown that although some further work is no doubt required, the basic effects of these plan-form variables are fairly well defined. Variations in the center-of-gravity position have been shown to have an important effect on flutter at transonic speeds. A method of analysis has been developed which accounts for the effect of center-of-gravity position and which indicates the important aerodynamic parameters influencing flutter of a certain class of wings at transonic speeds.

INTRODUCTION

An experimental study of the flutter characteristics of swept wings is being made in the Langley transonic blowdown tunnel. The purpose of this work is to determine the important effects of some of the plan-form variables and to provide the basis for a means of flutter prediction at transonic speeds. The investigations have consisted of studies of the effects of variations in sweepback angle, aspect ratio, and taper ratio through a Mach number range extending from about 0.8 to 1.35. The variations in the individual plan-form parameters were chosen with a view toward bracketing the range of practical interest and consisted of sweepback angles from 0° to 60° , aspect ratios from 2.0 to 6.0, and taper ratios from 1.0 to 0.2. The effects of variations in certain wing mass parameters have also been briefly studied. Some of the results of these investigations have been reported (refs. 1, 2, and 3), whereas other more recent data are not yet generally available. The present paper will attempt to summarize and correlate some of the trends shown by the results. The experimental techniques

employed in the investigations are fully described in references 2 and 3 and will not be discussed here.

SYMBOLS

Λ	sweep angle of wing quarter-chord line
A	wing aerodynamic aspect ratio
λ	wing taper ratio
M	Mach number
$\frac{V_{EXP}}{V_{REF}}$	ratio of experimental to calculated flutter speeds
$\frac{V_{EXP}}{V_{REF}'}$	ratio of experimental to modified calculated flutter speeds
$\frac{\omega_{n2}}{\omega_{\alpha 1}}$	ratio of measured coupled second bending frequency to first torsion frequency
$C_{L_{\alpha}}$	lift-curve slope
$\frac{x}{c}$	distance along wing chord measured from leading edge, fraction of chord
c	wing chord length normal to quarter-chord line
Subscripts:	
CG	center-of-gravity position
ac	aerodynamic-center position
M	Mach number
.8	stream Mach number of 0.8
N	direction normal to quarter-chord line


METHOD OF ANALYSIS

Before discussing the trends shown by the results for the various wings, a few remarks regarding the method of presentation and the definition of flutter speed may be appropriate. Some typical results for a swept wing are shown in figure 1. A definition of the exact plan form is not important in this case. The Mach number is plotted along the abscissa and the ratio of the experimental to a calculated, or reference, flutter speed is on the ordinate. The reference flutter speeds were determined from a Rayleigh type of analysis in which the flutter mode was represented by the superposition of the uncoupled modes of a cantilever beam and in which the aerodynamic coefficients were two-dimensional, incompressible values taken normal to the quarter-chord line (ref. 4). The necessity of employing such a normalizing factor as V_{REF} in the presentation of experimental flutter results seems unavoidable because of the large number of mass, elastic, geometric, and aerodynamic variables involved. Thus, by use of a reference flutter speed, the mass and stiffness properties of the models and the air density, all of which have a profound effect on the actual flutter speed, do not appear explicitly in the comparison of the various wings but are implicit in the values of V_{REF} . Curves of $\frac{V_{EXP}}{V_{REF}}$ against Mach number, therefore, show the departure of the actual flutter speed from a known reference level as a function of Mach number.

In many of our tests, difficulty is experienced in selecting a unique boundary which separates a condition of flutter from a condition of no flutter. The data points through which the solid line is faired in figure 1 indicate a condition of continuous flutter. The cross-hatched area represents a region of doubt in which the behavior of the model is characterized by random oscillations and intermittent bursts of flutter. As can be seen, the region of intermittent flutter is primarily associated with the supersonic range, although this is not always the case. The significance of this region of doubt and the extent to which the bursts of intermittent flutter may be due to excitation by tunnel turbulence in a region of low, but not zero, aerodynamic damping are open to some question. In any case, the flutter boundaries to be presented in succeeding figures correspond to the condition of continuous flutter as illustrated by the solid line in figure 1.

RESULTS AND DISCUSSION


The results of the study of the effect of varying sweep angle are shown in figure 2 where the flutter-speed ratio $\frac{V_{EXP}}{V_{REF}}$ is plotted against



Mach number. The wings had an aspect ratio of 4.0, a taper ratio of 0.6, and were about 4 percent thick in the streamwise direction. The sweep angles are seen to be 0° , 30° , 45° , 52.5° , and 60° . In the Mach number range below about 0.9, the agreement between experimental and calculated flutter speeds is very good, in spite of the oversimplified representation of the aerodynamic forces in the calculations. As indicated in the key of the figure, only two modes were employed in the calculations for the wings of 0° and 30° sweep. These were the uncoupled first torsion and first bending modes of a uniform cantilever beam. In addition to these modes, the second uncoupled bending mode was employed in the calculations for the other wings. The necessity for employing a third mode was found to be closely connected with the value of the ratio of second bending to first torsion frequency. The frequencies forming this ratio were the measured coupled values. The third mode appeared to be necessary in order to obtain good agreement between calculated and experimental flutter speeds when the ratio of second bending to first torsion frequency was in the vicinity of, or below, 1.0.


For Mach numbers greater than about 0.9, the value of the flutter-speed ratio increases with Mach number by an amount which depends on the sweep angle. Very little increase is noted for the 60° swept wing, with progressively more increase accompanying decreases in the sweep angle from 60° to 30° . An inversion in this trend is noted in the curve for the unswept wing which falls below the curves for the 30° and 45° swept wings. No entirely convincing reason for this behavior is apparent at the present time, although one possibility suggests itself. Difficulties with static divergence were experienced with some of the unswept-wing modes. These divergent tendencies may have, in some way, obscured the true zero-angle-of-attack flutter boundary. In any case, investigations are now being made of wings of about 10° sweepback angle in an effort to clarify these results.

Some effects of aspect ratio are shown in figure 3 in which the flutter-speed ratio $\frac{V_{EXP}}{V_{REF}}$ is again plotted as a function of Mach number. The data shown are for 45° sweptback wings having aspect ratios of 2, 4, and 6. The taper ratio is 0.6 and the airfoils are 4 percent thick. The calculated and experimental flutter speeds agree quite well at subsonic speeds for the wings having aspect ratios of 4 and 6. The calculated flutter speeds for the wing of aspect ratio 2 are, however, considerably lower than the experimental values at subsonic Mach numbers. The discrepancy between experimental and calculated flutter speeds in this case is perhaps due to the inadequacy of the two-dimensional aerodynamic coefficients employed in the calculation. At supersonic speeds, all three wings are characterized by values of the flutter-speed ratio which increased with increasing Mach number. The shape of the curves is, however, somewhat different for the three wings.



Some indication of the effect of taper ratio is provided in figure 4 in which the flutter-speed ratio is plotted against Mach number for 45° sweptback wings having taper ratios of 1.0, 0.6, and 0.2. The aspect ratio was 4.0 for all three wings and the airfoils were 4 percent thick. At subsonic Mach numbers, the agreement between calculated and experimental flutter speeds is seen to be good for the wings with taper ratios of 0.6 and 1.0. The calculations for the wing with a taper ratio of 0.2, however, give a flutter speed which is too low by about 20 percent. The flutter mode for these wings was characterized by high frequencies, between the still-air coupled second bending and torsion values, with large tip deflections. The first and second uncoupled bending and first uncoupled torsion mode shapes of a beam with a taper ratio of 0.2 were employed in the calculations. The flutter mode shape, however, may not have been adequately represented. Also, the still-air vibration modes for the wings having a taper ratio of 0.2 were highly coupled, which raises some question as to the approximate method employed for deducing the uncoupled torsion frequency from the coupled values. Consequently, the subsonic level of the $\frac{V_{EXP}}{V_{REF}}$ curve for the plan form with a taper ratio of 0.2 is not too well established. The data show, however, that the $\frac{V_{EXP}}{V_{REF}}$ curve tends to rise more steeply with increasing Mach number as the taper ratio decreases.

The results presented in the preceding three figures all show an increase in the flutter-speed ratio $\frac{V_{EXP}}{V_{REF}}$ as the Mach number increases into the supersonic range. The fact that the agreement between calculated and experimental flutter speeds becomes poorer as the Mach number increases is not surprising because no account was taken in the V_{REF} calculations of the effects of compressibility on the aerodynamic characteristics. The changes in aerodynamic characteristics with Mach number would seem to be primarily a function of wing-plan-form shape. An important question arises, however, as to whether the curves of $\frac{V_{EXP}}{V_{REF}}$ against Mach number are a function only of wing plan form or whether these curves may be altered by variations in some of the mass and elastic properties of the wing which are hidden in the V_{REF} calculation. Some understanding of the important aerodynamic parameters affecting the flutter speed may be obtained from the simple flutter formula given by Theodorsen and Garrick in reference 5. This empirical formula is based on the results of low-speed studies of two-dimensional wing flutter and is applicable to cases in which the ratio of first bending to first torsion frequency is small. A consideration of only those elements of the formula which contain the aerodynamic characteristics of the wing indicates the following important proportionality:



$$V \propto \sqrt{\frac{1}{C_{I\alpha} \left[\left(\frac{x}{c}\right)_{CG} - \left(\frac{x}{c}\right)_{ac} \right]}} \quad (1)$$

where the symbols have the following meaning:

V	flutter speed
$C_{I\alpha}$	lift-curve slope
$\left(\frac{x}{c}\right)_{CG}$	section center-of-gravity position
$\left(\frac{x}{c}\right)_{ac}$	section aerodynamic-center position

The assumption is now made that the departure of the curves of $\frac{V_{EXP}}{V_{REF}}$ from 1.0 as the Mach number increases is a function only of the well-known rearward shift in the aerodynamic center and reduction in lift-curve slope. On the basis of this assumption and with the use of the relation (1), the following expression for the flutter-speed ratio is obtained:

$$\frac{V_{EXP}}{V_{REF}} = \frac{(C_{I\alpha})_{.8} \left[\left(\frac{x}{c}\right)_{CG} - 0.25 \right]_{.8}}{(C_{I\alpha})_M \left[\left(\frac{x}{c}\right)_{CG} - \left(\frac{x}{c}\right)_{ac} \right]_M} \quad (2)$$

The subscript .8 refers to a Mach number of 0.8 for which the flutter-speed ratio $\frac{V_{EXP}}{V_{REF}}$ is usually about 1.0 and the corresponding aerodynamic center is near the 25-percent-chord station assumed in the V_{REF} calculation. The subscript M refers to some Mach number higher than 0.8. Equation (2) clearly shows that the reduction in lift-curve slope and rearward movement of the aerodynamic center which accompany an increase in Mach number beyond 1.0 should cause an increase in the flutter-speed ratio $\frac{V_{EXP}}{V_{REF}}$. Equation (2) also shows that the magnitude of the effect of rearward movements in the aerodynamic center on the flutter-speed ratio depends upon the position of the section center of gravity.

In order to obtain some indication of the correctness of these ideas, a short experimental investigation was made of three wings having

identical plan forms but different section center-of-gravity positions. The wings had a sweep angle of 45° , an aspect ratio of 4.0, a taper ratio of 0.6, and 4-percent-thick airfoil sections. The wings had section center-of-gravity positions of 34, 45, and 57 percent chord. The results of the investigation are shown in figure 5 in which the flutter-speed ratio $\frac{V_{EXP}}{V_{REF}}$ is plotted as a function of Mach number.

For any given supersonic Mach number, the value of $\frac{V_{EXP}}{V_{REF}}$ is seen to increase with forward movements of the center-of-gravity position. In fact, the wing with the most forward center-of-gravity position could not be fluttered at all, within the operating limits of the tunnel, above a Mach number of approximately 1.2. No-flutter points for this wing are indicated by solid symbols. The higher values of $\frac{V_{EXP}}{V_{REF}}$ for the more forward center-of-gravity locations are entirely consistent with equation (2).

Equation (2) suggests certain possibilities for generalizing the data of figure 5 to include other center-of-gravity positions. The values of the lift-curve-slope ratio and the aerodynamic-center positions appearing in relation (2) are unknown and must be found. One possibility is to use overall wing lift-curve slopes and aerodynamic-center positions as determined from static aerodynamic tests of rigid wings. Such a procedure does not yield good results, however, because the deflection of the wing is not considered. Another possibility is to regard again the aerodynamic parameters appearing in equation (2) as lumped or integrated values and to determine these values with the use of the flutter data of figure 5 and equation (2). This procedure has been followed herein. The aerodynamic-center position and the lift-curve-slope ratio at any given Mach number are assumed to be a function only of the plan form and, hence, would be the same for the three 45° swept wings having different center-of-gravity positions. This assumption implies that the flutter mode shapes for the three wings are not markedly different. Equation (2) indicates that the difference in the curves of $\frac{V_{EXP}}{V_{REF}}$ at supersonic speeds for the three wings of figure 5 is expressed by the difference in value of the ratio

$$\sqrt{\frac{\left[\left(\frac{x}{c}\right)_{CG} - 0.25\right].8}{\left[\left(\frac{x}{c}\right)_{CG} - \left(\frac{x}{c}\right)_{ac}\right]_M}}$$

whereas the lift-curve-slope ratio

$$\frac{\sqrt{(C_{L\alpha})_{.8}}}{\sqrt{(C_{L\alpha})_M}}$$

has the same effect on all three wings. On the basis of this synthesis of the effects of lift-curve slope and aerodynamic center, the faired curves of figure 5 for the three wings were cross-plotted in such a way as to determine the variation of the lumped, or effective, values of the aerodynamic-center position and lift-curve-slope ratio with Mach number. The resulting aerodynamic-center position is shown as a function of Mach number normal to the quarter-chord line in figure 6. The aerodynamic center is seen to shift from the 0.25c station to the 0.34c station as the normal Mach number varies from 0.55 to 0.95. These values appear quite reasonable. The variation of the lift-curve-slope

ratio $\frac{(C_{L\alpha})_{.8}}{(C_{L\alpha})_M}$ with Mach number normal to the quarter-chord line is

shown in figure 7. The ratio of the lift-curve slopes at stream Mach numbers of 0.9 and 1.2, as determined from some unpublished static aerodynamic tests of a rigid 45° sweptback aspect-ratio-4.0 wing, is shown by the symbol in this figure.

An indication of how well the deduced variations of aerodynamic-center position and lift-curve ratio describe the results obtained for the wings with different center-of-gravity positions is provided in

figure 8. In this figure, the ratio $\frac{V_{EXP}}{V_{REF}'}$ is plotted against stream

Mach number for the wings with different center-of-gravity positions. The values of V_{REF}' were determined from equation (2) by letting

$$\frac{V_{REF}'}{V_{REF}'} = \sqrt{\frac{(C_{L\alpha})_{.8} \left[\left(\frac{x}{c}\right)_{CG} - 0.25 \right]_{.8}}{(C_{L\alpha})_M \left[\left(\frac{x}{c}\right)_{CG} - \left(\frac{x}{c}\right)_{ac} \right]_M}} \quad (3)$$

and using the values of $\left(\frac{x}{c}\right)_{ac}$ and $\frac{(C_{L\alpha})_{.8}}{(C_{L\alpha})_M}$ as given in figures 6

and 7. The correlation is excellent, with no systematic trends evident for the wings with different center-of-gravity positions.

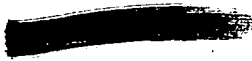
The variations of aerodynamic-center position and lift-curve-slope ratio shown in figures 6 and 7, respectively, were determined from flutter tests of a particular wing plan form. Application of the results

to an arbitrary wing plan form is not, in general, permissible. For the restricted case in which the sweep angle is the only plan-form parameter varied, however, one might expect the values of aerodynamic-center position and lift-curve-slope ratio for one sweep angle to be roughly applicable to other sweep angles on the basis of equal Mach numbers normal to the quarter-chord line. On the basis of this rather crude assumption, the aerodynamic-center position and lift-curve-slope data of figures 6 and 7, together with the formula (3), have been used in an attempt to correlate the swept-wing data of figure 2. The results are presented in figure 9 in the form $\frac{V_{EXP}}{V_{REF}}$ as a function of Mach number normal to the quarter-chord line. Also included in figure 9 are the data for the 45° swept wings with center-of-gravity positions of 34 and 57 percent chord. The unswept-wing data of figure 2 are not included. For normal Mach numbers less than 0.7, the correlation is within the scatter of the data for individual wings. At higher Mach numbers, the correlation is not quite so good, with the maximum disparity between the data points and the line $\frac{V_{EXP}}{V_{REF}} = 1.0$ being about 15 percent.

The correlation of figure 9 indicates that, at least for the class of wings considered, the aerodynamic center and lift-curve slope are the important aerodynamic characteristics controlling the variation of $\frac{V_{EXP}}{V_{REF}}$ with Mach number. The fact that the correlation, figure 9, was achieved without any consideration of the effect of compressibility on aerodynamic lag is perhaps also of some significance. The formula, equation (3), together with the values of aerodynamic-center position and lift-curve-slope ratio given in figures 6 and 7, respectively, may perhaps prove of some use in estimating the effect of variations in center-of-gravity position on the flutter speed of wing plan forms of the same general class as those considered. The generality of the method, in an absolute sense, is however difficult to access.

CONCLUDING REMARKS

Transonic flutter investigations have been made of swept wings having different sweep angles, aspect ratios, and taper ratios. Although some further work is no doubt required, the basic effects of these plan-form variables seem fairly well defined. Variations in the section center-of-gravity position have been shown to have an important effect on flutter at transonic speeds. A method of analysis has been



developed which accounts for the effect of center-of-gravity position and which indicates the important aerodynamic parameters influencing flutter of a certain class of wings at transonic speeds.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 27, 1955.

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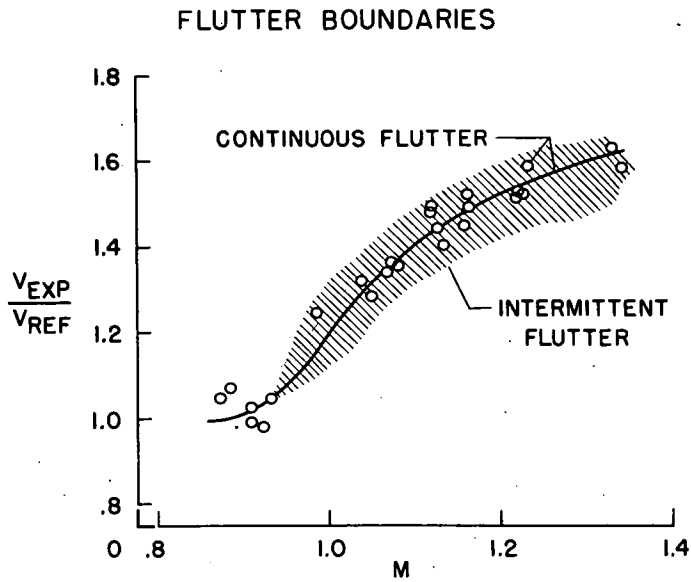


Figure 1

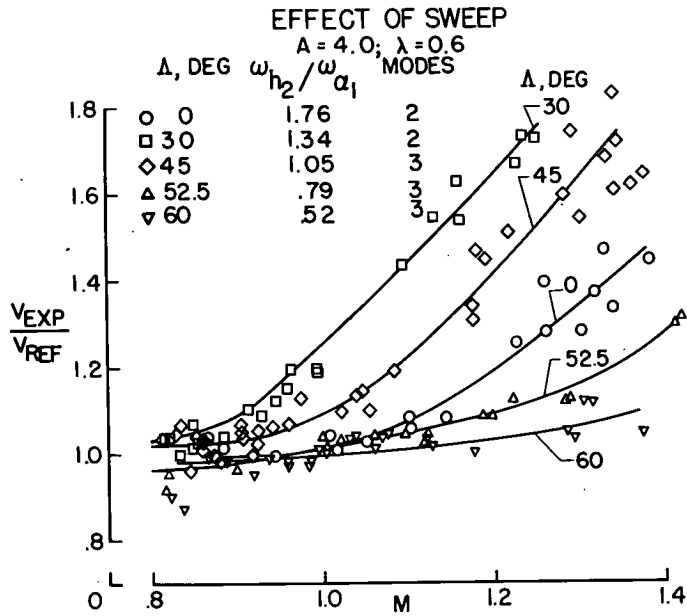


Figure 2

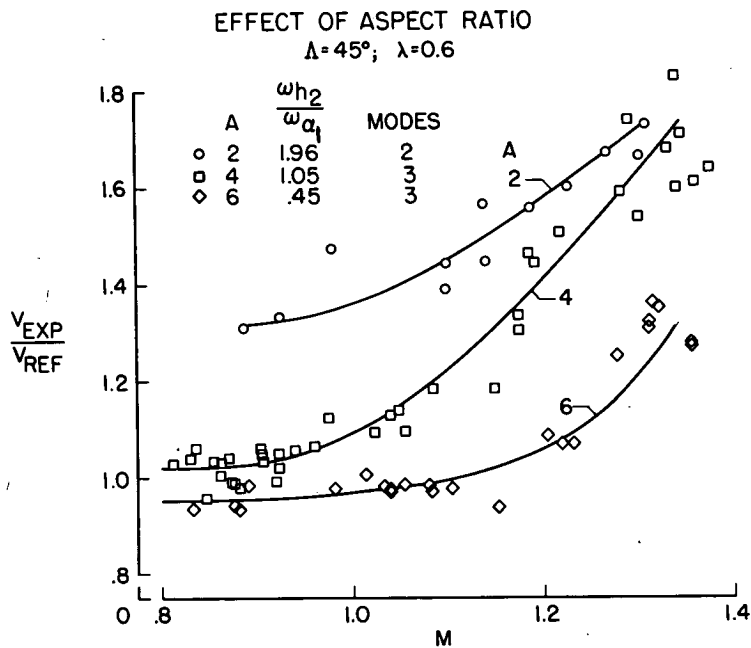


Figure 3

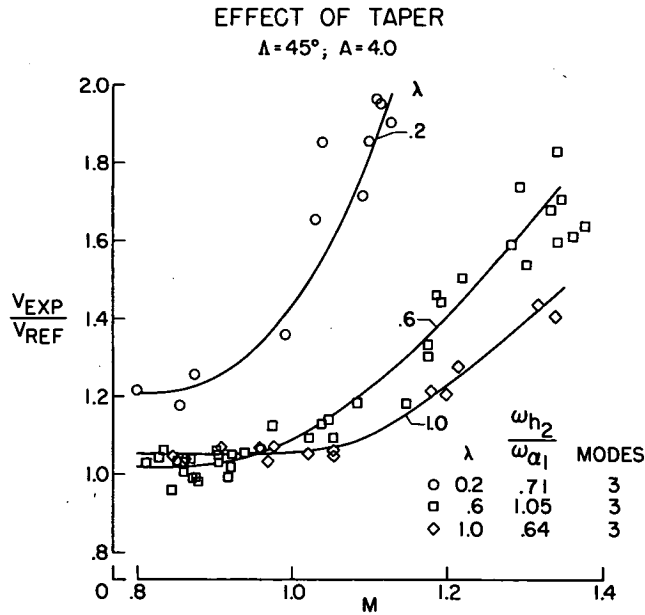


Figure 4

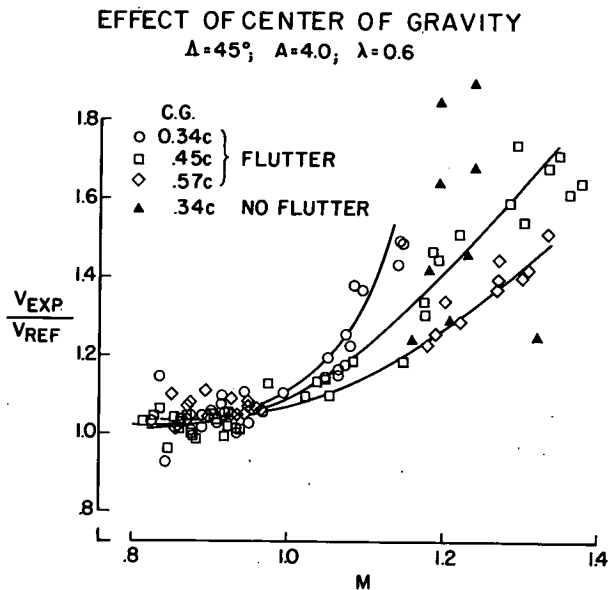


Figure 5

AERODYNAMIC-CENTER POSITION
 $\Lambda = 45^\circ; A = 4.0; \lambda = 0.6$

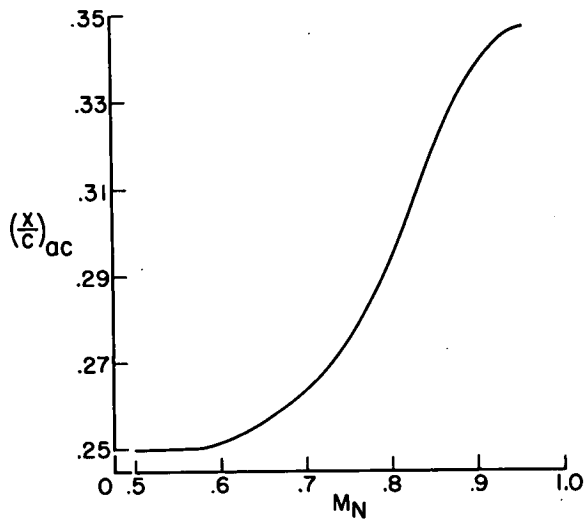


Figure 6

$C_{L\alpha}$ RATIO
 $\Lambda = 45^\circ; A = 4.0; \lambda = 0.6$

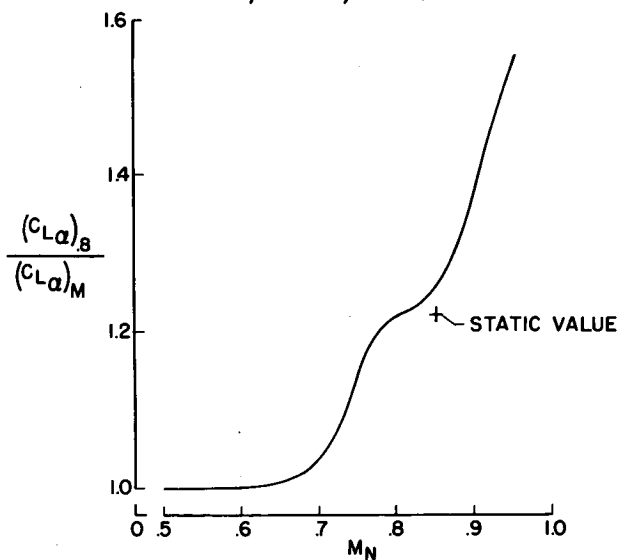


Figure 7

CENTER-OF-GRAVITY CORRELATION

$\Lambda=45^\circ; A=4.0; \lambda=0.6$

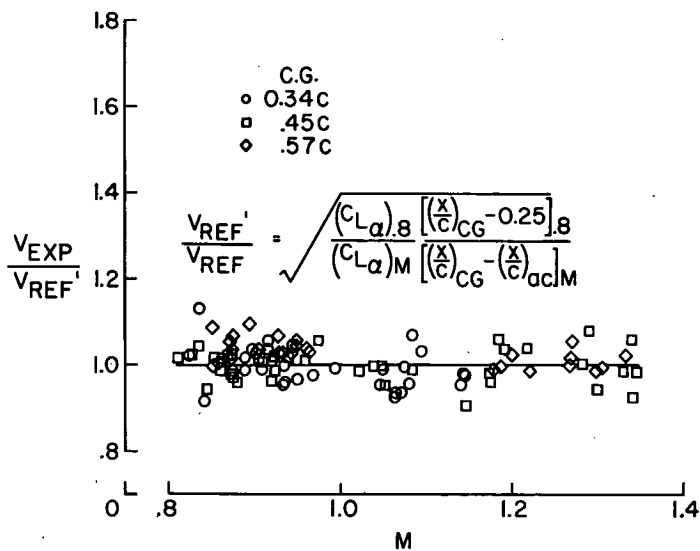


Figure 8

SWEPT-WING CORRELATION

$A = 4.0; \lambda = 0.6$

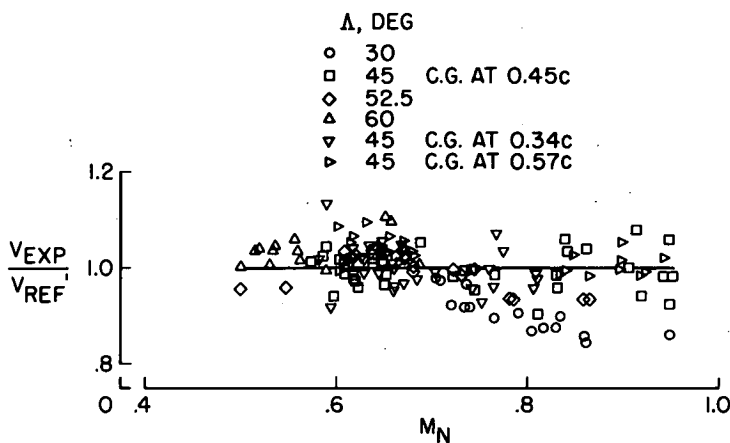


Figure 9

DECLASSIFIED