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ASD TECHNICAL REPORT 61-37

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(UNCLASSIFIED TITLE)

Hypersonic Flutter Model Results and Comparison with Piston Theory Predictions

Richard P. White, Jr.
CORNELL AERONAUTICAL LABORATORY, INC.

AND

Dale E. Cooley
FLIGHT DYNAMICS LABORATORY

ASIA

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ASD TECHNICAL REPORT 61-347

(UNCLASSIFIED TITLE)

Hypersonic Flutter Model Results and Comparison with Piston Theory Predictions

Richard P. White, Jr.

Cornell Aeronautical Laboratory, Inc.

and

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Flight Dynamics Laboratory

October 1961

Project No. 1370

Task No. 13474

Aeronautical Systems Division
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

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FOREWORD

This report is based on a technical paper entitled "Hypersonic Flutter Model Results and Comparison with Piston Theory Predictions" prepared by Mr. R. P. White, Jr., Cornell Aeronautical Laboratory, and Mr. D. E. Cooley, Aeronautical Systems Division. This paper was presented by Mr. D. E. Cooley on 24 April 1961 in Los Angeles, California at the Symposium on Structural Dynamics of High Speed Flight. The symposium was sponsored by The Aerospace Industries Association and The Office of Naval Research.

The applied research program reported herein was initiated and sponsored by the Flight Dynamics Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. The experimental and theoretical work upon which this report is based was accomplished by Cornell Aeronautical Laboratory, Inc., Buffalo, New York, under Air Force Contract AF33(616)-6173, Project 1370, "Dynamic Problems in Flight Vehicles," Task No. 13474, "Experimental Investigations of Dynamic Instability Phenomena." Mr. Richard P. White, Jr. was the Cornell Aeronautical Laboratory engineer in charge of the work performed under Contract AF33(616)-6173. Mr. Dale E. Cooley was Aeronautical Systems Division task engineer.

The results obtained during initial phases of Contract AF33(616)-6173 at Mach numbers up to 7.0 are presented in WADD TR 60-328, "Hypersonic Flutter Model Tests, M = 5 to 7." Results obtained during subsequent phases of this contract, including some tests to M = 8, are presented in Supplement 1 to WADD TR 60-328.

This report, except the title, is classified CONFIDENTIAL because it contains experimental flutter data in the supersonic and hypersonic speed regime that can be employed to determine design criteria for preventing flutter of lifting surfaces for future flight vehicles.

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ABSTRACT

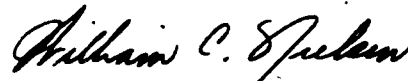
A series of flutter model tests have been conducted in the Mach number range 5 to 8 to provide flutter trends and evaluate theoretical flutter prediction methods. The tests were conducted by Cornell Aeronautical Laboratory, Inc., on rectangular planform models in AEDC Tunnel E-2. Experimental results were obtained on flutter effects from varying Mach number, uncoupled frequency ratio, center of gravity, thickness ratio, profile shape, and aspect ratio.

Results and trends, presented in terms of flutter velocity index, are compared with flutter data predicted by piston theory aerodynamics. Interesting results concerning the effects of structural damping on hypersonic flutter characteristics and relative flutter characteristics for hypersonic and lower speed ranges are presented. Using piston theory for predicting hypersonic flutter speeds is evaluated, and improvements in theoretical procedures are discussed.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:



WILLIAM C. NIELSEN
Colonel, USAF
Chief, Flight Dynamics Laboratory

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LIST OF SYMBOLS

AR	Aspect ratio of semispan
b	Model semichord, inches
c	Model chord, inches
l	Model semispan, inches
ξ_R	Structural damping coefficient of uncoupled roll mode, nondimensional
ξ_P	Structural damping coefficient of uncoupled pitch mode, nondimensional
I_R	Roll inertia of semirigid models, lb/in./sec ²
t	Model maximum thickness, inches
m	Model mass per unit span, lb/sec ² /in. ² (For semirigid models, an equivalent mass per unit span = $\frac{3I_R}{l^3}$ was used)
V	Velocity in test section, in./sec
ρ	Density of air in test section, lb/sec ² /in. ⁴
μ	Wing to air density ratio = $\frac{m}{4 \rho b^2}$
ω_f	Flutter frequency, rad/sec
ω_R	Frequency of uncoupled roll mode for semirigid models, rad/sec
ω_P	Frequency of uncoupled pitch mode for semirigid models, rad/sec
ω_α	Frequency of uncoupled torsion mode for cantilever models, rad/sec
ω_h	Frequency of uncoupled bending mode for cantilever models, rad/sec
CG	Center of gravity
M	Mach number

INTRODUCTION

Criteria for preventing flutter of lifting surfaces are needed for designing future hypersonic flight vehicles. These criteria must, of necessity, be based largely on theoretical analyses until sufficient experimental data from wind-tunnel tests are obtained for each configuration. No comprehensive and systematic experimental test program had been conducted, however, to provide data that could be used in verifying the accuracy and applicability of flutter prediction theories at high Mach numbers.

The Aeronautical Systems Division, recognizing the need for such experimental data, initiated an exploratory applied research program in 1958 to obtain flutter data that can be used to (1) define trends over a wide range of Mach numbers, and (2) check the accuracy of prediction methods based on piston theory aerodynamics. Thus far, only relatively simple wall-mounted rectangular planform models with uniform spanwise properties have been tested so that elastic and dynamic properties could be more easily determined and controlled. The first phase of this program, for Mach numbers ranging from 1.5 to 5.0 (reported in Ref. 1), was conducted by the Massachusetts Institute of Technology in the Arnold Engineering Development Center (AEDC) Wind Tunnel E-1. Cornell Aeronautical Laboratory, Inc., then tested similar models at Mach numbers ranging from 5 to 8 in the AEDC Wind Tunnel E-2. These models, which were tested at zero angle of attack, were designed so that the effects of aerodynamic heating and chordwise flexibility were essentially eliminated. The effects of these parameters -- angle of attack, chordwise flexibility, and aerodynamic heating -- on the flutter characteristics of the model are the subjects of other programs.

- This paper presents the results of the latter part of the program conducted by the Cornell Aeronautical Laboratory. Some results obtained at Mach numbers ranging from 5 to 7 during the early phases of that program were presented previously at a joint USAF-NASA conference on the subject "Lifting Manned Hypervelocity and Re-entry Vehicles," held at Langley Research Center, Virginia, in April 1960 (Ref. 2). Since that time, additional tests have been conducted that provide analytical data for other configurations in the Mach number range 5 to 8. Information in this report is concerned primarily with the results obtained from these later tests.

TEST PROGRAM AND RESULTS

Experimental flutter tests were conducted by Massachusetts Institute of Technology in the Mach number range 1.5 to 5.0 and by Cornell Aeronautical Laboratories in the range 5.0 to 8.0. For these tests, a basic cantilever model was designed with a modified double-wedge profile, a square planform, and a thickness ratio of 0.04. The center of gravity was located at 50 percent chord and the elastic axis at the 40 percent chord. The uncoupled bending-to-torsion frequency ratio was 0.5. A diagram of this model is shown at the right in Figure 1. Since these cantilever models were generally destroyed when the flutter boundary was reached, tests were conducted on many models of the same basic design but with small differences resulting from tolerances in construction.

Results of tests conducted on the cantilever models are presented as a composite flutter boundary in Figure 1. A corresponding flutter boundary predicted from third-order piston theory calculations, including spanwise mode shapes and assuming zero structural damping,

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is also presented for comparison. These data are plotted as the variation of flutter velocity index, $\frac{V}{b \omega_{\alpha} \sqrt{\mu}}$, with Mach number. The flutter velocity index for models of the same scale is proportional to the square root of the ratio of dynamic pressure to torsional stiffness. The data was corrected analytically for the small differences between the various models.

The results of these experiments show that, for the basic cantilever model, the flutter velocity index increases as Mach number is increased up to about $M = 5.5$, and then decreases as Mach number is further increased up to at least $M = 7$. The flutter velocity index at $M = 7$ as compared to that at about $M = 5.5$ is reduced approximately 7 percent. No experimental flutter data has as yet been obtained at Mach numbers as high as $M = 8$ with the cantilever models. Based on data obtained on several semirigid models (presented later in this report), however, we believe that the trend of flutter velocity index to decrease with Mach number might level off or begin to increase again at the Mach number range 7 to 8, as is plotted in Figure 1.

The boundary predicted by piston theory aerodynamics is unconservative from $M = 1.5$ to about $M = 3.5$, conservative from $M = 3.5$ to about $M = 6$, and again unconservative above $M = 6$. Theoretical results do not predict the detrimental effects that were determined experimentally at Mach numbers above $M = 5.5$.

The trends of flutter velocity index obtained with the cantilever models in the range $5 \leq M \leq 7$ were unexpected. To determine whether some of the deviations from predictions were due to the differences between the various cantilever models, we decided to verify the results by testing a similar semirigid model. The semirigid model was dynamically similar, but was designed with independent spring restraints at the root in the uncoupled roll and pitch degrees of freedom. This model was sturdier than the cantilever model and was not destroyed at the flutter boundary. The variation of the flutter velocity index with Mach number was therefore obtained with the same model throughout the Mach number range. Results of experiments with this model verified the trends established with the cantilever models. The decrease in flutter velocity index at the higher Mach numbers, therefore, was believed due to aerodynamic characteristics rather than to the small differences between the cantilever models.

The semirigid models were then used to study the effects on flutter from varying basic model parameters independently over the Mach number range 5 to 8. The parameters varied included thickness ratio, uncoupled frequency ratio, location of center of gravity, position of rotation axis, wing-air mass ratio, aspect ratio, and profile shape. Complete results of these investigations are presented in References 3 and 4. Some interesting discussions of these results, however, are presented as follows.

Flutter boundaries obtained from experiments on semirigid models having an aspect ratio of 0.5 are plotted in Figure 2. These semirigid models were dynamically similar to the basic semirigid model with an aspect ratio of 1.0, but the span was reduced by one-half. Trends at Mach numbers from 5 to 8 were obtained for three roll-to-pitch frequency ratios ($\frac{\omega_R}{\omega_P}$). Divergent type flutter was experienced and the flutter points were well-defined except for the points at $M = 7$ and $M = 8$ with a roll-to-pitch frequency ratio of 0.51. Constant amplitude oscillations at this frequency ratio began at the data points indicated on the flutter boundary, and the amplitude increased as the dynamic pressure

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increased. Divergent flutter, however, was not obtained at either $M = 7$ or $M = 8$. For the maximum dynamic pressures obtained, the flutter amplitude increased by a factor of 10 at $M = 7$ and by only a factor of 2 at $M = 8$. Tests using this model configuration and frequency ratio were repeated and yielded similar results.

The peculiar results obtained at these two points, $M = 7$ and $M = 8$, for the 0.51 frequency ratio, have not been fully explained. The important fact to be noted from these results, however, is that the flutter velocity index for each configuration decreases from $M = 6$ to $M = 7$, then tends to level off or increase at $M = 8$. The most significant destabilizing trend above $M = 6$ was experienced with this model for a frequency ratio of 0.51: the flutter velocity index was about 25 percent lower at $M = 8$ than at $M = 6$.

Flutter data for a model having an aspect ratio of 0.5 were obtained throughout the Mach number range. Points obtained in experiments are plotted in Figure 3 and the trend is shown by the solid line. Boundaries predicted from piston theory aerodynamics are presented for zero structural damping and for the structural dampings determined for the actual model ($g_R = 0.015$ and $g_P = 0.04$).

The theoretical results were more conservative when structural damping was included than when damping was assumed zero. This effect was noted for most, but not all, of the model configurations investigated. Flutter velocity index with Mach number predicted by piston theory, either with or without structural damping included in the analysis, however, does not indicate the trend determined experimentally.

A comparison of the flutter frequency ratios for the same semirigid model as determined experimentally and as predicted theoretically are plotted in Figure 4. Theoretical results for both zero structural damping and the actual structural dampings for the model are also presented. When structural damping is included in the analyses, the prediction of flutter frequency is better than that predicted with zero structural damping. This trend was generally true for all the configurations investigated.

The variation of flutter velocity index with thickness ratio at $M = 5$ for the basic semirigid model is plotted in Figure 5. Plots are included for the experimental results and piston theory calculations with and without structural damping. These data indicate that increasing the thickness ratio is detrimental to flutter stability. Agreement between theoretical and experimental results is very good for thickness ratios of less than 6 percent. When the thickness ratio is increased to 8 percent, however, theoretical predictions indicate a more detrimental effect than the experimental results. The trend with thickness ratio obtained at $M = 6$ was essentially the same as that shown at $M = 5$.

The variation in the flutter velocity index from changes in the location of the center of gravity at Mach number 6.0 as determined experimentally and as predicted theoretically are plotted in Figure 6. A comparison of the experimental results with the predictions based on piston theory aerodynamics shows that the theoretical predictions do not agree well with the experimental results when the center of gravity is located forward of the 50 percent chord. A possible reason for the poor correlation at the forward location of the center of gravity is shown in Figure 6. From the theoretical results, we note that the flutter velocity index increases very rapidly as the center of gravity approaches the center of pressure. If we assume that the rapid increase in the experimental results is due to this cause, then we might conclude that the actual center of pressure is further aft than that which was predicted theoretically.

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Some approximate analyses were conducted, therefore, to determine whether a shift in the position of the center of pressure for the basic model would improve the prediction of the effects from variations in frequency ratio. Although these brief analyses did not provide conclusive results, they indicated that moving the center of pressure aft from the predicted position (39 percent chord) would improve the correlation between experimental and theoretical results. Locating the center of pressure at 43 percent chord gave reasonably good correlation.

The effect on the flutter velocity index resulting from variations in the uncoupled roll-to-pitch frequency ratio at $M = 6$ is shown in Figure 7 for the basic model having an aspect ratio of 1.0 and for a model with a blunt leading edge but otherwise dynamically similar. The radius of the leading edge of the blunt-nose model is equal to one-half the thickness of the model. The predicted flutter boundary for the basic model with a sharp leading edge is close to the boundary determined experimentally at frequency ratios above 0.5. At lower frequency ratios, however, the experimental boundary increases at a greater rate than the theoretical boundary, both with and without structural damping included in the analyses. Essentially the same trend was obtained when the aspect ratio of the basic model was reduced by one-half.

The experimental data obtained from tests at $M = 6$ indicated that, for all frequency ratios tested, the blunt-nose model was more stable than the model with the sharp-wedge nose. MIT also noted a stabilizing effect at $M = 3$ from blunting the nose of a similar model (Ref. 1). The data at $M = 3$, however, indicated a stabilizing effect of only about 20 percent at a frequency ratio of 0.5. Although flutter could not be obtained at this frequency ratio within the tunnel limits at $M = 6$, the stabilizing effect appears to be far greater than 20 percent. These results indicate that the flutter velocity index rises more rapidly and at a higher roll-to-pitch frequency ratio for the blunt-nose model than for the sharp-wedge-nose model. The stabilizing effect of the blunt nose, however, appears to be less pronounced as the frequency ratio approaches unity.

The variation of the flutter velocity index with Mach number for the blunt-nose model in the Mach number range 5 to 8 is presented in Figure 8. For this model, the flutter velocity index increases from $M = 5$ to $M = 6$, decreases from $M = 6$ to $M = 7$, and increases again at $M = 8$. A region of low damping preceded the flutter point at $M = 8$.

The trend for the blunt-nose model was similar to that for the sharp-nose model with an aspect ratio of 0.5. Since the two trends are similar with two different leading edges, the variation in flutter velocity index with Mach number probably did not result from the angle chosen for the leading edge of the models. Further experimentation, however, is required to determine what causes this variation.

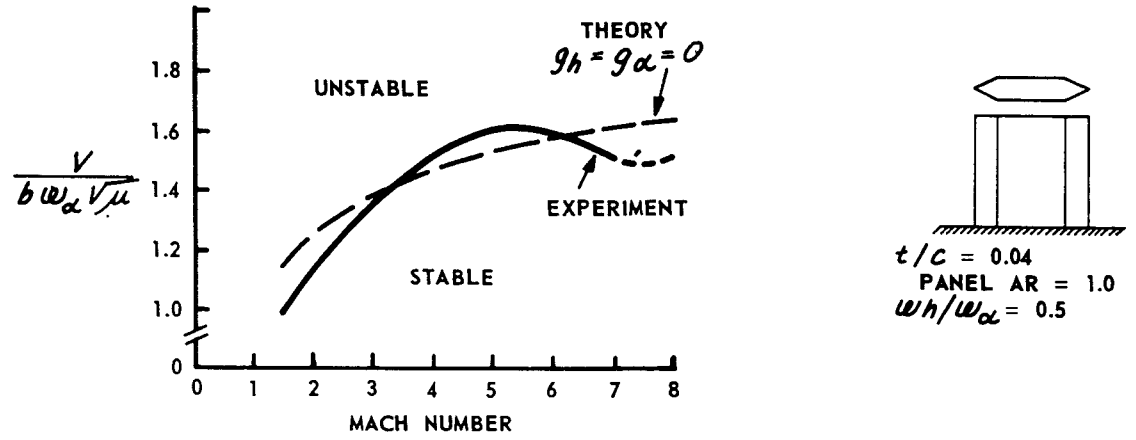


Figure 1. Variation of Flutter Velocity Index with Mach Number

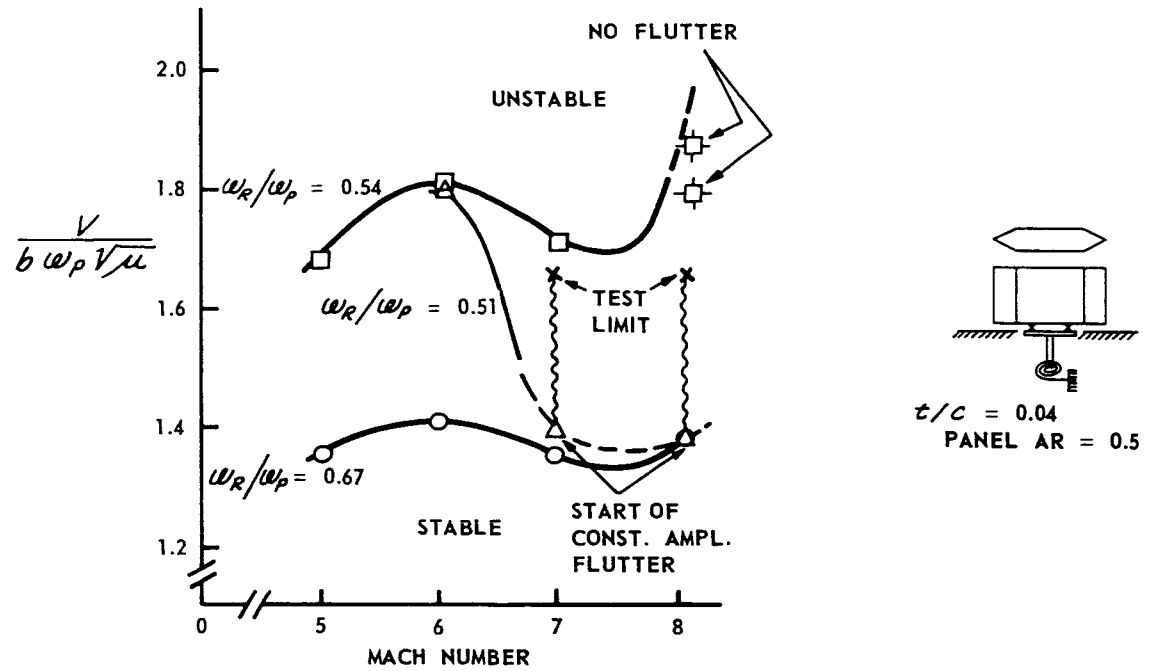


Figure 2. Variation of Flutter Velocity Index with Mach Number for Several Frequency Ratios

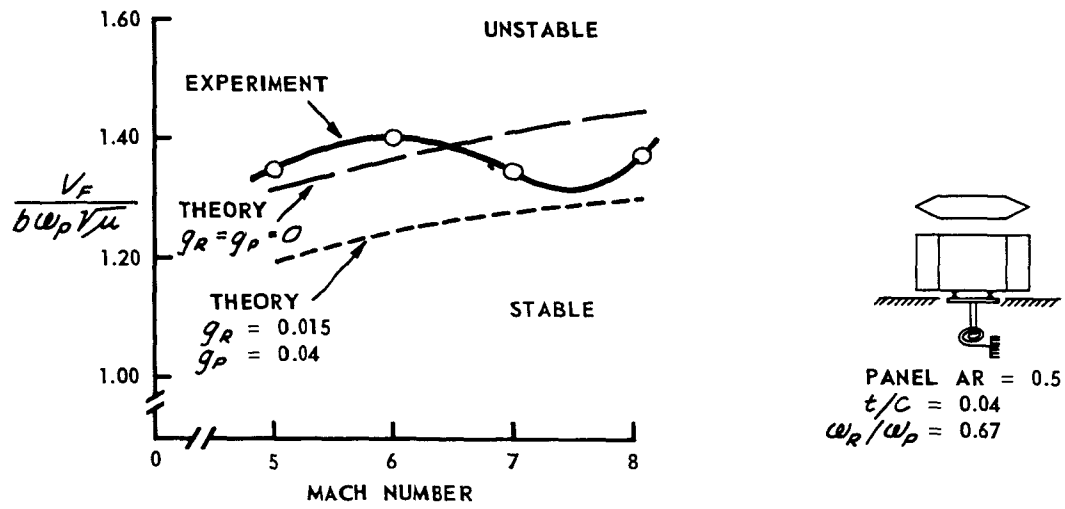


Figure 3. Comparison of Experimental and Predicted Flutter Velocity Index with Mach Number

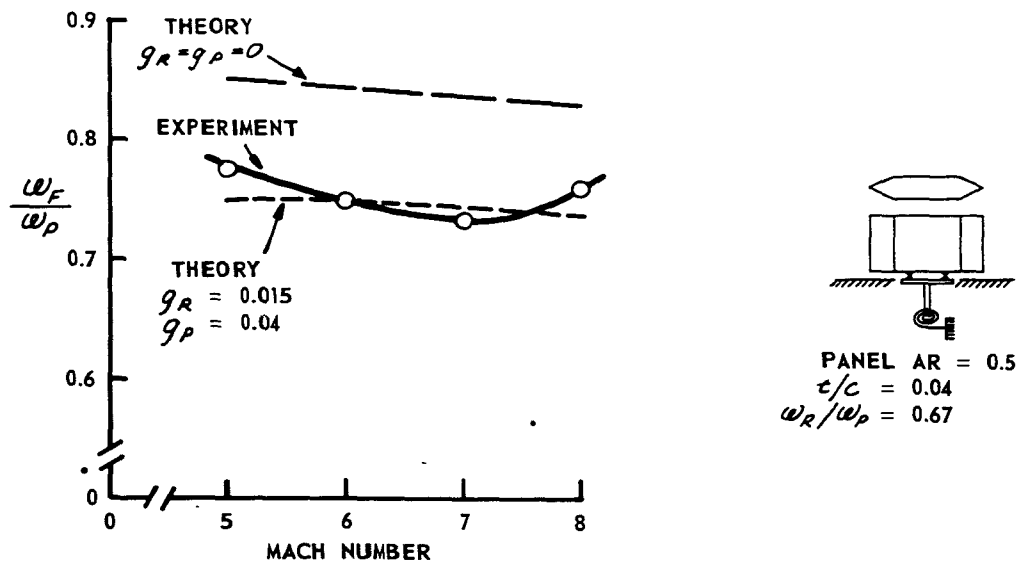


Figure 4. Variation of the Flutter Frequency Ratio with Mach Number

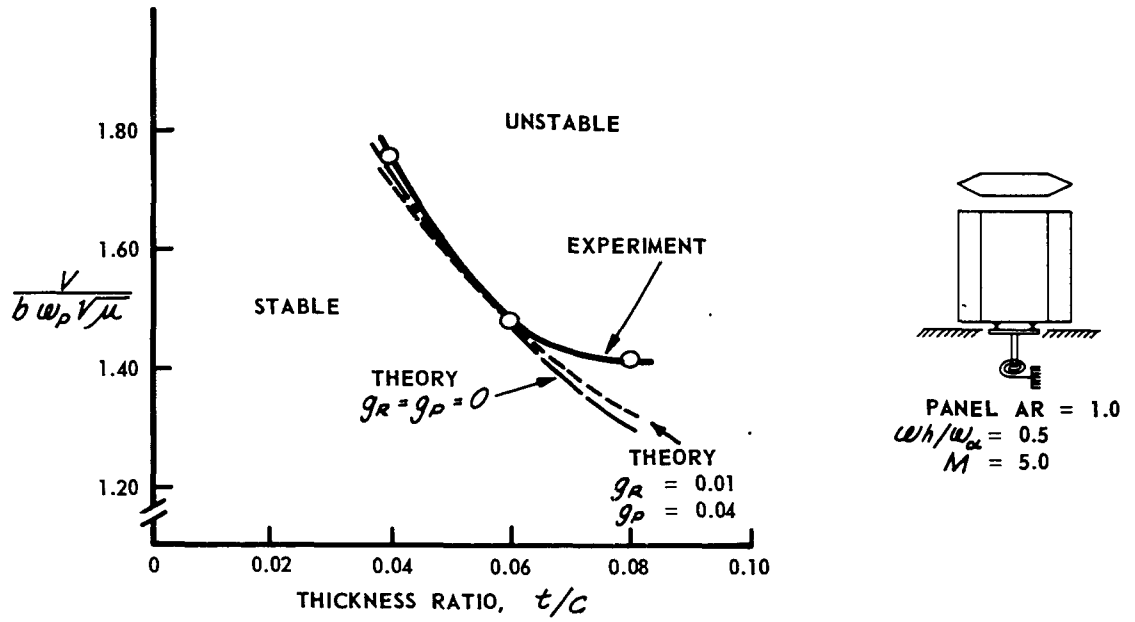


Figure 5. Variation of the Flutter Velocity Index with Thickness Ratio

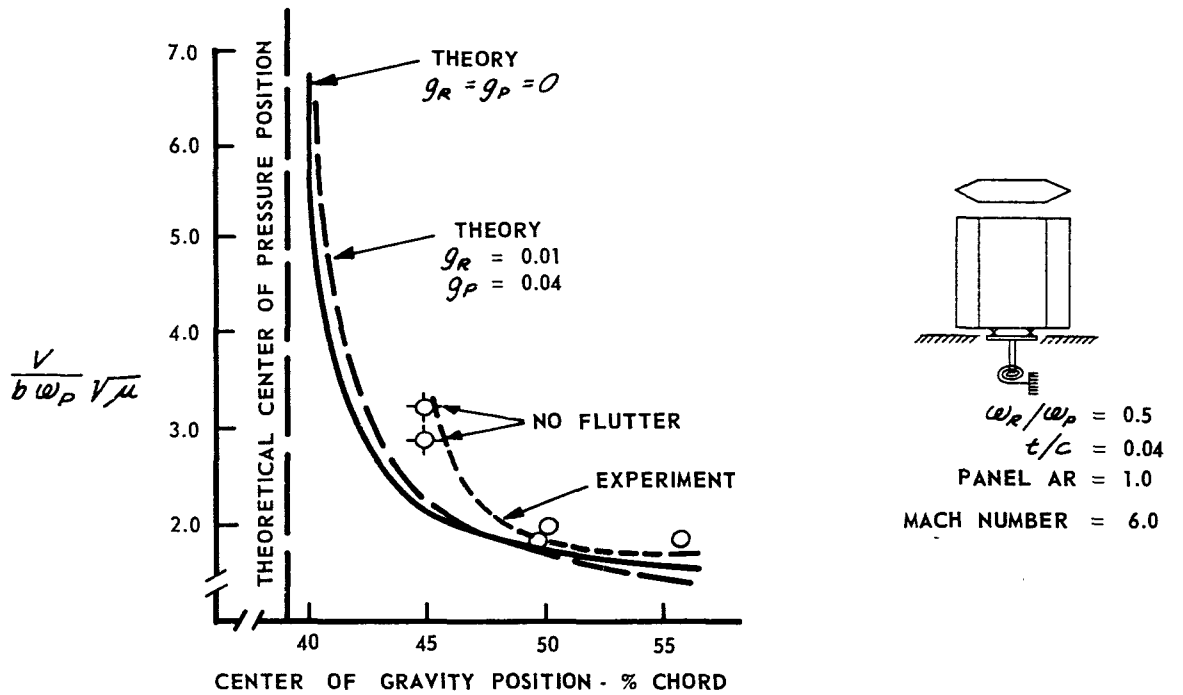


Figure 6. Variation of Flutter Velocity Index with Position of Center of Gravity

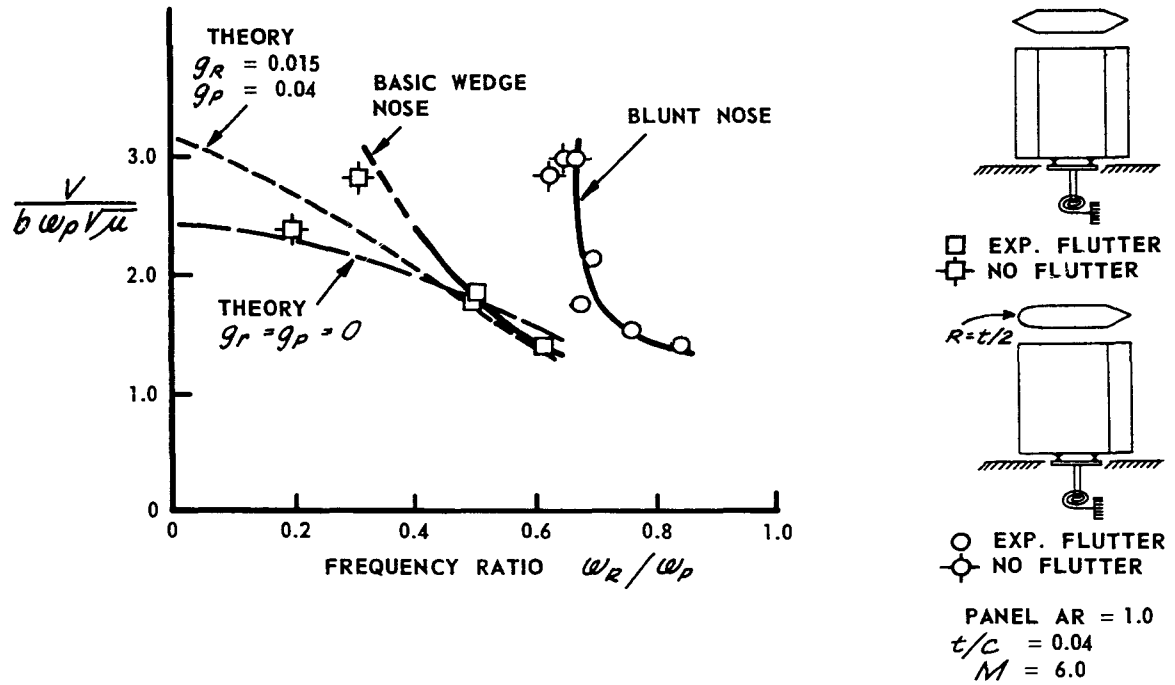


Figure 7. Variation of the Flutter Velocity Index with Frequency Ratio

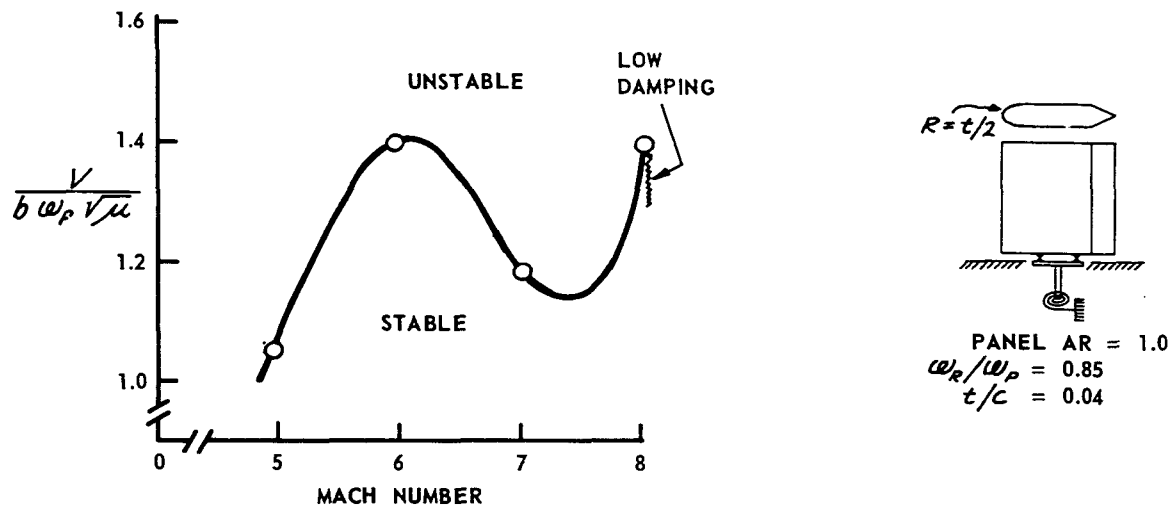


Figure 8. Variation of the Flutter Velocity Index with Mach Number, Blunt Leading Edge

CONCLUSIONS AND RECOMMENDATIONS

The experimental data obtained during this research program indicates that flutter stability, at least for the configurations tested, is reduced at Mach numbers above $M = 6$. This decreasing trend begins to level off or starts to increase again at $M = 8$. The amount of the reduction in the flutter velocity index from $M = 6$ to $M = 7$ and the increase at $M = 8$ depends upon the model configuration and other parameters. Calculations based upon piston theory aerodynamics did not adequately predict the flutter trends at these hypersonic Mach numbers. We believe that the differences noted between theoretical and experimental results might be caused by viscous or other flow effects on basic aerodynamic characteristics that are not accurately accounted for by theory. The effects of location of center of gravity, frequency ratio, thickness ratio, aspect ratio, and shape of the leading edge on the flutter velocity index have been discussed briefly and deviations from predicted values are pointed out. The detailed results of this study in the Mach number range 5 to 8 are presented in References 3 and 4.

Since the trends obtained from the experiments deviated from theoretical values in an unexpected manner, the hypersonic flutter analyses for advanced low-aspect-ratio wing configurations should be substantiated by wind-tunnel flutter tests whenever possible. The aerodynamic flutter coefficients used for hypersonic flutter analyses should be verified and corrected as necessary, based on experimental aerodynamic tests. The Cornell Aeronautical Laboratory is now conducting a program to measure the aerodynamic flutter coefficients for the basic model in the Mach number range 5 to 8 to investigate reasons for the differences between theoretical trends and experimental trends obtained during this program. These measurements will include integrated center of pressure, lift curve slope, and pitch rate and roll rate lift and moment terms. Undistorted wind-tunnel models and models with linear twist and camber will be used for this test program. The Aeronautical Systems Division has also initiated a program with Cornell Aeronautical Laboratory to extend the research of this program to $M = 10$ by tests in AEDC Wind Tunnel C. Similar flutter studies to even higher Mach numbers are being planned for the near future as test facilities become available. These studies will provide information concerning the dynamic instability phenomena of future flight vehicles throughout their entire anticipated flight regime.

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4. (U) Flutter Model Tests at Hypersonic Speeds, WADD TR 60-328, Supplement 1. (CONFIDENTIAL).

<p>Flight Dynamics Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.</p> <p>(U) HYPERSONIC FLUTTER MODEL RESULTS AND COMPARISON WITH PISTON THEORY PREDICTIONS, by Richard P. White, Jr., Cornell Aeronautical Laboratory, Inc., and Dale E. Cooley, October 1961. 15 p. incl. illus. (Proj. 1370; Task 13474) (ASD TR 61-347)</p> <p>CONFIDENTIAL Report</p> <p>A series of flutter model tests have been conducted in the Mach number range 5 to 8 to provide flutter trends and evaluate theoretical flutter prediction methods. The tests were conducted by Cornell Aeronautical Laboratory, Inc., on rectangular planform models in AEDC Tunnel E-2.</p> <p>(over)</p>	<p>CONFIDENTIAL</p>	<p>CONFIDENTIAL</p> <p>Flight Dynamics Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.</p> <p>(U) HYPERSONIC FLUTTER MODEL RESULTS AND COMPARISON WITH PISTON THEORY PREDICTIONS, by Richard P. White, Jr., Cornell Aeronautical Laboratory, Inc., and Dale E. Cooley, October 1961. 15 p. incl. illus. (Proj. 1370; Task 13474) (ASD TR 61-347)</p> <p>CONFIDENTIAL Report</p> <p>A series of flutter model tests have been conducted in the Mach number range 5 to 8 to provide flutter trends and evaluate theoretical flutter prediction methods. The tests were conducted by Cornell Aeronautical Laboratory, Inc., on rectangular planform models in AEDC Tunnel E-2.</p> <p>(over)</p>	<p>CONFIDENTIAL</p>
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