EXPERIMENTAL AND CALCULATED RESULTS OF SUPERSONIC FLUTTER CHARACTERISTICS OF A LOW ASPECT-RATIO FLAT-PLATE SURFACES

Eiichi NAKAI, Toshiro TAKAGI, and Koji ISOGAI
Research Engineers
The First Airframe Division
National Aerospace Laboratory
Chofu, Tokyo, Japan

SUMMARY

An experimental investigation of the supersonic flutter characteristics of thin cantilever plate surfaces having a plate aspect-ratio of 1.0 and a taper ratio of 0.63 has been conducted in the N.A. L. 1m x 1m supersonic blow-down wind tunnel at Mach numbers from 1.519 to 4.140. Each model was cantilevered on the side wall of test section of the wind tunnel with a model injection-rejection rig.

The experimental results were compared with the calculated results employing piston theory and quasi-steady second-order theory as the required oscillatory aerodynamic forces and utilizing the first three normal coupled modes which include cambering deflections. Both theories were unconservative for the configuration of the models experimented and the range of Mach numbers investigated.

INTRODUCTION

Although some works of experimental investigation of the supersonic flutter characteristics of low aspect-ratio surfaces have been done, i. e., refs. 1 - 4, almost all of them are up to Mach number 3.0 and the intervals of Mach numbers investigated are rather wide, and also data was unavailable for the plan form of the surfaces experimented, which is identical to that of the wings of "NAL-16" research rocket (reference 5). There was a need for more information of the supersonic flutter characteristics of the configuration, both to provide the data for design criteria and to provide a basis for comparison of theory and experiment extending Mach number up to 4.0.

The semi-span models of twelve different sizes of a same plan form, keeping the thickness of the surfaces constant, were constructed, and flutter data were obtained by nine of the models at Mach numbers from 1.519 to 4.140. The experimental results were compared with theoretical calculations with the use of theory of ref. 6, based on piston theory of ref. 7 for the full range of Mach numbers experimented and quasi-steady second-order theory of ref. 8 for Mach numbers under 2.5. Mode shapes of the models used in the computation were determined by the method of ref. 9.

SYMBOLS

A	panel aspect-ratio (semi-span^2/panel, area)
b_R	semi-chord at root
$\frac{b_R \omega_\alpha}{a}\sqrt{\mu_e}$	stiffness-altitude parameter
c	local chord
a	velocity of sound
f_f	flutter frequency
f_n	natural frequency of n-th mode (n = 1, 2, and 3)
l	length of semi-span of model, measured normal to stream direction
M	Mach number
q	dynamic pressure
t	thickness
W	total weight of surface
x	chordwise station, measured parallel to root chord from leading edge
Y	spanwise station, measured parpendicular to root chord from the root
δ	leading- and trailing-edge bevel, measured parpendicular to edges
μ_e	mass density parameter
ρ	air density
ω_α	wing torsional circular frequency

Subscript:

ex	experimental
th	theoretical

MODEL DESCRIPTION

The model configuration used in the investigation is shown in figure 1. With keeping the plate thickness constant, the size of the models was gradually varied from the full-size of the wing of "NAL-16" rocket to the scale of 65%, designated as "Model-190" and "Model-65" respectively, totaling the number of models constructed to twelve as indicated in table 1, for the purpose of obtaining flutter points at the lower stagnation pressure during the operation of the wind tunnel for the respective Mach number experimented.

All models were made from magnesium sheets of 2mm thickness with alminum alloy root. Leading and trailing edges were beveled with the angle of 60°, and the larger the model, the longer the length of the over-hung part of the root chord, as shown in figure 1. The model was attached to the mounting block with two steel pins of 10mm diameter. This method of attaching the model to the block was same as in the wings of "NAL-16" rocket. The model, being attached to the model injection-rejection rig, was mounted on the side wall of the wind tunnel. By the use of the model injection-rejection rig, the breakage of the model was avoided during the starting- and stopping-shock passing through the test section of the wind tunnel. The method of mounting the model in the injection-rejection rig is illustrated in figure 2.

TEST PROCEDURE

The tests were conducted in the N. A. L. 1 m x 1 m supersonic blow-down wind tunnel (reference 10). This tunnel is of the intermittent type with flexible nozzle which facilitate to vary Mach numbers continuously from 1.5 to 4.0, and operates from a high pressure source to atmosphere.

The tests were made at constant Mach number with stagnation pressure being increased during the operation of the wnid tunnel until flutter was encountered or until the tunnel limits were reached.

Each model was instrumented with strain gages externally mounted on the wing near the root and oriented so as to distinguish between wing bending and torsion deflections. However, the gages could not be oriented so as to eliminate completely cross coupling between the bending and torsion signals. The strain gages were used to provide an indication of the start of flutter and to obtain a record of the frequency of wing bending and torsion oscillations.

During each test, continuous records of wind tunnel conditions, i. e., stagnation pressure and temperature and static pressure of the test section, and model behavior were simultaneously recorded on self-halancing potentiometer recorders and an multi-channel recording oscillograph, respectively.

A high-speed, 16mm motion-picture camera was used at approximately 4,000 frames per second to obtain a visual record of wing deflection during some of the tests. These films served as an aid. in defining the mode shape and magnitude of flutter.

The tests were originally intended to be conducted at Mach numbers from 1.5 to 4.0 with interval of Mach number of 0.25, but the measured Mach numbers were slightly different from them as shown in table 1. The models were not damaged during flutter tests and could be used for succeeding tests, except only "Model-85" which was broken by stoping-shock in the test section after fluttering, because of mulfunction of wind tunnel control system. It was tried to obtain flutter points with more than one model at the same Mach number in order to ensure the results of the experiment, whenever possible.

The natural frequencies were measured by the use of similar testing rig described in reference 11, without adding any mass'to the model surface, and are listed in table 1. The first three natural mode shapes of "Model-90" were measured by a bouncing sound technique of reference 9 for use in the analysis and presented in table 2 along with the natural vibration node lines.

RESULTS AND DISCUSSION

The experimental and theoretical results are listed in table 1, and are shown in figure 3 in which both an experimental and a theoretical stiffness-altitude parameter $\frac{b_R\omega_\alpha}{a}\sqrt{\mu_e}$ required for flutter are plotted as a function of Mach number. The ω_α is the second natural frequency f_2 which is predominantly torsional for models. The mass density parameter μ_e is the ratio of the mass of the wing to the mass of a volume of air enclosing the wing. The volume is that of a truncated cone with the two ends parallel to the airstream with diameter equal to the root and tip chords. The air density ρ, which is used in the computation of μ_e, is the test section density at flutter. The flutter region is below the curves and the non-flutter region is above the curves.

The theoretical flutter boundaries shown in figure 3 were calculated with the use of aerodynamic forces obtained from piston theory for the full range of Mach numbers experimented and from quasi-steady second-order theory for Mach numbers under 2.5, and using the first three natural vibration. modes. When the theoretical and experimental flutter boundaries are compared, it is seen that the shape of the boundaries agrees well. And, the agreement between the experimental and theoretical flutter boundaries is fairly good at all Mach numbers, that is, the values of the theoretical stiffness-altitude parameters by piston theory are less than those of the experimental stiffness-altitude parameters by about 20%, and the stiffness-altitude parameters calculated by quasi-steady second-order theory followed the experimental trend of stiffness-altitude parameters more closely at the lower supersonic Mach numbers with decreasing Mach number. Furthermore, since the lifting-pressure expression associated with piston theory and with quasi-steady second— rder theory approaches each other as Mach numbers approach infinity, the speeds indicated by the two theories also approach each other as Mach number increases up to around 2. 5.

The. both theories were unconservative for the configuration of the models investigated and the range of Mach numbers experimented.

Figure **4** shows the variation of the ratio of theoretical flutter frequency calculated by piston theory to experimental flutter frequency with Mach numbers, and the ratio decreases with the increase of Mach number slightly. The agreement between the theoretical and experimental flutter frequencies was better than that between flutter boundaries. There was little difference between the theoretical flutter frequencies obtained from piston theory and from quasi-steady second-order theory.

CONCLUSIONS

The results of an experimental investigation conducted in the N. A. L. 1m x 1m supersonic blowdown wind tunnel of a low aspect-ratic flat-plate surfaces indicated the following conclusions for the configuration of the models investigated and the range of Mach numbers experimented:

I. Both piston theory and quasi-steady second-order theory were unconservative.

2. The agreement between the experimental and theoretical flutter boundaries is fairly good at all Mach numbers experimented.

3. *At* the lower supersonic Mach numbers, the stiffness-altitude parameters calculated by quasi-steady second-order theory followed the experimental trend of stiffness-altitude parameters more closely with the decrease of Mach number than by piston theory.

4. The agreement between the experimental and theoretical flutter frequencies was good, and there was little difference between the flutter frequencies obtained from piston theory and from quasi-steady second-order theory.

REFERENCES

1. Tuovila, W. J., and McCarthy, J. L.: Experimental Flutter Results for Cantilever Wing Models at Mach Numbers up to 3. 0. NACA RM L55E11, 1955.

2. Runyan, H. L., and Morgan, H. G.: Flutter at Very High Speeds. NASA TN D-942, August 1961.

3. Bennett, R. M., and Pates, E. C., Jr.: A Study of Several Factors Affecting the Flutter Characteristics Calculated for iwo Swept Wings by Piston Theory and by Quasi-Steady Second-Order Theory and Comparison with Experiments. NASA TN D-1794, May 1963.

4. Hanson, P. W., and Levey, G. M.: Experimental and Calculated Results of a Flutter Investigation of Some Very Low Aspect-Ratio Flat-Plate Surfaces at Mach Numbers from 0. 62 to 3.00. NASA TN D-2038, October 1963.

5. Kuroda, Y., et al.: Single-Stage Solid-Propellant Rocket "NAL-16" - Design and Flight Experiment. NAL TH-115 (To be published).

6. Morgan, H. G., Huckcl, V., and Runyan, H. L.: Procedure for Calculating Flutter at High Supersonic Speed Including Camber Deflections and Comparison with Experimental Results. NACA TN 4335, September 1953.

7. Ashley, H., and Zartarian, G.: Piston Theory - A New Aerodynamic Tool for the Aeroelastician. Jour. Aero. Sci., Vol. 23, No. 12, December 1956, pp. 1109 - 1119.

8. Van Dyke, M. D.: A Study of Second-Order Supersonic Flow Theory. NACA Rept. 1081, 1952.

9. Hanson, P. W., and Tuovila, W. J.: Experimentally Determined Natural Vibration Moues of Some Cantilever Wing Flutter Models by Using an Acceleration Method. NACA TN 4010, 1957.

10. Staff of tile Second Aerodynamics Div., N. A. L.: On Design and Construction of the 1m x 1m Supersonic Blow-Down Wind Tunnel. NAL TR-29, October 1962 (In Japanese).

11. McCarthy, J. F., Jr., Asher, G. W., Prigge, J. S., and Levey, G. M.: Three-Dimensional Supersonic Flutter Model Tests near Mach Number 1. 5 - Part 1. Model Design and Testing Techniques. WADC Technical Report 54-113, December 1955.

MODEL	FREQUENCIES, C.P.S. f_1	f_2	f_3	$f_{f,ex}$	Stract. Damp. Coeff.	M	FLUTTER CONDITIONS ρ $kg\text{-}s^2/m^4$	a m/s	q kg/m²	μ_e	$\frac{b_R \omega_\alpha}{a}\sqrt{\mu_e}$ EXP.	THEORY P.T.	THEORY Q.S.T.	$f_{f,th}/f_{f,ex}$ THEORY P.T.	THEORY Q.S.T.
t	84.5	222.8	474.6												
70	72.5	193.1	410.5	120.5	0.0123	1.527	0.0965	283.2	9012	29,556	2.200	1.752	1.999	1.103	1.108
72.5	67.7	175.6	375.4	116.9	0.0121	1.519	0.0864	283.6	8021	31,890	2.147	1.736	2.029	1.088	1.082
				114.9		1.780	0.0750	269.6	8639	36,734	2.426	1.909	2.106	1.107	1.100
75	63.7	167.6	354.9	108.7	0.0124	1.771	0.0718	268.3	8111	37,096	2.419	1.907	2.095	1.106	1.106
				111.1		2.037	0.0687	253.7	9177	38,817	2.617	2.056	2.200	1.082	1.082
77.5	58.9	149.0	325.3	102.0	0.0105	2.037	0.0567	253.9	7588	45,466	2.599	2.081	2.222	1.055	1.050
				103.1		2.282	0.0555	240.8	8376	46,481	2.769	2.209	2.341	1.044	1.038
80	54.9	141.3	296.8	96.1	0.0236	2.528	0.0541	227.9	8977	46,256	2.860	2.328	2.428	1.033	1.039
82.5	52.2	137.4	291.5	94.1	0.0165	2.517	0.0532	228.9	8825	45,600	2.835	2.314	2.420	1.034	1.034
				91.7		2.828	0.0499	213.0	9055	48,606	3.145	2.491		1.052	
85	48.9	120.8	264.1	84.7	0.0225	3.064	0.0415	201.7	7929	56,771	3.249	2.613		1.009	
87.5	45.4	117.8	251.9	81.6	0.0152	3.071	0.0391	202.8	7596	58,472	3.291	2.599		1.023	
				81.6		3.280	0.0432	194.1	8765	52,916	3.273	2.672		1.028	
				81.3		3.595	0.0425	181.4	9028	53,866	3.532	2.834		1.027	
90	43.9	110.0	238.5	76.9	0.0158	3.583	0.0388	182.4	8282	57,438	3.483	2.833		1.015	
				76.9		3.848	0.0383	172.7	8460	58,155	3.702	2.938		1.015	
				76.3		4.140	0.0344	163.7	7909	64,718	4.121	3.082		1.023	
95 *	38.5	91.4	200.9												
100 *	33.9	86.4	182.2												

* NO FLUTTER WAS OBTAINED,

P.T. : PISTON THEORY
Q.S.T. : QUASI-STEADY SECOND-ORDEF? THEORY

TABLE- I EXPERIMENTAL AND THEORETICAL RESULTS

X/C	NORMALIZED DEFLECTION AT Y/L 0.2	0.4	0.6	0.8	1.0
			1st MODE		
0	0.072	0.210	0.389	0.617	0.884
0.2	0.078	0.219	0.421	0.661	0.915
0.4	0.085	0.239	0.459	0.697	0.950
0.6	0.092	0.251	0.486	0.732	0.976
0.8	0.095	0.263	0.500	0.747	0.990
1.0	0.099	0.270	0.507	0.753	1.000
			2nd MODE		
0	0.250	0.548	0.891	0.991	1.000
0.2	0.182	0.407	0.577	0.632	0.538
0.4	0.095	0.213	0.261	0.246	0.070
0.6	0.006	-0.014	-0.082	-0.159	-0.358
0.8	-0.098	-0.259	-0.500	-0.616	-0.692
1.0	-0.197	-0.526	-0.751	-0.903	-0.952
			3rd MODE		
0	-0.446	0.773	-0.619	-0.142	0.787
0.2	-0.311	0.526	-0.345	0.187	0.919
0.4	-0.207	0.316	-0.121	0.302	1.000
0.6	-0.207	0.329	-0.194	0.199	0.837
0.8	-0.265	0.469	-0.408	-0.058	0.578
1.0	-0.331	0.657	-0.619	-0.349	0.337

MODE	NODE LINE
1st	AT ROOT
2nd	--------
3rd	—·—·—

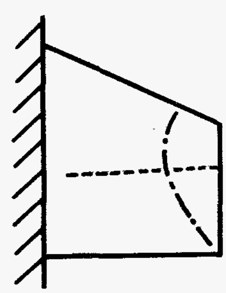

TABLE- 2 REPRESENTATIVE MODE SHAPES AND NODE LINES OF MODEL

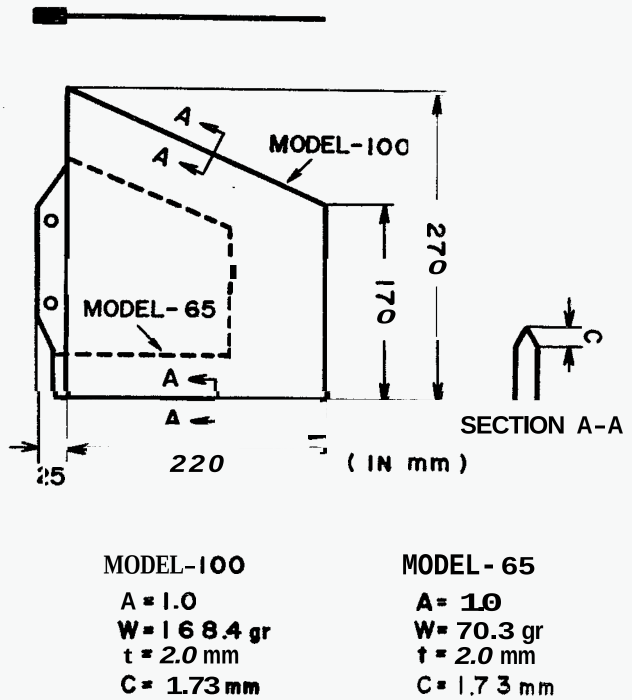

FIG-I MODEL PLAN FORM

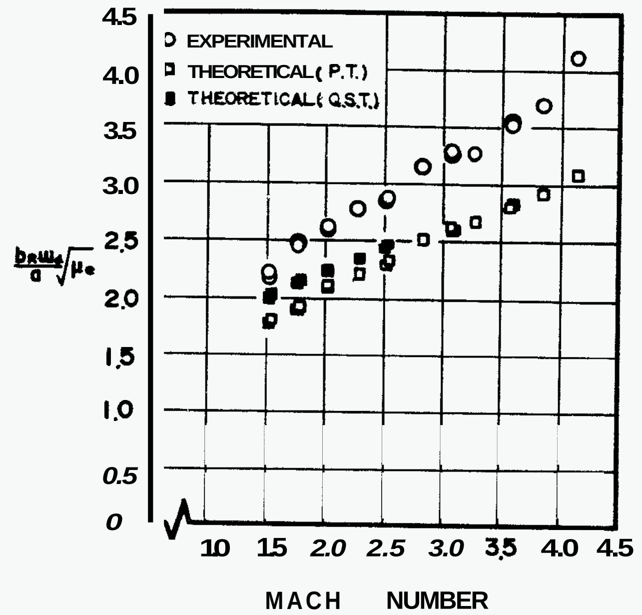

FIG-3 EXPERIMENTAL AND THEORETICAL VARIATION OF STIFFNESS — ALTITUDE PARAMETER WITH MACH NUMBER

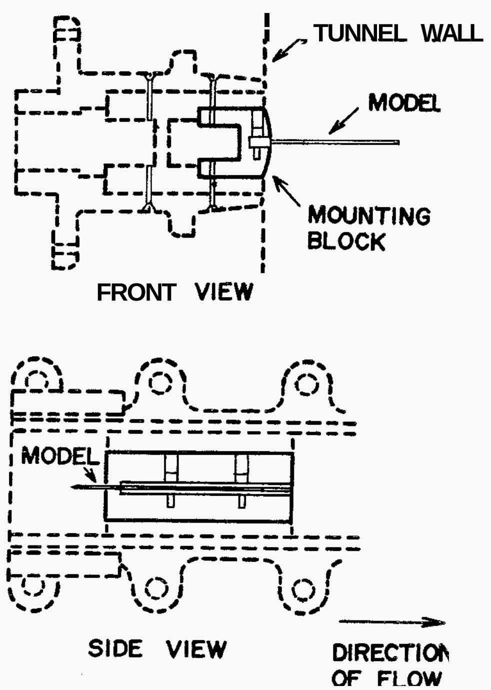

FIG-2 METHOD OF MOUNTING MODEL

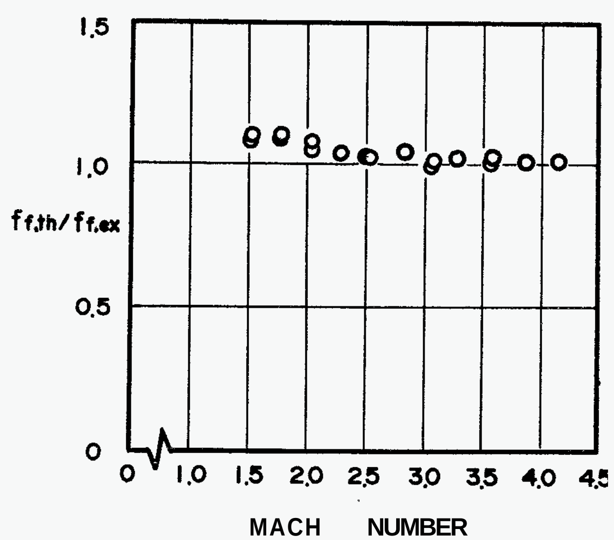

FIG-4 VARIATION OF THE RATIO OF THEORETICAL TO EXPERIMENTAL FLUTTER FREQUENCY WITH MACH NUMBER