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RESEARCH MEMORANDUM

EXPERIMENTAL FLUTTER RESULTS FOR CANTILEVER-WING MODELS

AT MACH NUMBERS UP TO 3.0

By W. J. Tuovila and John Locke McCarty

Langley Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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EXPERIMENTAL FLUTTER RESULTS FOR CANTILEVER-WING MODELS AT MACH NUMBERS UP TO 3.0

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SUMMARY

Experimental flutter tests have been made at Mach numbers up to 3.0 using cantilever-wing models with 0° to 60° sweepback and 45° and 60° delta-wing models. The effects of high Mach number and center-of-gravity location on the flutter trends are indicated. For wings with the center-of-gravity location ahead of the midchord and with small sweep angles, the stiffness requirements to prevent flutter at a given altitude are determined essentially at transonic speeds. For wings with rearward center-of-gravity locations and high sweep angles, the stiffness requirements continue to increase with increase in Mach number. Shifting the center-of-gravity location forward reduces the stiffness requirements to prevent flutter, particularly for wings of low sweep angle.

INTRODUCTION

One of the questions that arises when aircraft are being designed for high Mach number flight is whether or not there is still a serious flutter problem after the transonic range has been traversed. The trends as a function of Mach number have been fairly well defined for various configurations at transonic and low supersonic speeds. These data have been made available from free-flight rocket-model and wind-tunnel tests as indicated in references 1 to 5.

The available flutter data at the higher supersonic Mach numbers are very limited, especially for wing plan forms of current interest. Systematic wind-tunnel tests of two-dimensional wings at Mach numbers of 1.5 and 1.72 are reported in references 6 and 7, respectively, and comparisons with two-dimensional theory are given. Flutter data in free flight at Mach numbers up to approximately 2.1 have come mainly from isolated rocket-model tests, such as those described in references 8, 9, and 10, and pertain to 60° delta-wing plan forms.

The present paper extends the range of trend studies on cantilever-swept-wing and delta-wing plan forms up to a Mach number of 3.0. Part of these tests were made with the simple untapered models of reference 5 and thus represent an extension of that work to higher Mach numbers. In addition, some data are presented on the effect of center-of-gravity location and taper on flutter at supersonic speeds.

SYMBOLS

A	aspect ratio
a	speed of sound
b	wing semichord measured parallel to airstream
c	chord
f	frequency
f_1, f_2, f_3	first three coupled frequencies
f_f	flutter frequency
f_α	assumed torsional frequency
l	semispan
M	Mach number
q	dynamic pressure referred to speed of sound
t	thickness of wing
V	free-stream velocity
Λ	sweepback angle
λ	taper ratio
μ	mass-density parameter
μ_o	reference value of μ
ρ	density of air
ω_α	wing torsional circular frequency

TEST APPARATUS AND MODELS

The flutter studies were made in the Langley supersonic flutter apparatus. This tunnel is an intermittent flow blowdown tunnel which operates at stagnation pressures up to about 80 pounds per square inch absolute using dried air. The testing technique used is described in reference 11.

The wing models that were tested are illustrated in figure 1. The untapered swept-wing models were cut from sheet metal and had the leading and trailing edge beveled 1/4 inch to form a hexagonal section shape. The chords of all these models were 2 inches measured perpendicular to the leading edge, and the thicknesses were all 0.0410 inch. The 45° and 60° delta-wing models were cut from 0.034-inch sheet magnesium and the leading edges were beveled 1/8 inch. The tapered-wing models were made from wood and magnesium. The root chord for the models with taper ratio (λ) of 0.2 was 5 inches and for the models with taper ratio of 0.4 was 4.25 inches. The sweepback, aspect ratio, thickness ratio measured parallel to the airstream, and taper ratio of the models are given in the figure.

METHOD OF PRESENTING RESULTS

Some wing parameters and also the test conditions at flutter are presented in table I. The first three coupled frequencies and the flutter frequencies are listed along with the wing weights and air densities at flutter. The assumed torsional frequency is designated as f_{α}.

The results of these tests are presented in the form of a stiffness-altitude parameter $\frac{b\omega_{\alpha}}{a}\sqrt{\frac{\mu}{\mu_{o}}}$. (The symbol μ is the ratio of the mass of the wing to the mass of a cylinder of air of a diameter equal to the wing chord. The values of μ are based on the semichord b measured perpendicular to the leading edge for the untapered swept models; for the delta wings the mass of air is based on a cone with base parallel to the airstream and diameter equal to the root chord; for the tapered models the mass of air is based on a truncated cone with base perpendicular to the midchord line and base diameter equal to the wing chord where the midchord line intersects the root.) Part of this parameter represents the wing torsional stiffness and part refers to the altitude, hence, the name stiffness-altitude parameter. The $b\omega_{\alpha}$ part may be thought of as representing the wing torsional stiffness, and the speed of sound a and the mass-density parameter μ depend on the altitude. The stiffness-altitude parameter is effectively the torsional stiffness divided by q referred to speed of sound. It depends only upon the physical properties of the wing – in particular, the torsional stiffness – and upon the atmosphere in which it operates. Its value increases as the torsional stiffness increases and as the altitude increases.

RESULTS AND DISCUSSION

Untapered Swept Models

Figure 2 presents the results of the tests with the untapered swept wings. The altitude-stiffness parameter is plotted against test Mach number and the results are referred to a nominal value of $\mu = 50$ in order to eliminate the effect of differences in μ caused by flutter testing at varying densities. The flutter curves are the boundary between the flutter region, which is below the curves, and the no-flutter region above the curves. When the stiffness-altitude parameter for a particular wing lies above its flutter curve, the wing is free of flutter and thus the stiffness-altitude parameter may serve as a flutter criterion. For example, the dashed line represents a value of stiffness-altitude parameter which is sufficient to prevent flutter at all Mach numbers up to 3.0 for the 15° swept model. It is of interest to note the two different types of flutter curves. The curves for the 15° and 30° swept models rise to a maximum value at a Mach number of 1.2 and then drop off as the Mach number increases further, whereas the curves for the 45° and 60° models continue to rise as the Mach number increases. If the 15° and 30° swept models were designed to be free of flutter at Mach number 1.2, they would also be free of flutter at the higher Mach numbers at least up to 3.0. The 30° model would be near the flutter border, however, at the higher Mach numbers. If the 45° and 60° swept models are free of flutter up to a particular Mach number, any increase in Mach number requires an increase in stiffness or an increase in altitude. Subsonic points have been included to complete the flutter curves through the transonic range. The curves are dashed because the interpolations through the transonic range are based on previous flutter experience rather than on experiments of the present tests.

It should be noted that these results refer to the particular series of wings tested, and it is expected that the curves will vary as additional factors such as the center-of-gravity location, bending-to-torsion frequency ratio, aspect ratio, and sweepback are changed. For these models the center of gravity is located at 50 percent chord, the frequency ratios are near 0.2, and the aspect ratios vary from 5.35 to 1.39 as indicated.

Delta Models

Figure 3 shows flutter curves for the simple 45° and 60° delta-wing models. The first three coupled natural frequencies along with the range of flutter frequencies are indicated for each model. The assumed torsional frequency is indicated by f_α. On the basis of the interpolation, once the 45° delta-wing model passed a Mach number of 1.0 safely, it could go to almost 2.0 before any increase in stiffness or altitude would be needed. The 60° delta-wing model, however, needs considerable increase in stiffness or altitude to fly at increased Mach numbers.

Tapered Models

Figure 4 shows the effect of Mach number on the stiffness requirements for the series of tapered wings with center of gravity located at 46 percent chord and the mass-density ratio having a nominal value of 50. The 45° swept model with a taper ratio of 0.4 has a flutter curve which reaches a peak, according to the interpolation, near a Mach number of 1.0, and, if the transonic range is passed safely, the model is free of flutter up to a Mach number of 2.0. If the 60° model with a taper tatio of 0.2 is free of flutter at a Mach number of about 1.2, it is also free of flutter up to Mach number 2.0, but it is not far from the flutter boundary. The 60° model with a taper ratio of 0.4 requires increased stiffness for increased Mach numbers. Two of these models were also tested at Mach number 3.0, but no flutter was encountered probably because of the low densities available. For the 45° model, the lowest no-flutter point was at 0.29, and, for the 60° model with a taper ratio of 0.2, it was 0.34.

Effect of Center-of-Gravity Location

One of the important flutter parameters is the center-of-gravity location and figure 5 shows the effect of this location on the stiffness-altitude parameter for the simple swept-wing models at a Mach number of 2.0. Here, the stiffness-altitude parameter is plotted against the center-of-gravity location. These results have been referred to $\mu_o = 50$. Moving the center of gravity forward from 50 to 44 percent chord gives a pronounced reduction in the stiffness needed to prevent flutter. As the sweepback is increased, this effect is reduced. At 15° sweepback this decrease is about 30 percent whereas at 60° sweepback it is only about 10 percent. The influence of center-of-gravity location is illustrated in figure 6 for a tapered unswept model. This model was flown normally with the center of gravity at 46 percent chord and it was then reversed and flown backward with the center of gravity at 54 percent chord. The changes in airfoil shapes and sweep that occurred should not have had any appreciable additional effect on the flutter over the center-of gravity effect. At a Mach number of 2.0, there is a considerable reduction in the stiffness-altitude parameter as the center of gravity is shifted from 54 to 46 percent chord. At a Mach number of 1.3, the reduction is less. These curves also illustrate that the wing with a center-of-gravity location at 46 percent chord is free of flutter at least up to a Mach number of 2.0 if it is free of flutter in the transonic range. With a 54-percent-chord center-of-gravity location, however, any increase in Mach number requires an increase in stiffness or altitude. This effect of center-of-gravity location has been noted in reference 12.

SOME REMARKS ON COMPARISON WITH THEORY

Flutter analyses of wings in the subsonic and low supersonic range, based on two-dimensional air-force coefficients and a normal-flow concept usually results in flutter speeds which are lower than the measured ones. This previous experience was confirmed by a few calculations of the present tests at $M = 1.3$ in which values lower than experiment were also obtained. The fact that the theory is, in general, conservative, has made it useful for the subsonic and low supersonic range of flight speeds.

The limited experience to date in the higher supersonic range has indicated that the two-dimensional theory is no longer conservative and that it should be used with caution. Flutter calculations in references 6 and 7 show that at Mach numbers of 1.5 and 1.72 the calculations give higher values of flutter-speed coefficients than are measured. This type of result was also obtained for a limited number of cases treated in the present studies at Mach numbers of 2.0 and 3.0.

CONCLUDING REMARKS

The results of these experimental studies indicate that, for wings with center-of-gravity location ahead of the midchord and with small sweep angles, the stiffness requirements to prevent flutter at a given altitude are determined essentially at transonic speeds. For wings with rearward center-of-gravity location and high sweep angles, the stiffness requirements continue to increase with increase in Mach number. A forward shift of the center-of-gravity location has the effect of reducing the stiffness requirements to prevent flutter, particularly for wings of low sweep angle.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 21, 1955.

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[redacted]

TABLE I.- FLUTTER PARAMETERS

(a) Untapered swept-wing models

[All models were 0.041 inch thick and had 2-inch chords measured perpendicular to leading edge]

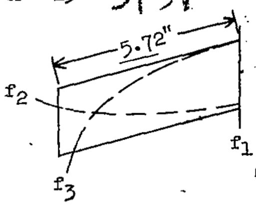
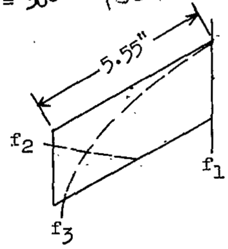
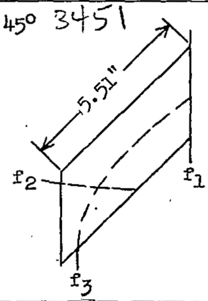
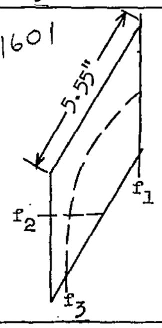
	C.G. location, percent c	Wing weight, lb	Air density, ρ, slugs/cu ft	μ	M	V, fps	f_1, cps	f_2, cps	f_3, cps	f_α, cps	f_f, cps	Material
Λ = 15° 5151  A	50	0.0257	0.00093	83	3.00	2,030	37	218	270	218	146	Magnesium
B	50	.0257	.00053	146	2.00	1,680	35	205	234	205	134	Magnesium
1 C	50	.040	.00049	244	1.30	1,280	36	210	254	210	102	Aluminum
D	50	.040	.0023	52	.45	495	36	210	242	210	120	Aluminum
E	44	.027	.00098	82	2.00	1,680	33	181	219	181	116	Magnesium
Λ = 30° 4301 	50	.0251	.00067	115	3.00	2,030	42	215	297	215	158	Magnesium
2.5	50	.0251	.00043	180	2.00	1,680	38	210	261	210	142	Magnesium
1.65	50	.0388	.00044	271	1.30	1,280	39	210	274	210	94	Aluminum
	50	.0388	.0023	52	.47	517	35	210	270	210	120	Aluminum
	44	.0264	.00064	126	2.00	1,680	37	178	256	178	132	Magnesium
Λ = 45° 3451 	50	.0249	.00061	127	3.00	2,030	45	220	342	220	170	Magnesium
	50	.0249	.00044	176	2.00	1,680	43	206	310	206	148	Magnesium
	50	.0386	.00063	189	1.30	1,280	42	210	370	210	180	Aluminum
	50	.0386	.0023	52	.50	550	35	198	294	198	120	Aluminum
	44	.0262	.00056	143	2.00	1,680	41	180	298	180	140	Magnesium
Λ = 60° 1601 	50	.0251	.00069	112	3.00	2,030	47	200	388	200	180	Magnesium
	50	.0251	.00072	107	2.00	1,680	45	199	354	199	166	Magnesium
	50	.0388	.0013	92	1.30	1,280	50	214	399	214	174	Aluminum
	50	.0388	.0022	54	.76	836	48	210	396	210	110	Aluminum
	44	.0264	.00080	100	2.00	1,680	52	190	360	190	170	Magnesium

TABLE I.- FLUTTER PARAMETERS - Continued

(b) Delta-wing models

[Models were 0.034 inch thick]

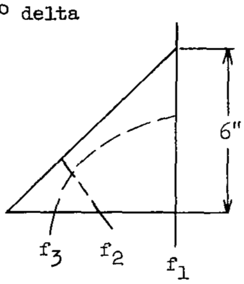
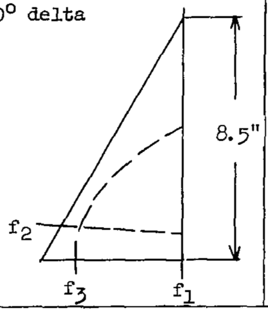
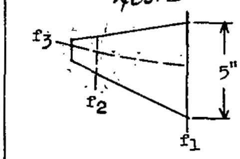
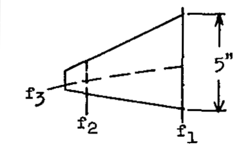
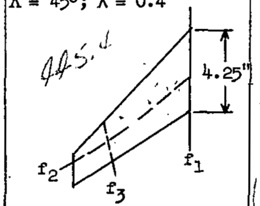
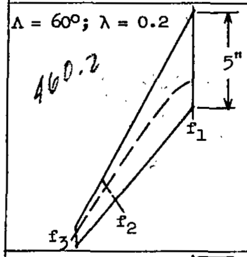
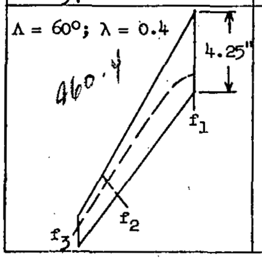
	C.G. location, percent c	Wing weight, lb	Air density, ρ, slugs/cu ft	μ	M	V, fps	f_1, cps	f_2, cps	f_3, cps	f_α, cps	f_f, cps	Material
45° delta	50	0.0391	0.00072	52	3.00	2,030	49	183	257	257	159	Magnesium
	50	.0391	.00070	53	2.00	1,680	50	185	261	261	159	Magnesium
	50	.0391	.00066	56	1.30	1,280	48	180	273	273	150	Magnesium
	50	.0391	.0023	16	.40	440	48	178	244	244	140	Magnesium
60° delta	50	.0453	.00063	42	3.00	2,030	67	193	342	342	180	Magnesium
	50	.0453	.00070	38	2.00	1,680	66	200	341	341	170	Magnesium
	50	.0453	.00087	30	1.30	1,280	67	190	338	338	172	Magnesium
	50	.0453	.0023	12	.54	594	66	194	340	340	162	Magnesium

TABLE I.- FLUTTER PARAMETERS - Concluded

(c) Tapered wing models

[All models had 6-inch semispans measured perpendicular to root]

	C.G. location, percent c	Wing weight, lb	Air density, ρ, slugs/cu ft	μ	M	V, fps	f_1, cps	f_2, cps	f_3, cps	f_α, cps	f_f, cps	Material
$\Lambda = 0^\circ$; $\lambda = 0.2$ A00.2  (a+X_α = -.100 read a, r_α² from curves)	A 46	0.047	0.0025	21	2.00	1,680	120	360	505	505	433	Magnesium
	B 46	.047	.0014	37	1.30	1,280	120	360	480	480	420	Magnesium
$\Lambda = 0^\circ$; $\lambda = 0.2$  (X)	54	.047	.0012	44	2.00	1,680	121	360	520	520	431	Magnesium
	54	.047	.00096	55	1.30	1,280	120	344	495	495	384	Magnesium
	54	.047	.0023	23	.67	736	120	330	492	492	282	Magnesium
$\Lambda = 45^\circ$; $\lambda = 0.4$ A45.4  (a+X_α = -.080 read a, r_α² from curves)	A 46	.030	.0011	45	2.00	1,680	93	320	405	320	276	Wood
	B 46	.030	.0013	39	1.30	1,280	100	344	408	344	212	Wood
	C 46	.030	.0023	22	.57	626	102	360	420	360	210	Wood
$\Lambda = 60^\circ$; $\lambda = 0.2$ A60.2  (?)	46	.033	.0012	55	2.00	1,680	68	207	420	420	378	Wood
	46	.033	.00080	82	1.30	1,280	68	217	420	420	288	Wood
	46	.033	.0023	29	.58	638	70	210	420	420	213	Wood
$\Lambda = 60^\circ$; $\lambda = 0.4$ A60.4  (a+X_α = -.10 ?)	46	.030	.00048	152	2.00	1,680	42	154	320	320	180	Wood
	46	.030	.00049	148	1.30	1,280	41	152	315	315	144	Wood
	46	.030	.0023	32	.45	495	46	170	321	321	156	Wood

FLUTTER MODELS TESTED UP TO M = 3.0

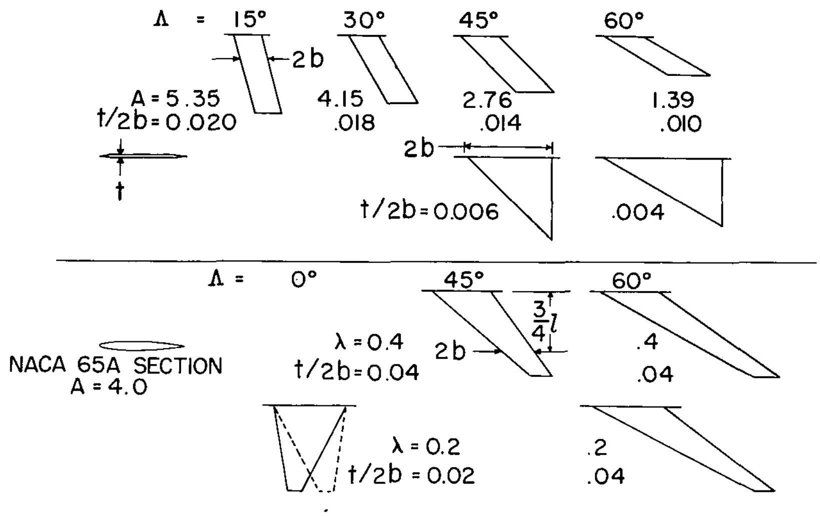


Figure 1

EFFECT OF MACH NUMBER

μ_0 = 50; C.G. LOCATION = 50% c

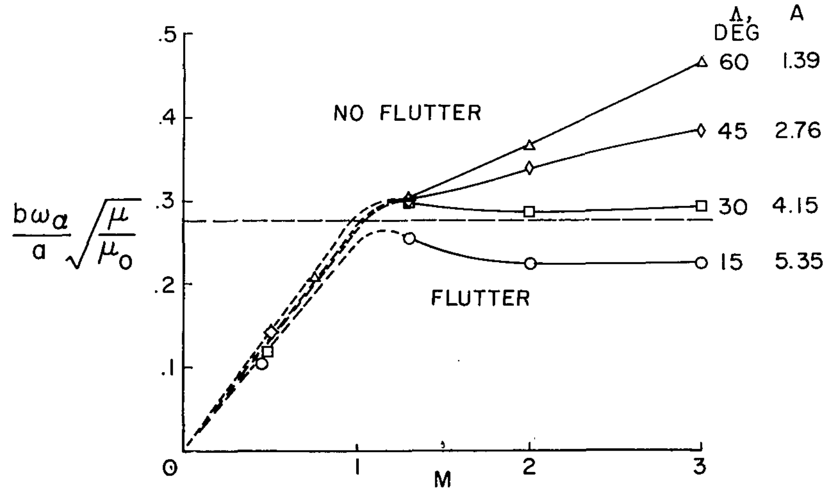


Figure 2

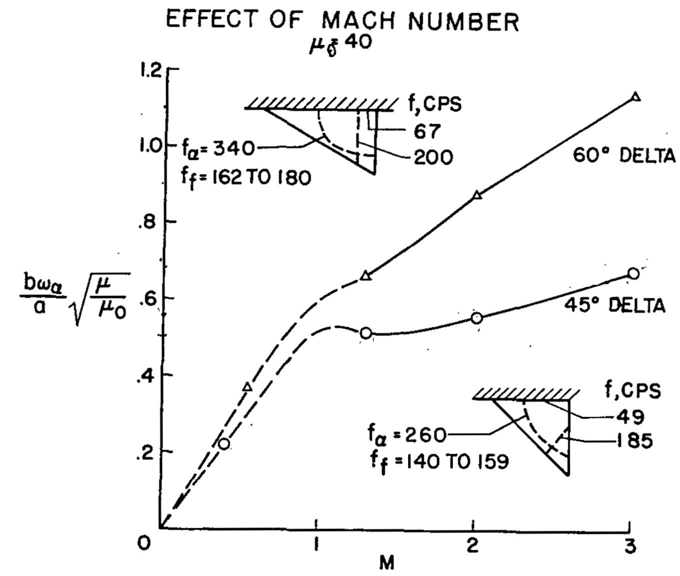


Figure 3

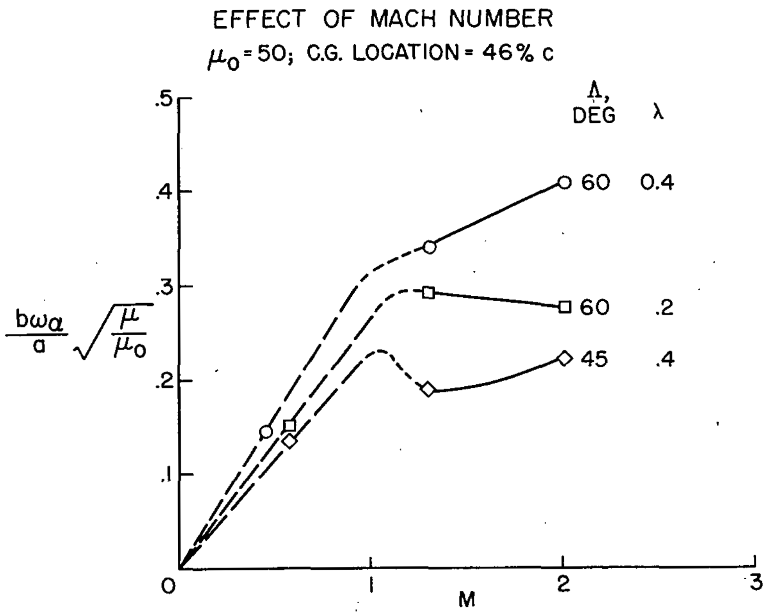


Figure 4

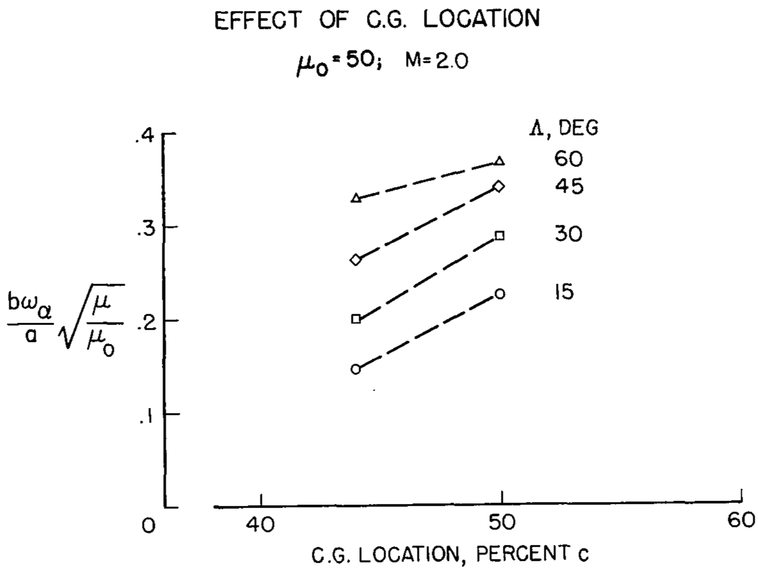


Figure 5

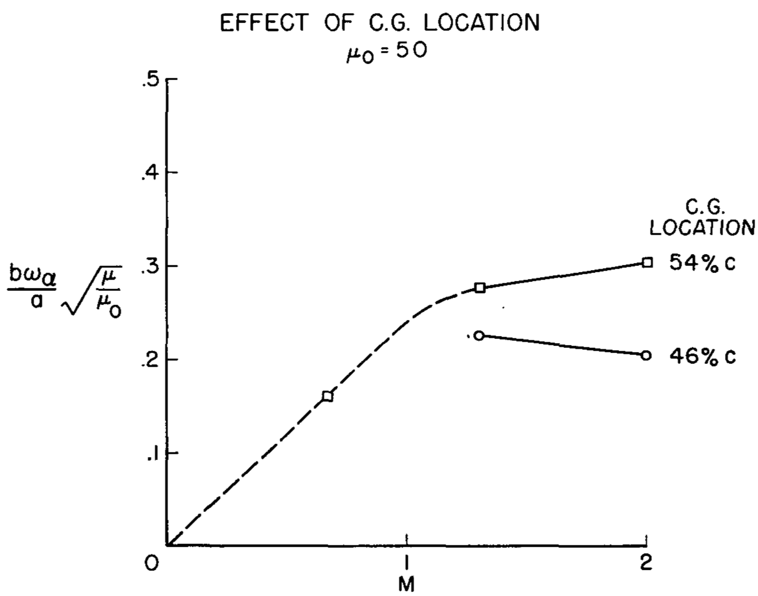


Figure 6