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By

W. G. MOLYNEUX, B.Sc. and F. RUDDLESDEN, A.M.I.E.I.

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Flutter Tests on some Delta Wings using Ground-Launched Rockets

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Summary.—This report gives the results of tests on flutter models of cropped delta wings having 40, 50 and 60 deg leading-edge sweepback and a taper ratio of 1 : 7.

A comparison is made between the measured flutter speeds and the speeds estimated using a flutter speed formula, and the estimated speeds are found to be within ±15 per cent of the measured speeds. A modification to the formula is proposed to allow for the high values of stiffness ratio that are obtained for delta wings.

1. *Introduction.*—Some flutter tests at high Mach number on unswept and swept wings have been described in earlier reports[1, 2], and the results of these tests have been used for the development of a formula that enables a reasonable estimate of wing flutter speeds to be obtained from known properties of the wings.

In the present report tests on cropped delta wings having 40, 50 and 60 deg leading-edge sweepback and a taper ratio 1 : 7 are described. The flutter speed formula[2] is used to obtain estimates of flutter speeds for the wings, and in general the estimated speeds are in reasonable agreement with the measured speeds.

The ratio of flexural to torsional stiffness is in practice generally greater for delta wings than for unswept and swept wings, and is frequently outside the limits prescribed in the flutter speed formula. An amendment to the factor in the formula that involves stiffness ratio is therefore proposed to enable the formula to be applied over a wider range of stiffness ratio.

With this modification the estimated speeds are within ±15 per cent of the measured speeds for all the delta wings tested. These limits are similar to those obtained on unswept and swept wings[1, 2].

2. *Details of the Models.*—A typical assembly of a delta wing on a five-inch diameter rocket is shown in Fig. 1. The peak speed that could be achieved for this assembly was about 2,000 ft/sec, 1·8 Mach number. Wings having 40, 50 and 60 deg leading-edge sweepback and a taper ratio of 1 : 7 were tested. The external dimensions of the wings and details of the wing construction are given in Table 1. The thickness/chord ratio as measured in the line-of-flight direction was 0·090 for the wings with 40 deg leading-edge sweepback, 0·070 for 50 deg sweepback and 0·045 for 60 deg sweepback. Included in Table 1 are details of a delta wing tested in a low speed

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wind tunnel[3]. The leading-edge sweepback of this wing was 45 deg, the taper ratio was 1 : 16 and the thickness/chord ratio was $0 \cdot 10$. Details of these tests are included to provide information on the low speed flutter characteristics of delta wings, which cannot easily be obtained by the rocket method.

3. *Test Procedure.*—Measurements of the inertia and elastic characteristics were made on all the wings. To determine the elastic characteristics the wing was rigidly fixed at the root and measurements were made with loads applied to a wing section in the line of flight at 70 per cent root-to-tip length outboard from the root. Torsional stiffness was determined from measurements with a pure torque applied in the plane of the loading section and flexural stiffness was determined from measurements with a load applied to the loading section at the flexural centre.*

The mean values of torsional and flexural stiffnesses and flexural centre positions for the port and starboard wings of each model are given in Table 2.

Resonance tests were made on the wings with fixed root, and the frequencies and nodal line positions for the first three modes were determined. For all the wings the fundamental mode was mainly flexural, the first overtone mode was mainly overtone flexure and the second overtone mode was mainly torsional. The frequencies and nodal line positions for each wing are shown in Fig. 2.

For the flutter tests, models 1193, 1195 and 1198 (40, 50 and 60 deg leading-edge sweepback respectively) were fitted with a vibration pickup in each wing to determine whether symmetric or antisymmetric flutter was obtained. The remaining models were fitted with a pickup in one wing only. All models were launched at an elevation of $12\frac{1}{2}$ deg and a continuous photographic record was obtained of the signals from the vibration pickups in the wings. The flight path of each model was followed by ciné cameras and the velocity was measured by radio reflection Doppler equipment. From these records the speed and acceleration of the model at commencement of flutter, the flutter frequency and the speed at which the wings failed were determined. These measurements are given in Table 2. Also included in Table 2 are the results of the flutter tests on the wind tunnel delta wing[3] described in Section 2.

4. *Discussion of Results.*—The range of variation of stiffness ratio for these wings (from $0 \cdot 59$ to $3 \cdot 40$) is wider than was obtained for unswept and swept untapered wings[1,2]. Also, the first overtone mode for the delta wings is flexural, whereas in the tests on swept and unswept wings the first overtone mode was, in general, torsional. Both these features probably result from the high taper ratio of the delta wings.

The telemetry records of wing oscillations in flight were of three distinct types (Fig. 3):

(1) Divergent flutter oscillations leading to wing failure during the rocket acceleration period.

(2) Intermittent oscillations during the rocket acceleration period with divergent flutter oscillations leading to wing failure during the deceleration period.

(3) Intermittent oscillations during the rocket acceleration and deceleration periods without wing failure.

A record of type (2) was obtained on model 1195 only. This type of record may be explained by the existence of a region of speed for divergent flutter oscillations that is traversed during the acceleration period before the flutter develops to wing failure. The speed at which the oscillations commenced was taken as the flutter speed, and the frequency of the oscillations (which was the same as that of the final flutter oscillations) was taken as the flutter frequency.

A record of type (3) was obtained on model 1179 only. The oscillations were irregular and occurred in very short bursts of some four or five complete cycles. The existence of flutter could not be established positively but the speed at which the oscillations were most apparent

* The flexural centre is here defined as the point in the loading section at which a load applied normal to the wing produces no change of incidence of the loading section.

was taken as the 'flutter' speed and the frequency of the oscillations as the 'flutter' frequency. The record may be explained by a near flutter condition in which the damping is small, so that the wing oscillates for a few cycles when disturbed.

The three models (1193, 1195, 1198) that were fitted with two pickups to establish whether symmetric or antisymmetric flutter was obtained, all gave records of symmetric flutter.

No oscillations were recorded on models 1194 and 1197 up to the peak speeds of the rockets.

5. *Comparison of Estimated and Measured Speeds.*—An estimate of wing flutter speeds was obtained using the following flutter speed formula[2].

$$V_1 = \left(\frac{m_0}{\rho_0 s c_m^2}\right)^{1/2} \frac{(0\cdot 9 - 0\cdot 33k)(1 - 0\cdot 1r)(0\cdot 95 + 1\cdot 3/\sigma_w)}{0\cdot 78\,(g - 0\cdot 1)} \sec^{3/2}\left(\Lambda - \frac{\pi}{16}\right) \quad \ldots \quad (1)$$

$$V_2 = V_1\,(1 - 0\cdot 166 M_1 \cos\Lambda)\;;\quad M_1 \cos\Lambda \leqslant 1\cdot 265$$

$$= 0\cdot 79\, V_1\;;\quad M_1 \cos\Lambda > 1\cdot 265$$

where V_2 is the required estimated speed. (The symbols are defined in Table 2.) The estimated speeds and the ratio of measured speed to estimated speed are given in Table 2. The ratio of measured speed to estimated speed is plotted against $M_1 \cos\Lambda$ in Fig. 4a.

It should be noted that definite flutter points are obtained only for values of $M_1 \cos\Lambda < 1$. Flutter of model 1179 ($M_1 \cos\Lambda = 1\cdot 76$) was not positively established, and the points shown for models 1194 and 1197 are based upon peak rocket speed in the absence of any indications of flutter.

The results for the remainder of the models, which definitely fluttered, give estimated flutter speeds within ± 15 per cent of the measured values, over a range of $M_1 \cos\Lambda$ up to $0\cdot 74$. This order of agreement is similar to that obtained for unswept and swept, untapered wings[2] and indicates that the formula can reasonably be applied to cropped delta wings despite the highly tapered plan-form. However, further tests would be required to ascertain whether the formula could be applied to the pointed tip delta wing. It seems probable that the formula would give a reasonable result in this case, since the estimated speeds for the wind tunnel delta, taper ratio 1 : 16, give the same order of agreement with the measured speeds as was obtained for the flight models with taper ratio 1 : 7.

6. *Modification to the Stiffness Ratio Factor.*—A feature of delta wings is the high values of the stiffness ratio, r, that are obtained (Table 2). These are frequently outside the limits of variation $0\cdot 5 < r < 2\cdot 0$ specified for the formula[4], and in fact a stiffness ratio of 8 has been estimated in a recent design study for a delta wing. With the present form of the stiffness ratio factor the formula gives an unduly low estimate for the flutter speeds of high stiffness ratio wings. For instance, the estimated speed for model 1194 ($r = 3\cdot 4$) was 1,660 ft/sec whereas no flutter was recorded up to 2,000 ft/sec. Recent theoretical investigations for swept and unswept wings have shown that provided the fundamental flexural and torsional modes are well separated in frequency the effect of high stiffness ratio on flutter speed is small. This proviso is, in general, satisfied for delta wings.

In order, therefore, that the formula may be applied for a wide range of stiffness ratio it is proposed to modify the stiffness ratio factor from $(1 - 0\cdot 1r)$, $0\cdot 5 < r < 2\cdot 0$ to $(0\cdot 77 + 0\cdot 1/r)$, $0\cdot 5 \leqslant r$. In the range of stiffness ratio from $0\cdot 5$ to $2\cdot 0$ the effect of this modification is small. At the same time the terms in the basic formula that involve taper ratio and inertia axis position are simplified by the substitutions

$$\frac{(0\cdot 9 - 0\cdot 33k)}{c_m} \simeq \frac{0\cdot 61}{c_{0\cdot 7}}\;; \qquad 0 \leqslant k \leqslant 1$$

where $c_{0\cdot 7}$ is the wing chord at $0\cdot 7s$

$$0\cdot 78\,(g - 0\cdot 1) \simeq 0\cdot 61g\;; \qquad 0\cdot 35 \leqslant g \leqslant 0\cdot 6\,.$$

With these substitutions the expression for V_1 is then given by

$$V_1 = \left(\frac{m_0}{\rho_0 s c_{0\cdot 7}{}^2}\right)^{1/2} \frac{(0\cdot 77 + 0\cdot 1/r)\ (0\cdot 95 + 1\cdot 3/\sigma_w)}{g} \sec^{3/2}\left(\Lambda - \frac{\pi}{16}\right) \quad \ldots \quad \ldots \quad (2)$$

The effect of this revised formula for these wings is shown in Table 2 and Fig. 4b. The agreement between measured and estimated speeds for wings of high stiffness ratio is, in general, improved, and in particular the estimated speed for model 1194 is raised from 1,660 ft/sec to 1,984 ft/sec which is within 1 per cent of the peak speed of the rocket. The above modifications have also been applied to flutter speed estimates for the unswept and swept wings[2] and in general the effect is small. However, the agreement between measured and estimated speeds for wings of high stiffness ratio is somewhat improved, and for one wing the error in the estimated speed is reduced from -27 per cent to -13 per cent of the measured speed.

7. *Definition of the Sweepback Line.*—In the results of Figs. 4a and 4b the estimated flutter speeds are obtained by taking the sweepback angle Λ in the formula as the sweepback of the leading edge. It has been customary, both for tapered sweptback wings and delta wings, to consider the effective sweepback angle as lying between the leading and trailing-edge sweepback angles. It is clear, however, that for the delta wings tested the use of the leading-edge sweepback in the flutter speed formula gives the best results. In Fig. 5 the results of Fig. 4b are replotted using for Λ the sweepback of the 36 per cent chord line (*i.e.*, 5 per cent of the chord behind the line of maximum thickness), as recommended in the official design requirements (AP.970, Part 5). The mean ratio of measured to estimated speeds is about 25 per cent greater than that obtained using the leading-edge sweepback, and represents a considerable margin of stiffness from the design viewpoint. However, this margin should not be regarded too seriously since it is obtained from results on a small number of wings.

It is perhaps worth noting that the original derivation[5] of the sweepback factor in the flutter speed formula was on the basis of rotation of unswept wings (aspect ratio $= 8$) to a swept position, resulting not only in a variation of leading-edge sweep but also a variation in wing aspect ratio.

As a result of more recent work[6] it has been possible to separate the aspect ratio and sweep effects for swept wings. For the original wings[5] the substitution can be made :

$$\sec^{3/2}(\Lambda - \pi/16) \simeq 0\cdot 9\ (1 + 0\cdot 8/A)\ \sec(\Lambda - \pi/16)$$

where A is the exposed wing aspect ratio ($A = 2s/c_m$) ,

leading to the current expression for V_1 for swept wings[7].

$$V_1 = \left(\frac{m_0}{\rho_0 s c_{0\cdot 7}{}^2}\right)^{1/2} \frac{0\cdot 9\ (0\cdot 77 + 0\cdot 1/r)\ (1 + 0\cdot 8/A)}{g} \sec\left(\Lambda - \frac{\pi}{16}\right) \quad \ldots \quad \ldots \quad (3)$$

(The term $(0\cdot 95 + 1\cdot 3/\sigma_w)$ is omitted from (3) since for current designs of swept wing aircraft it has a negligible effect.)

Expression (3) has been applied to the present series of delta wings, and the results are shown in Table 3.

It can be seen that this formula leads to an overestimate of flutter speed for delta wings, the agreement between measured and predicted speeds becoming progressively worse with increasing wing sweepback (decreasing aspect ratio). Apparently, for delta wings of high taper ratio where sweepback and aspect ratio are closely related, Expression (2) for V_1 is to be preferred.

8. *Conclusions.*—Flutter tests have been made on uniformly tapered cropped delta wings, and estimates of wing flutter speeds have been obtained using a flutter speed formula. The estimated speeds, are, in general, in reasonable agreement with those measured. However,

it is proposed to introduce a modified stiffness ratio factor into the formula so as to avoid unduly low speed estimates for wings of high stiffness ratio, such as delta wings. The modified formula is as follows :

$$V_1 = \left(\frac{m_\theta}{\rho_0 s c_{0\cdot 7}{}^2}\right)^{1/2} \frac{(0\cdot 77 + 0\cdot 1/r)\ (0\cdot 95 + 1\cdot 3/\sigma_w)}{g} \sec^{3/2}\left(\Lambda - \frac{\pi}{16}\right)$$

$$V_2 = V_1\,(1 - 0\cdot 166\, M_1 \cos \Lambda)\ ; \qquad M_1 \cos \Lambda \leqslant 1\cdot 265$$

$$= 0\cdot 79\, V_1\ ; \qquad M_1 \cos \Lambda > 1\cdot 265$$

where V_2 is the required flutter speed estimate, M_1 is the Mach number corresponding to the speed V_1 and Λ is the sweepback of the wing leading edge.

The formula gives flutter speed estimates for these wings that are within ± 15 per cent of the measured speeds.

Acknowledgement.—Acknowledgements are due to the Staff of Guided Weapons Dept., Trials Division for their assistance in the calibration and testing of these models.

NOTATION

Basic formula

$$V_1 = \left(\frac{m_0}{\rho_0 s c_m^2}\right)^{1/2} \frac{(0\cdot9 - 0\cdot33k)\,(1 - 0\cdot1r)\,(0\cdot95 + 1\cdot3/\sigma_w)}{0\cdot78\,(g - 0\cdot1)} \sec^{3/2}\left(\Lambda - \frac{\pi}{16}\right)$$

Modified formula

$$V_1 = \left(\frac{m_0}{\rho_0 s c_{0\cdot7}^2}\right)^{1/2} \frac{(0\cdot77 + 0\cdot1/r)\,(0\cdot95 + 1\cdot3/\sigma_w)}{g} \sec^{3/2}\left(\Lambda - \frac{\pi}{16}\right)$$

M_1	$=$	$\frac{V_1}{a_0}$ (a_0 = local speed of sound-ft/sec
V_2	$=$	$V_1\,(1 - 0\cdot166\,M_1 \cos \Lambda)$; $M_1 \cos \Lambda \leqslant 1\cdot265$
	$=$	$0\cdot79\,V_1$; $M_1 \cos \Lambda > 1\cdot265$
V		Measured critical flutter speed—ft/sec
M		Mach number at critical speed
V_F		Speed at wing failure—ft/sec
c_m		Wing mean chord—ft
$c_{0\cdot7}$		Wing chord at $0\cdot7s$—ft
g		Distance of wing inertia axis aft of L.E. ÷ wing chord ; $0\cdot35 \leqslant g \leqslant 0\cdot6$
h		Distance of wing flexural centre aft of L.E. ÷ wing chord
k		Wing taper ratio
	$=$	$\frac{\text{tip chord}}{\text{root chord}}$; $0 \leqslant k \leqslant 1$
n		Flutter frequency—c.p.s.
r		Stiffness ratio
	$=$	$\frac{l_\phi\,c_m^2}{0\cdot81\,m_0\,s^2}$; $0\cdot5 \leqslant r$
s		Wing length root to tip—ft
f/G		Rocket acceleration ÷ gravitational acceleration
l_ϕ		Wing flexural stiffness measured at $0\cdot7s$—lb ft/rad
m_0		Wing torsional stiffness measured at $0\cdot7s$—lb ft/rad
Λ		Leading-edge sweepback
ρ_0		Air density at sea level—slugs/cu ft
ρ_w		Wing density—slugs/cu ft
	$=$	$\frac{\text{mass of one wing}}{s c_m^2}$
w_m		Flutter frequency parameter
	$=$	$\frac{2\pi\,n\,c_m}{V}$
σ_w		Wing relative density
	$=$	ρ_w/ρ_0

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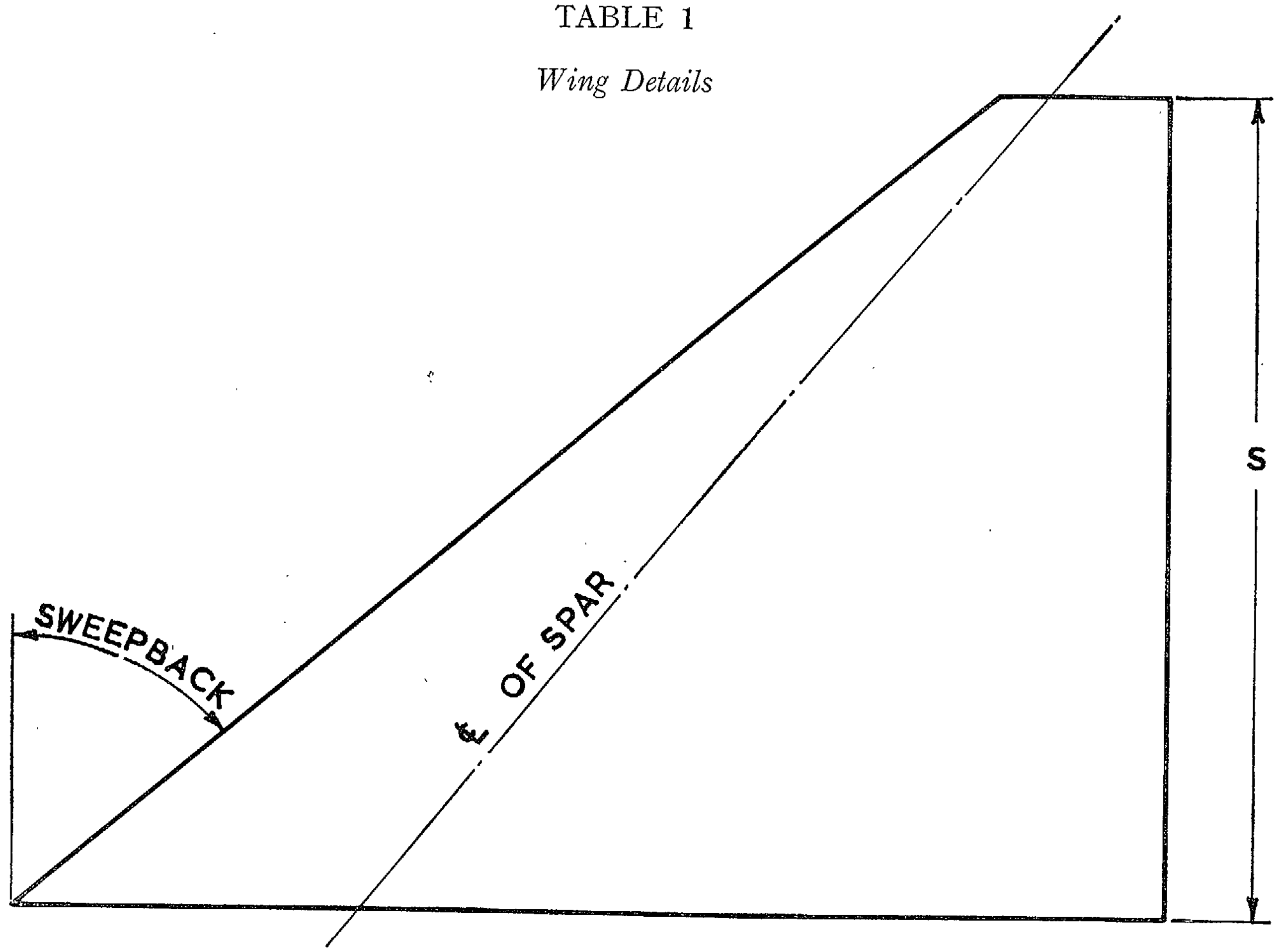
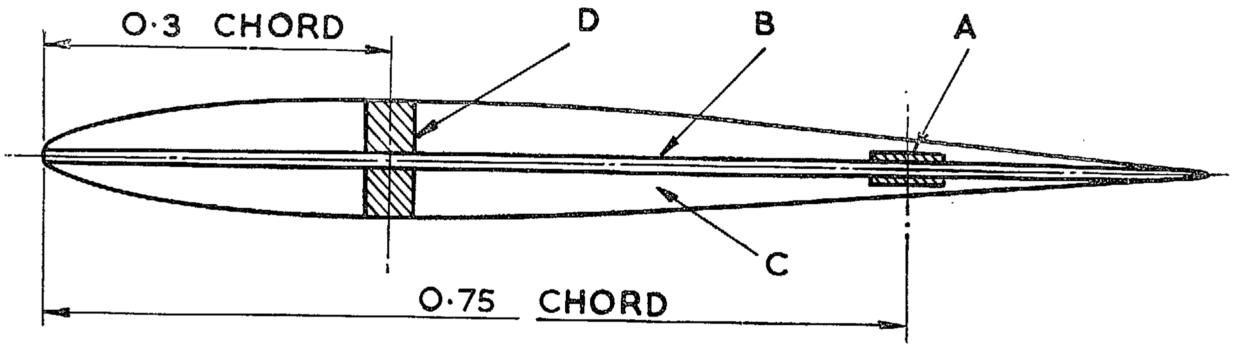
TABLE 1

Wing Details





Model No.	Sweepback Λ deg	Root to tip length S in.	Tip chord C_T in.	Root chord C_R in.	$k = C_T/C_R$	Wing section	Thickness/chord ratio	Wing Construction A	Wing Construction B	Wing Construction C	Wing Construction D	Radius of gyration of streamwise strip about C.G. of strip ÷ chord length
1176	40	24	3·35	23·4	0·143	RAE 101	0·090	lead strip	$\frac{1}{8}$ in. thick plywood	solid balsa	no spar	0·29
1179	40	24	3·35	23·4	0·143	RAE 101	0·090	lead strip	nil	solid spruce	no spar	0·27
1193	40	24	3·35	23·4	0·143	RAE 101	0·090	lead strip	$\frac{1}{8}$ in. thick plywood	solid balsa	$\frac{1}{2}$ in. wide spruce spar	0·29
1177	50	24	4·75	33·3	0·143	RAE 101	0·070	lead strip	$\frac{1}{8}$ in. thick plywood	solid balsa	no spar	0·26
1194	50	24	4·75	33·3	0·143	RAE 101	0·070	lead strip	nil	solid spruce	no spar	0·24
1195	50	24	4·75	33·3	0·143	RAE 101	0·070	lead strip	$\frac{1}{8}$ in. thick plywood	solid balsa	$\frac{1}{2}$ in. wide spruce spar	0·28
1196	60	24	6·90	48·3	0·143	RAE 101	0·045	nil	$\frac{1}{8}$ in. thick plywood	solid balsa	no spar	0·29
1197	60	24	6·90	48·3	0·143	RAE 101	0·045	nil	nil	solid spruce	no spar	0·23
1198	60	24	6·90	48·3	0·143	RAE 101	0·045	nil	$\frac{1}{8}$ in. thick plywood	solid balsa	$\frac{1}{2}$ in. wide spruce spar	0·28
wind tunnel delta	45	45	3·0	48·0	0·0625	RAE 101	0·10					

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TABLE 2

Comparison of Estimated Speeds with Measured Speeds

Model	Data from Laboratory Tests										Estimated Speeds			Measured Flutter Values						Ratio V/V_2	Modified Formula			
No.	Λ deg	s ft	c_m ft	k	l_ϕ lb ft/radn	m_θ lb ft/radn	h	r	g	σ_w lb/cu ft	V_1 ft/sec	$\frac{M_1}{\sec \Lambda}$	V_2 ft/sec	V ft/sec	M	n c.p.s.	ω_m	f/g	V_F ft/sec		V_1	$\frac{M_1}{\sec \Lambda}$	V_2	V/V_2
1176	40	2·0	1·12	0·143	745	485	0·10	0·59	0·50	1·39	910	0·62	826	840	0·75	68	0·57	23	910	1·02	948	0·650	845	0·99
1179	40	2·0	1·12	0·143	24,000	4,450	0·42	2·07	0·45	2·59	2,570	1·76	2,030	1,820	1·63	85	0·33	43	—	0·90	2,692	1·846	2,126	0·86
1193	40	2·0	1·12	0·143	2,340	525	0·21	1·72	0·50	1·51	832	0·57	753	840	0·75	62	0·52	26	950	1·12	869	0·596	783	1·07
1177	50	2·0	1·58	0·143	1,600	1,060	0·03	1·17	0·50	1·14	1,100	0·63	984	1,000	0·90	59	0·59	20	1,070	1·02	1,112	0·640	994	0·99
1194	50	2·0	1·58	0·143	22,400	5,090	0·33	3·40	0·44	1·78	2,060	1·18	1,660	No flutter up to 2,000 ft/sec						—	2,511	1·445	1,984	—
1195	50	2·0	1·58	0·143	2,570	750	0·14	2·65	0·43	0·94	945	0·54	859	910	0·81	60	0·65	49	980	1·06	1,042	0·600	938	0·97
1196	60	2·0	2·30	0·143	817	1,060	0·01	1·26	0·43	0·60	1,240	0·56	1,125	1,030	0·92	50	0·70	49	1,200	0·92	1,207	0·540	1,099	0·94
1197	60	2·0	2·30	0·143	15,200	8,310	0·27	2·99	0·42	1·04	2,680	1·20	2,150	No flutter up to 1,900 ft/sec						—	3,053	1·367	2,412	—
1198	60	2·0	2·30	0·143	2,570	2,260	0·08	1·86	0·43	0·75	1,630	0·73	1,435	1,270	1·14	45	0·51	39	1,840	0·89	1,653	0·740	1,450	0·88
Wind	45	3·75	2·12	0·0625	375	62	0·15	2·40	0·50	0·92	117	0·074	115	131·5	0·12	8·1	0·82			1·14	133·8	0·085	131·9	1·00
Tunnel									0·45		134	0·085	127	143·5	0·13	7·5	0·70			1·13	145·1	0·092	142·8	1·00
Delta									0·40		156	0·099	153	146·0	0·13	7·3	0·67			0·95	167·5	0·106	164·6	0·89

TABLE 3

Application of Swept Wing Formula to Delta Wings

Model No.	V_1	$M_1 \cos \Lambda$	V_2	V/V_2
1176	1,092	0·749	956	0·88
1179	3,197	2·159	2,526	0·72
1193	1,001	0·686	887	0·95
1177	1,440	0·829	1,242	0·81
1194	3,350	1·928	2,647	—
1195	1,324	0·762	1,157	0·79
1196	1,749	0·783	1,522	0·68
1197	4,710	2·108	3,721	—
1198	2,477	1·109	2,021	0·63
Wind	153·2	0·097	150·7	0·87
Tunnel	166·0	0·105	163·1	0·88
Delta	192·2	0·122	188·3	0·78

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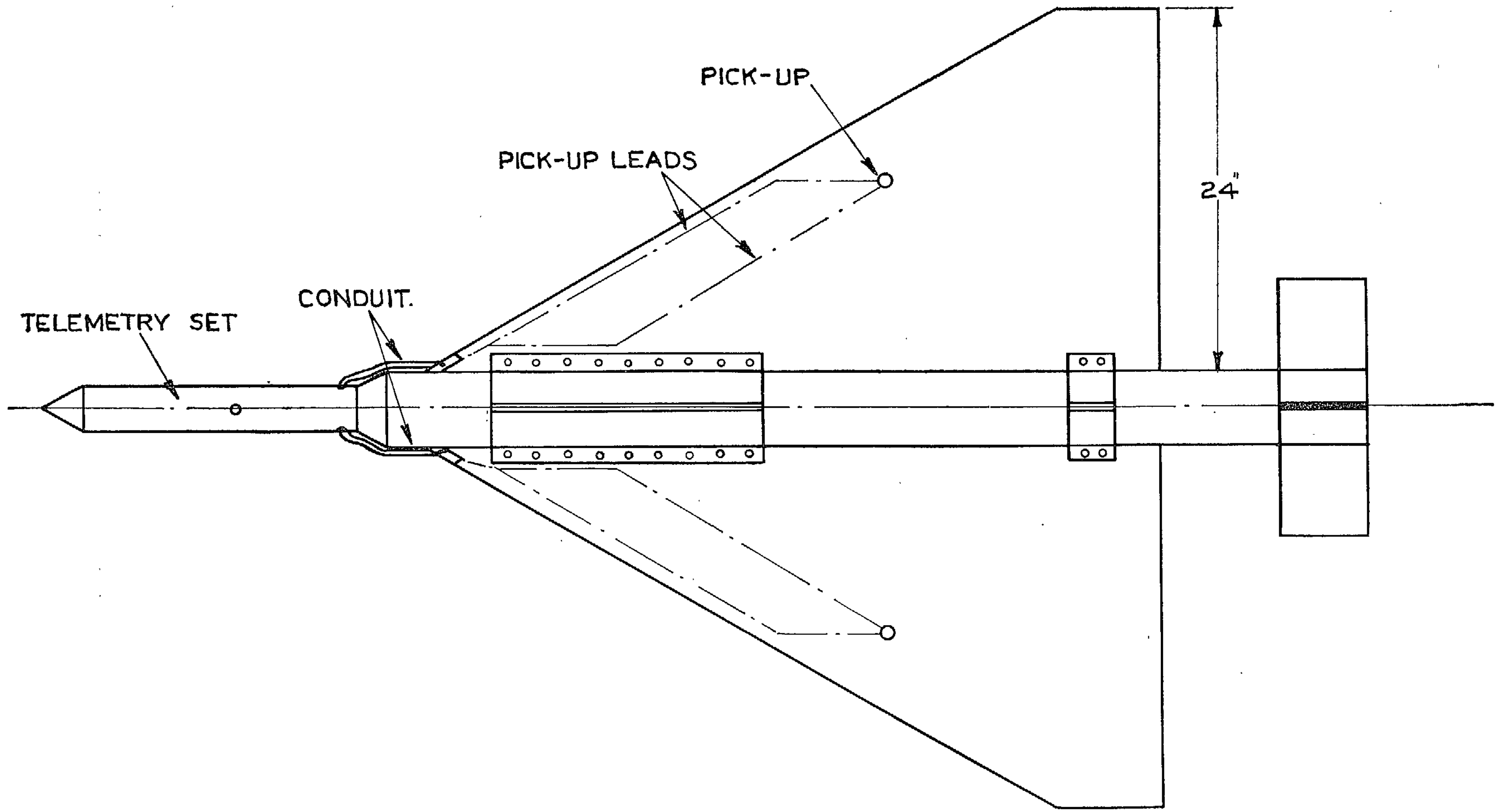

FIG. 1. Typical assembly—5 in. rocket.

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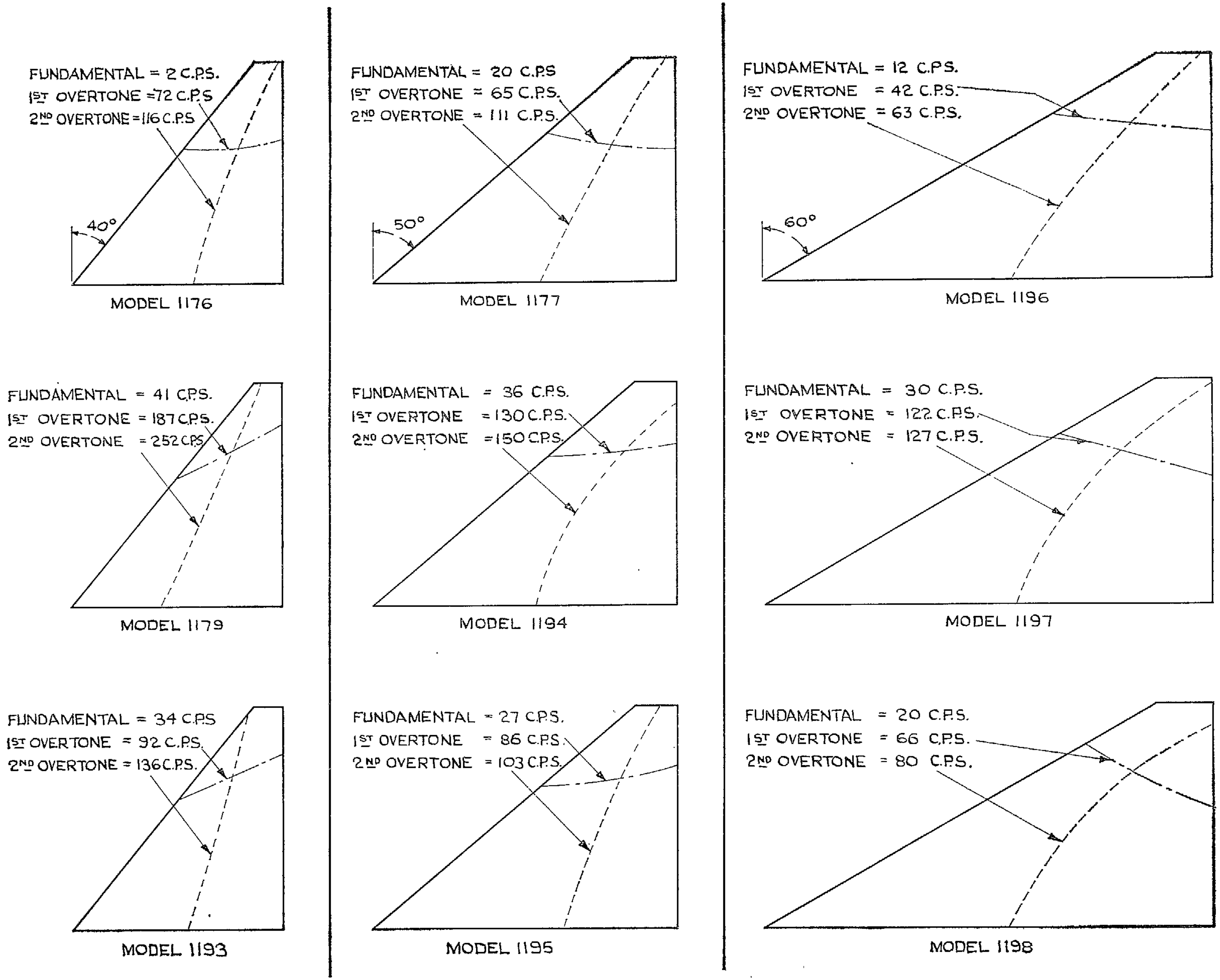


FIG. 2. Wing frequencies and nodal line locations—fixed root conditions.

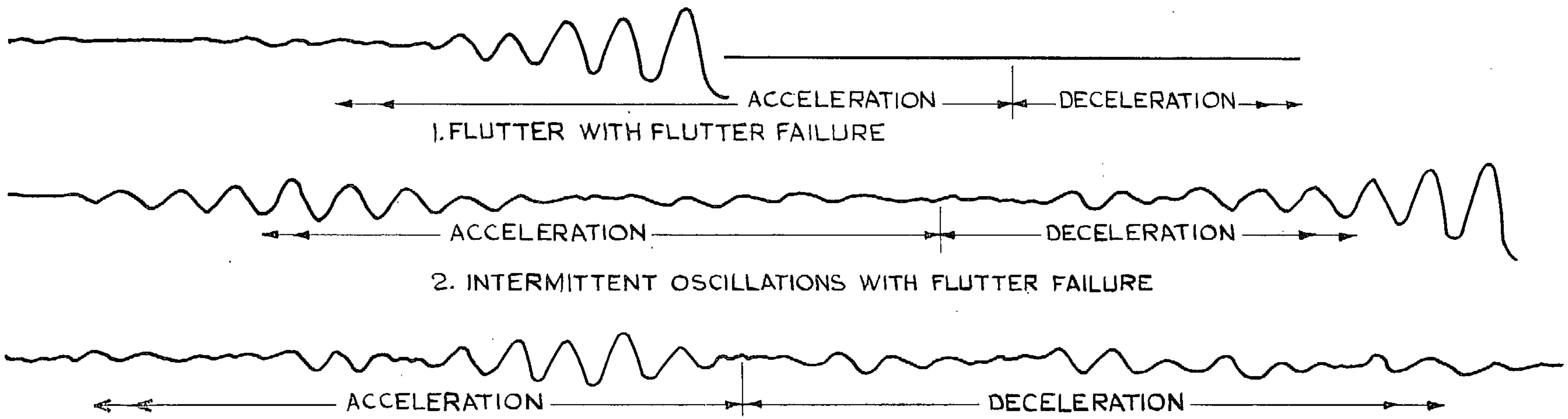


FIG. 3. Typical records of wing oscillations.

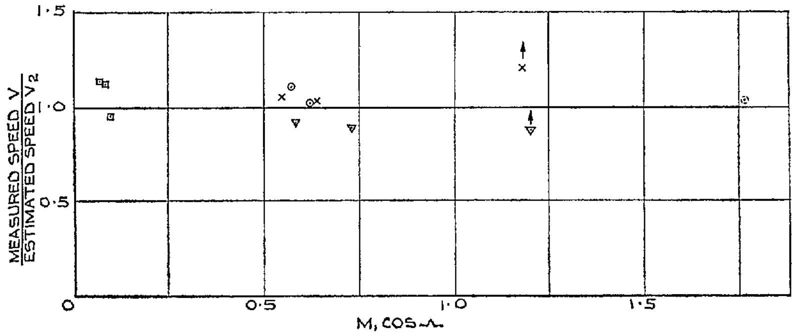


FIG. 4a. Comparison of measured and estimated flutter speeds.

KEY	
SYMBOL	LEADING EDGE SWEEPBACK Λ
⊙	40°
⊡	45°
×	50°
▽	60°

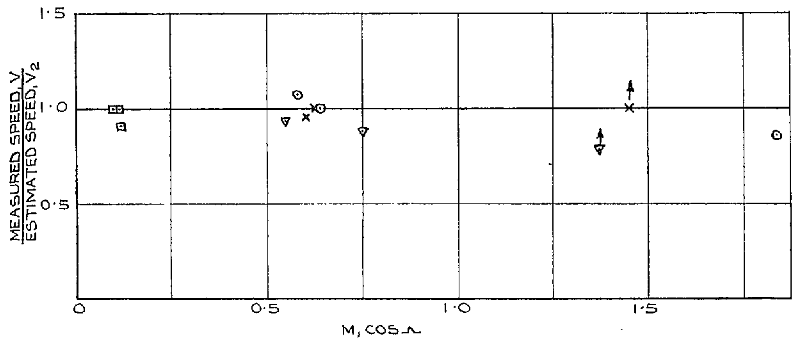
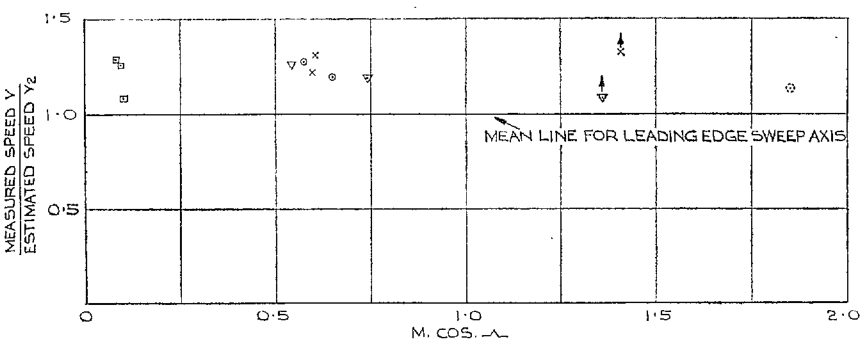


FIG. 4b. Effect of modified formula on comparison of measured and estimated flutter speeds.



KEY	
SYMBOL	SWEEPBACK OF 36% CORD LINE, Λ
⊙	28° 12′
⊡	32° 36′
×	37° 18′
▽	48° 0′

FIG. 5. The effect of sweep axis position on flutter speed ratios.

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