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Flutter of Control Surface Tabs

By

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Summary.—Oscillation of control-surface tabs has occurred in flight. General experience and the investigations of this report suggest that the oscillations were flutter, involving translation of the tab, arising from bending of the local control-surface structure, coupled with rotation of the tab about its hinge, arising from either backlash or elasticity of the tab controlling mechanism. Binary flutter calculations show that, for this coupling, the normal remedy, *i.e.* mass-balancing, is only partially effective (static mass-balancing roughly doubles the backlash flutter speed but may decrease the elastic flutter speed). If the tab controlling mechanism is adequately stiff, elimination of backlash gives higher flutter speeds than would be obtained by mass-balancing alone and in practice probably removes the danger of flutter. Flutter is completely prevented by aerodynamically balancing and dynamically mass-balancing (C.G. on hinge line) the tab.

1. *Introduction.*—1.1. High-frequency oscillations (dither) of trimming and balancing tabs have been observed in flight, some accidents have been attributed to fatigue failures of the tab control arm resulting from this dither. It was first thought that the dither was auto-buffeting, but all cases were cured by mass-balancing the tab, thus suggesting that the dither was tab flutter. In theory, trimming and balancing tabs have no separate degree of freedom and thus cannot flutter. In practice, due to backlash from wear or poor initial design and to general elasticity of connections, tabs can be moved relative to the control surface, and where dither has been observed there was appreciable backlash or elasticity. It is thus probable that the dither was tab flutter and that one of the degrees of freedom in the flutter was rotation of the tab about its hinge. For the other degree of freedom the obvious choice was rotation of the control surface about its hinge; but both full-scale experience and theory, particularly on rudder-servo tab flutter, show that this degree of freedom would give low-frequency oscillations, whereas the dither observed has been of a very high frequency. From general considerations, it appears that this high-frequency dither involves bending of the control-surface structure supporting the tab. Binary-flutter calculations have therefore been made for rotation of the tab about its hinge, coupled with translation of the tab. These calculations will apply to trimming, balancing and servo (including spring) tabs for the two degrees of freedom considered, and should give minimum flutter speeds for trimming and balancing tabs.

1.2. *Range of Theoretical Investigation.*—The classical theory of R. & M. 1155[1] is used in the flutter calculations; the equations of motion, flutter derivatives and general data are given in the Appendix. The calculations are mainly concerned with the effect of mass-balancing the tab (this being the standard remedy for control-surface flutter), but variations of the following parameters are also considered:—(a) chordwise distribution of mass in the tab (two cases), (b) mass of local control-surface structure participating in the motion (c) stiffness of control-surface structure, (d) tab-control stiffness (zero stiffness giving the backlash case), (e) inertia

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characteristics of tab, and (f) location of tab hinge. Since pure translation of the tab is one degree of freedom, dynamic and statis mass balance are both obtained when the C.G. of the tab is on its hinge line. Because of various factors, discussed in the Appendix, this work is only qualitative.

1.3. *The Model Experiments.*—To test the validity of the conclusions derived from the theoretical work some wind-tunnel experiments were made. The tunnel used gave a maximum speed of 100 ft/sec. in a 1-ft square working section. The experiments were not meant to give quantitative results. The model consisted quite simply of two sheets of 3/16 in. plywood; the first, representing the control-surface structure, was a rectangular sheet, 18 × 11 in. clamped at its leading edge to the tunnel roof and floor, and with a section cut from its trailing edge to allow the sheet representing the tag to be inset. The tab was a 6 × 3 in. rectangular sheet hinged along its leading edge with a tongue 1 in. wide and 3 in. long projecting forward for mounting the mass-balance weights. The tab operating control stiffness was represented by two flat springs bolted one on either side of the main sheet and bearing on the tongue of the tab. The experiments did not cover so wide a range of conditions as the theoretical work because the tunnel was only available for a short time.

2. *Statement and Discussion of the Results of the Theoretical Calculations.*—2.1. *Results.*—The notation is defined in the Appendix, the results are given in Figs. 1 to 3. Figs. 1 (a), 1 (b), 1 (c) show the variation of flutter speed with the ratio of the stiffnesses for various degrees of mass balance. These figures are for a tab hinged at its leading edge, and except for the broken line curve in Fig. 1 (a) the mass-balance arm is equal to the tab chord. The factor k_1/k_0 is the ratio of the mass-balance weight* to the tab weight. The tab weight is kept constant but the distribution of the weight chordwise has been varied. Owing to the triangular and uniform mass distribution assumed. the tab (with no mass balance weight) of Fig. 1 (b) has a greater torsional moment of inertia G_3 and product of inertia P than the tab of Fig. 1 (a); the tab of Fig. 1 (c) is the same as that of Fig. 1 (b) except that mass is assumed distributed along the tab hinge line to represent the weight of the control surface supporting structure which participates in the motion. In Fig. 1 (b) the flutter frequency and natural rotational frequency in vacuo are also plotted, as fractions of the translational frequency in vacuo for the tab with its C.G. on its hinge line.

The case of no play at the hinge, but backlash in the tab-control mechanism permitting rotation of the tab about its hinge is given by $m_\theta = 0$. The points for which $m_\theta/C^2 l_z = 0$ in Figs. 1 (a), (b) (c) are replotted in Fig. 2 to give the variation of flutter speed with mass-balance weight. Since mass-balancing alone is not always sufficient to prevent flutter, variation in hinge position of a mass-balanced tab C.G. on the hinge line) is also considered, the results are shown in Fig. 3. The tab is similar to that of Fig. 1 (b). The minimum value of the flutter speed for variation of m_θ (*see* equations (6a) and (6b) section 4, Appendix) is also plotted in Fig. 3.

2.2. *Discussion.*—2.2.1. Figs. 1 (a), (b), (c) relating to tabs hinged at the leading edge are very similar; for a tab without mass-balance weight the flutter speed increases as the stiffness ratio increases; for a mass-balanced tab (*i.e.* C.G. on hinge line) the flutter speed falls as the stiffness ratio increases until the natural frequencies in the two degrees of freedom are nearly equal, after which it suddenly increases very rapidly and tends to infinity just before the natural frequencies coincide. For values of the tab stiffness m_θ greater than that giving equal natural frequencies there will be no flutter for the statically mass-balanced tab. Over a fairly wide range of stiffness ratios, statically mass-balancing the tab lowers its flutter speed and gives a minimum flutter speed lower than that for the tab alone. The backlash case ($m_\theta = 0$) gives the lowest flutter speed for the tab alone, mass-balancing roughly doubles this flutter speed.

* Since the designer is interested in the weight necessary to prevent flutter, the mass-balance weight has been taken as a variable (strictly it is only a mass-balance weight for one particular value of the variable) and the curves are for values of this weight over tab weight (k_1/k_0) instead of values of the product of inertia P. P is zero, for the particular conditions assumed, when the C.G. of the tab and balance weight is on the tab hinge line, *i.e.* for $k_1 k_0 = 1/3$ in Figs. 1(*a*), $= 1/2$ in Figs. 1(*b*), 1(*c*). For smaller values of $k_1 k_0$ P is positive, for larger values P is negative. A_1, P, and G_3 have been varied together instead of the more usual practice of varying P independently.

Over mass-balancing eliminates the very low flutter speeds which occur for certain stiffness ratios when the tab is statically mass-balanced and also gives an increase in the backlash flutter speed. Fig. 2 shows that, at least for the mass-balance arm chosen, it is impossible to eliminate the backlash flutter by increase of mass-balance weight alone; the flutter speed can be roughly trebled by using an over mass-balance equal to the tab weight at a distance equal to the tab chord ahead of the hinge, but this may be impractical because it involves a considerable increase in the control surface mass-balance weight. *Obviously it is preferable to design so that there is no backlash rather than to mass-balance the tab to avoid flutter due to backlash.*

2.2.2. Comparison of the broken line and the full line curves for $k_l/k_0 = 1/2$ in Fig. 1 (a), which relate to the same weight on different arms, shows that the arm giving over mass-balance is preferable to that giving static balance.

2.2.3. Mass-balancing may result in a drop in the critical speed when the tab hinge is at the leading edge; the effects of changing the hinge position for a statically mass-balanced tab are shown in Fig. 3. In the backlash case the flutter speed rises steadily as the hinge position is moved back and tends to infinity just before the tab becomes aerodynamically balanced ($V_c \rightarrow \infty$ as $h \rightarrow 0 \cdot 248$; *see* Appendix section 3.3. for reasons why the hinge position for aerodynamic balance is $1/4c$ in this report, whereas in practice it would be $0{\cdot}3 - 0{\cdot}4c$ behind the leading edge); there is no backlash flutter for further aft positions. [Approach to aerodynamic balance of a mass-balanced aileron can result in an increase in the flexural-aileron flutter speed of a wing as was shown by Lockspeiser and Callen in R. & M. 1464[3].]

For stiffness ratios greater than certain values* *e.g.* $0{\cdot}545$ at $h = 0$, there is no flutter if the tab is not aerodynamically overbalanced. The minimum flutter speed for variation of stiffness ratio increases as the hinge position moves towards the quarter-chord position from either direction, there is a small range ($0{\cdot}248 < h < 0{\cdot}252$) of hinge position for which there is no flutter for any positive value of the stiffness ratio. It should be noted that the mass-balance weight required for static mass-balance decreases as the hinge position is moved back; in the case considered the tab C.G. is at $0{\cdot}5c$ so that no mass-balance weight would be required when the hinge is at $0{\cdot}5c$. In practice no difficulty should arise in designing a tab so that its C.G. is within $0{\cdot}3$ to $0{\cdot}4c$ behind the leading edge without any additional weight being necessary.

2.2.4. *To gain absolute freedom from flutter of the type considered, the tab hinge should be set back so that the tab is aerodynamically balanced and the tab* C.G. *should be on the hinge line.* If it is certain that backlash will not develop in service conditions, and if the stiffness ratio is greater than the value required to give equal natural frequencies for the statically mass-balanced tab, then to avoid flutter the C.G. should be on the hinge line and the tab not overbalanced aerodynamically.

It is probable that these precautions would eliminate the possibility of flutter from tab motion coupled with any other degree of freedom (rotation of control surface, flexure of main surface, etc.) It should be noted that if the tab is aerodynamically balanced the loads in the tab-controlling mechanism are negligible, consequently backlash due to wear should not arise.

With regard to other factors the concentration of the tab weight near the hinge gives better results at high values of the stiffness ratio, but worse in the backlash case (compare Figs. 1 (a), (b)); decrease in the weight of the tab compared with the weight of the local control-surface structure gives a considerable improvement at high stiffness ratio values but decreases the backlash flutter speed (Figs. 1 (b), (c)). These effects are opposite according to whether the stiffness ratio is high or zero. From general considerations the tab should be as light as possible and its moment of inertia should be low.

3. *Model Tests.*—The model tests of a tab hinged at its leading edge confirmed the results given in Figs. 1, 2. With zero spring stiffness flutter occurred with the tab statically mass-balanced at about twice the wind speed as for the tab without mass-balance. A particular spring stiffness was found for which the flutter speed of the statically mass-balanced

* Except when the tab is closely balanced aerodynamically, these certain values (of which $0{\cdot}545$ is the maximum) are very nearly those which give equal natural frequencies.

tab was about 40 ft/sec while, with the same spring stiffness but with the mass-balance weights removed, no flutter occurred up to the top speed of the tunnel (about 100 ft/sec); the natural frequencies of the mass-balanced tab were approximately equal (of the order of 5 per sec).

The model tests also showed that flutter with a mass-balanced tab was much less violent than with an unmass-balanced tab. Flutter with the unmass-balanced tab was so violent, and the amplitude increased so rapidly that it was necessary to shut down as soon as the oscillation started; even so, the model gradually deteriorated due to excessive amplitudes. With the tab statically mass-balanced there was no need to shut down and the wind speed could be increased by 20 ft/sec or more, the amplitudes were large but not so large that there appeared to be any danger of breaking the model.

4. *Spanwise Distribution of Mass-balance Weights.*—The foregoing theoretical analysis, in which the tab has been assumed rigid, gives no guidance as to the best spanwise distribution of mass-balance weights; from general considerations the best distribution for these weights, as for control-surface mass-balance weights, is uniformly along the span.

5. *Practical Conclusions.*—It is probable that the tab dither observed in flight was flutter due to coupling of the tab rotation about its hinge with translational movement due to bending of the local control surface structure. The freedom of the tab to rotate about its hinge is due either to backlash or to elasticity of the tab-controlling mechanism; backlash and elasticity will give very different flutter characteristics, both must be considered in any particular case.

(i) *Backlash.*—This is the more important case since in general it leads to lower flutter speeds. The methods for prevention or cure, in order of preference are :—

(a) Eliminate the backlash.

(b) Set the hinge on or behind the point giving aerodynamic balance (hinge about $0 \cdot 3c$–$0 \cdot 4c$ behind the leading edge) and add sufficient mass-balance weights uniformly distributed spanwise to bring the C.G. on or ahead of the hinge line. (It is simple to design a tab so that its C.G. is not aft of its aerodynamic centre, in which case no mass-balance weights would be required.) This will eliminate backlash flutter.

(c) If the hinge line cannot be set back and the back lash cannot be eliminated then the tab should be mass-balanced so that the C.G. is on or ahead of the hinge line. This will not eliminate the possibility of flutter but *may* set the flutter speed higher than the maximum flight speed. Further increase in the flutter speed could be obtained by increasing the mass-balance weights, but it should be noted that any increase in tab weight will normally lead to a much greater increase in the control surface mass-balance weight required.

(ii) *Elasticity.*—In general it is not expected that trouble will arise from this cause if common sense is used in such matters as placing irreversible units close to the tab and making the tab-control mechanism stiff. The following methods, given in order of preference, for prevention or cure, are:—

(a) Make the tab-controlling mechanism reasonably stiff (*e.g.*, in trimming-tab installations place the irreversible unit close to the tab and make the parts connecting the tag to the unit stiff). This will eliminate the flutter or give a very high flutter speed.

(b) Set back the hinge to the position giving aerodynamic balance and mass-balance (if necessary) to bring the C.G. of the tab on or ahead of the hinge line. The hinge can be ahead of the aerodynamic centre if, as should be the case, the natural rotational frequency of the mass-balanced tab about that hinge position is appreciably higher than the translational frequency. This will eliminate flutter due to elasticity.

(c) Mass-balance, so that the tab C.G. is on or ahead of the hinge line. If the rotational frequency of the statically mass-balanced tab is less than the translational frequency, as will usually happen with spring tabs and all tabs in which spring-loaded ball-joints are used in the controlling mechanism, the mass-balance weights should be increased by about 50 per cent. if the controlling mechanism cannot be stiffened. It should be possible by these means to eliminate flutter in the case of trimming and balancing tabs (unless the stiffness of the controlling mechanism is unusually low); in the case of spring tabs or tabs with unduly flexible controlling mechanism mass-balancing cannot eliminate flutter entirely but it may raise the flutter speed above the maximum flight speed.

6. *Summary of Practical Conclusions.*—Flutter due to the tab should not arise if either

(a) the general design is such that backlash will not occur in service and the controlling mechanism is adequately stiff

or (b) the tab is aerodynamically balanced and statically mass-balanced (C.G. on hinge line).

If neither (a) nor (b) can be satisfied, then

(c) mass-balancing (C.G. on or ahead of hinge line according to the circumstances) may remove the flutter speed from the flight speed range.

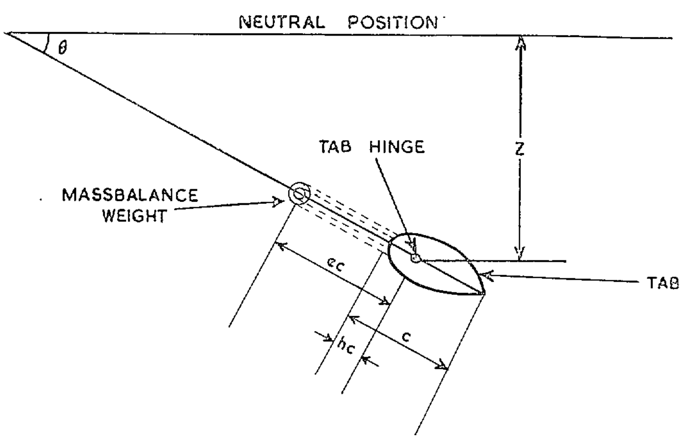
The designer should aim at satisfying either (a) or (b); (c) should only be used as a temporary remedy when neither (a) nor (b) has been attained.

APPENDIX

Fundamental Equations and Standard Data Employed.

1. *Notation.*

θ	angle of rotation of tab about its hinge.
z	deflection (ft) vertically of tab hinge due to bending of control-surface structure
m_θ	stiffness (lbft/radian) governing rotation of tab about its hinge (defined in section 3.2. below).
l_z	stiffness (lb/ft) governing vertical deflection of tab hinge (defined in section 3.2 below).
c	tab chord (ft).
h_c	distance (ft) of tab hinge from tab leading edge backwards.
ec	distance (ft) of mass-balance weight from tab hinge forward.
V	air speed (ft/sec).
V_c	flutter speed (ft/sec).
$k_0\rho c^2$	mass of tab per foot length (slugs/ft).
$k_1\rho c^2$	mass of balance weight per foot length of tab (slugs/ft).
$k_2\rho c^2$	mass (per foot length of tab) assumed to be placed along tab hinge to represent control surface local structure (slugs/ft).



2. *Equations of Motion.*—The tab is assumed to be infinitely stiff in torsion and flexure; there are two degrees of freedom, namely, rotation of the tab about its hinge (due to elasticity or backlash of the control) and vertical movement of the tab hinge (due to bending of the control-surface structure which supports the tab), denoted by θ and z respectively. The equations of motion giving θ and z are obtained by equating vertical forces and by equating hinge moments about the tab hinge; as in R. & M. 1155[1] these equations are written in the form:—

Vertical forces

$$A_1\ddot{z} + B_1\dot{z} + C_1 z + G_1\ddot{\theta} + J_1\dot{\theta} + K_1\theta = 0 \qquad (1)$$

Hinge moments

$$A_3\ddot{z} + B_3\dot{z} + C_3 z + G_3\ddot{\theta} + J_3\dot{\theta} + K_3\theta = 0 \qquad (2)$$

In these equations A and G are inertia terms, B and J are aerodynamic damping terms, C and K are aerodynamic plus elastic stiffness terms.

3. *Determination of the Values of the Coefficients.*—3.1. *Inertia Coefficients A and G.*—It is assumed that the mass distribution along the span is uniform. Two chordwise mass distributions are assumed; in the first, the mass per unit distance chordwise falls linearly from a finite value at the leading edge to zero at the trailing edge; in the second, the mass distribution along the chord is uniform. The first is denoted by "triangular mass distribution chordwise," the second by "uniform mass distribution chordwise," the coefficients are given in section 3.4. $k_0 = 90$ is taken; this corresponds to a tab of 4-in. chord weighing $0 \cdot 77$ lb. per foot length for ground level ($\rho = 0 \cdot 002378$). The product of inertia P is zero when the centre of gravity of the tab and its mass-balance weight is on the tab hinge line.

3.2. *Elastic Stiffness Coefficients.*—The elastic cross-stiffnesses are zero; there are direct elastic stiffnesses but these are difficult to measure and they probably vary between wide limits, so no definite values are taken. The coefficients are then

$$\begin{aligned} \text{elastic part of } C_1 &= l_z \\ \text{elastic part of } K_1 &= 0 \\ \text{elastic part of } C_3 &= 0 \\ \text{elastic part of } K_3 &= m_\theta \end{aligned}$$

where $l_z = \dfrac{P}{z}$ (lb/ft) $\quad$ P (lb) is the force which when applied at the tab hinge produces a deflection z (ft) of the tab hinge due to bending of the control-surface structure which supports the tab,

$m_\theta = \dfrac{T}{\theta}$ (lb ft/radian), $\quad$ T (lb/ft) is the moment, which, when applied about the tab hinge, produces a rotation θ (radians) of the tab about its hinge due to the elasticity of the parts connecting the tab to its irreversible operating unit or main surface structure.

The case of backlash in the operating control is given by $m_\theta = 0$. Otherwise m_θ should be large except for tabs with spring-loaded ball-joints (fitted to eliminate backlash) or spring tabs.

3.3. *Aerodynamic Coefficients.*—The aerodynamic coefficients are obtained by considering the tab to be a small wing and using the normal wing data from R. & M. 1782[2]. This assumption is made for the following reasons:—(1) simplicity, (2) there is not reliable data for all the aerodynamic flutter coefficients of tabs in the normal case when the control surface is considered to be rigid; in this case, for which bending of the control surface is assumed, practically nothing is known, (3) the work for this report is intended to be qualitative only. The resulting aerodynamic coefficients are given in section 3.4.

3.4. *Summary of Coefficients.*

$$
\begin{array}{lll}
B_1 & = 1\cdot5\ \rho csV & = B_1'V \\
C_1 & = l_z & = l_z \\
J_1 & = (1\cdot4 - 1\cdot5h)\ \rho c^2sV & = J_1'V \\
K_1 & = 1\cdot6\ \rho csV^2 & = K_1'V^2 \\
B_3 & = (0\cdot375 - 1\cdot5h)\rho c^2sV & = B_3'V \\
C_3 & = 0 & \\
J_3 & = (0\cdot7 - 1\cdot775h + 1\cdot5h^2)\ \rho c^3sV & = J_3'V \\
K_3 & = m_\theta + (0\cdot4 - 1\cdot6h)\ \rho c^2sV^2 & = K_3'V^2 + m_\theta
\end{array}
$$

$$
\begin{array}{lll}
 & \text{Triangular mass distribution chordwise} & \text{Uniform mass distribution chordwise} \\
A_1 & = \rho c^2s\ (k_0 + k_1 + k_2) & = \rho c^2s\ (k_0 + k_1 + k_2) \\
P = A_3 = G_1 & = \rho c^3s\ \{(\tfrac{1}{3} - h)\ k_0 - ek_1\} & = \rho c^3s\ \{(\tfrac{1}{2} - h)\ k_0 - ek_1\} \\
G_3 & = \rho c^4s\ \{(\tfrac{1}{6} - \tfrac{2}{3}h + h^2)k_0 + e^2k_1\} & = \rho c^4s\ \{(\tfrac{1}{3} - h + h^2)k_0 + e^2k_1\}
\end{array}
$$

4. *Solution of Equations.*—4.1. *General Case.*—Solution of equations (1) and (2) can be obtained as usual or, since $B_1'K_3' = B_3'K_1'$, directly from R. & M. 2605[4]; the flutter speed and frequency are given by

$$V_c^2 = \frac{bfe - ae^2 - b^2g}{b(bk - ed)}$$

which can also be written as

$$V_c^2 = \frac{ap^4 - fp^2 + g}{dp^2 - k} \qquad \text{(3a)}$$

and $$p^2 = \frac{e}{b} \qquad \text{(3b)}$$

where V_c = flutter speed (ft/sec)

$\frac{p}{2\pi}$ = flutter frequency (cycles/sec)

$$
\begin{aligned}
a &= A_1G_3 - P^2 \\
b &= A_1J_3' + B_1'G_3 - P\,(J_1' + B_3') \\
f &= A_1m_\theta + G_3l_z \\
d &= A_1K_3' + B_1'J_3' - B_3'J_1' - PK_1' \\
e &= B_1'm_\theta + J_3'l_z \\
g &= l_zm_\theta \\
k &= l_zK_3'
\end{aligned}
$$

The motion is stable up to the flutter speed if a, b, $(f + dV^2)$, e, $(g + kV^2)$ and $(bfe - ae^2 - b^2g)$ are positive for $V < Vc$. Equation (3b) shows that the flutter frequency is of the same order as the translational frequency of the tab due to bending of the control-surface structure (which is approximately $\frac{1}{2\pi}\sqrt{\left(\frac{l_z}{A_1}\right)}$ and therefore the degrees of freedom assumed will give flutter frequencies of the same order as those observed in flight.

4.2. *Product of Inertia $P = 0$, i.e., C.G. on hinge line.*—When $P = 0$, equations (3a) and (3b) give

$$V_c^2 = \frac{B_1' J_3' (A_1 m_\theta - G_3 l_z)^2}{(A_1 J_3' + B_1' G_3)\{- B_1' K_3' (A_1 m_\theta - G_3 l_z) - (B_1' J_3' - B_3' J_1')(B_1' m_\theta + J_3' l_z)\}} \qquad (4a)$$

$$p^2 = \frac{B_1' m_\theta + J_3' l_z}{B_1' G_3 + A_1 J_3'} \quad \ldots \quad (4b)$$

Natural frequencies in a vacuum are

$$\text{Rotation about hinge, frequency} = \frac{1}{2\pi}\sqrt{\left(\frac{m_\theta}{G_3}\right)} \quad \ldots \quad (5a)$$

$$\text{Vertical deflection, frequency} = \frac{1}{2\pi}\sqrt{\left(\frac{l_z}{A_1}\right)} \quad \ldots \quad (5b)$$

The flutter frequency therefore lies between the two natural frequencies.

Except when the hinge line is nearly at $\frac{1}{4}c$ from leading edge (K_3' small) or when the natural frequencies are nearly equal ($A_1 m_\theta - G_3 l_z$ small) the flutter speed is approximately

$$V_c^2 \simeq \frac{- J_3' (A_1 m_\theta - G_3 l_z)}{K_3' (A_1 J_3' + B_1' G_3)} \quad \ldots \quad (4c)$$

Equations (4a) and (4c) show that for a hinge position appreciably ahead of the aerodynamic centre the flutter speed will fall as the natural frequency of the tab about its hinge is increased until the two natural frequencies are nearly equal, when the flutter speed increases rapidly to infinity; there is no flutter when the natural frequency of the tab about its hinge is greater than the natural frequency of the tab vertically due to bending of the control surface. For a hinge position appreciably behind the aerodynamic centre the flutter speed will again be a minimum when the two natural frequenices are nearly equal, but in this case, flutter will only occur when the natural frequency of the tab about its hinge is greater than the natural frequency vertically.

The minimum flutter speed for variation of m_θ occurs when

$$\frac{m_\theta}{l_z} = \frac{A_1 G_3 B_1' K_3' - (2A_1 J_3' + B_1' G_3)(B_1' J_3' - B_3' J_1')}{A_1 B_1' \{A_1 K_3' + (B_1' J_3' - B_3' J_1')\}} \quad \ldots \quad (6a)$$

and is given by

$$\frac{V_c^2}{l_z} = \frac{4 A_1 J_3' (B_1' J_3' - B_3' J_1')}{B_1' \{A_1 K_3' + (B_1' J_3' - B_3' J_1')\}^2} \quad \ldots \quad (6b)$$

If K_3' is not too small, *i.e.*, if the hinge position is not too close to the aerodynamic centre, then equation (6a) is approximately

$$\frac{m_\theta}{l_z} \simeq \frac{A_1 G_3 B_1' K_3'}{A_1 B_1' A_1 K_3'} = \frac{G_3}{A_1}$$

This, from equations (5a) and (5b), is the condition for the two natural frequencies to be nearly equal.

4.3. *Backlash Case, i.e.,* $m_\theta = 0$.—The equations for this case are obtained by putting $m_\theta = 0$ in equation (3a) (general case) and in equation (4a) (particular case of $P = 0$) : the particular case ($m_\theta = 0 = P$) gives

$$\frac{V_c^2}{l_z} = \frac{B_1'J_3'G_3^2}{(A_1J_3' + B_1'G_3)\{B_1'K_3'G_3 - J_3'(B_1'J_3' - B_3'J_1')\}} \quad \ldots \quad (7)$$

Equation (7) shows that " backlash " will not cause flutter when $P = 0$, if K_3' is negative, *i.e.*, if the tab C.G. is on the hinge line and the hinge line is not ahead of the aerodynamic centre.

4.4. *Tab Divergence Speed.*—The tab divergence speed, V_d is given by $K_3 = m_\theta + K_3' V_d^2 = 0$. There is a divergence speed if K_3' is negative, *i.e.* if the hinge line is behind the aerodynamic centre; then

$$\frac{V_d^2}{l_z/\rho s} = \frac{1}{(1\cdot 6h - 0\cdot 4)} \; \frac{m_\theta}{c^2 l_z}$$

The divergence speed decreases steadily from an infinite value as the hinge line is moved back from the quarter-chord position. The divergence speed in the backlash case ($m_\theta = 0$), for $h > 0\cdot 25$, is zero; this means that the tab will move to the limit allowed by the backlash and will also have a higher divergence speed corresponding to the normal value of m_θ. For the range of values shown in Fig. 3 the divergence speed will not be less than the flutter speed except if

$$\frac{m_\theta}{c^2 l^2} = 0\cdot 23 \text{ and } 0\cdot 25 < h < 0\cdot 365.$$

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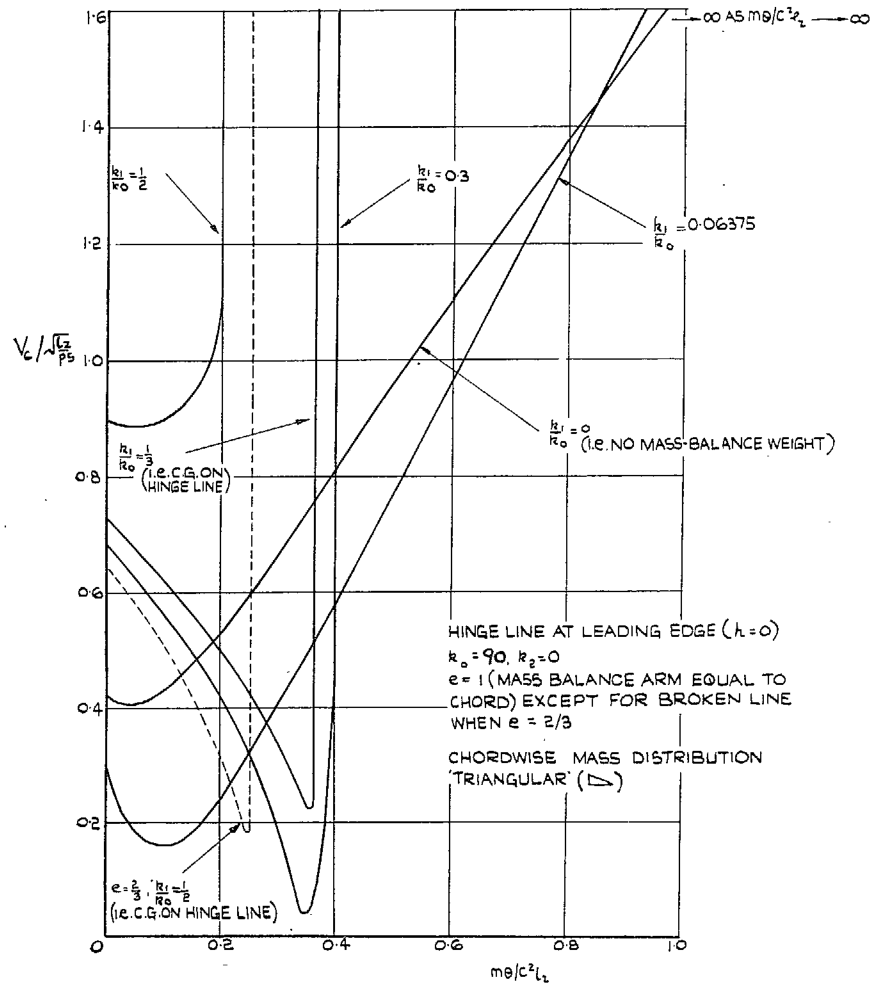

FIG. 1(*a*).—Variation of Flutter Speed with Stiffness Ratio and Various Degrees of Mass Balance.

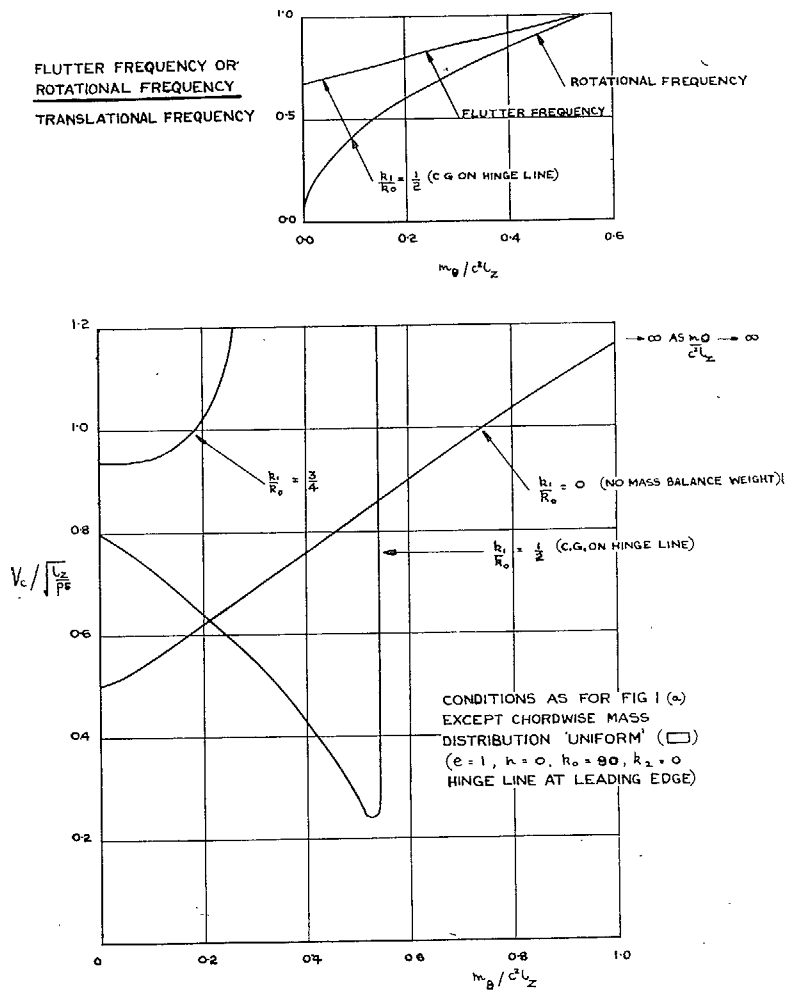

FIG. 1(*b*).—Variation of Flutter Speed with Stiffness Ratio and Various Degrees of Mass Balance.

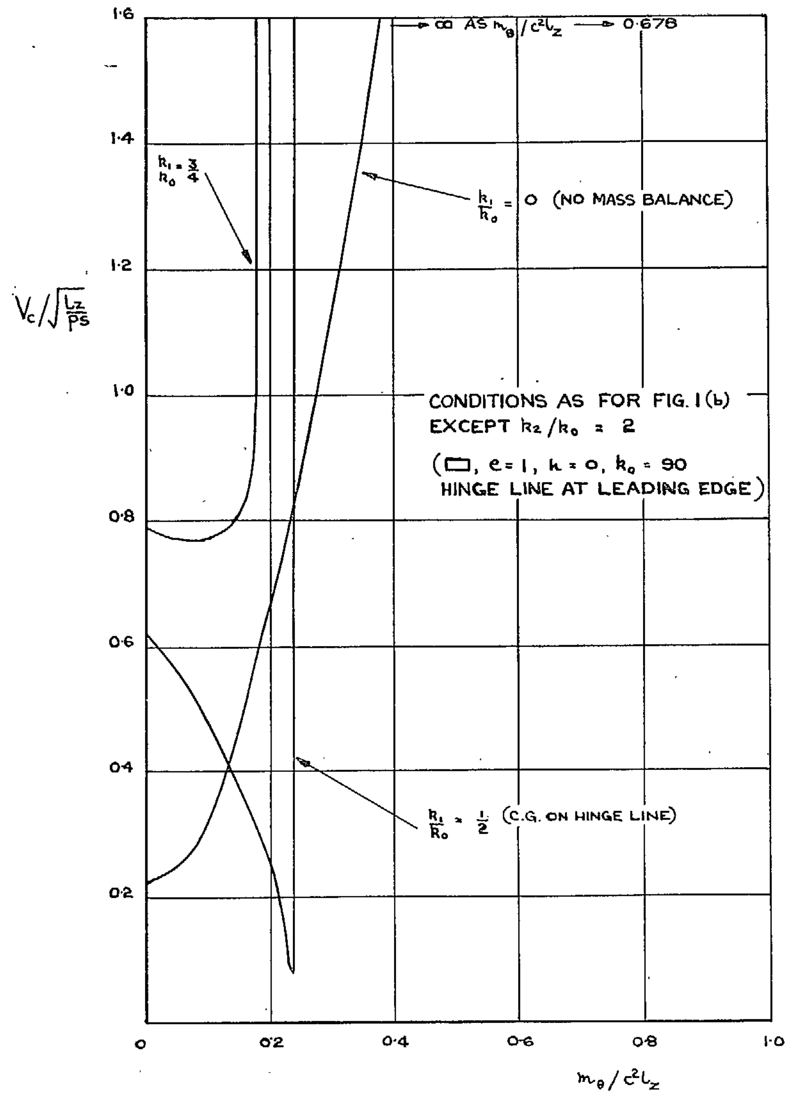

FIG. 1(*c*).—Variation of Flutter Speed with Stiffness Ratio and Various Degrees of Mass Balance.

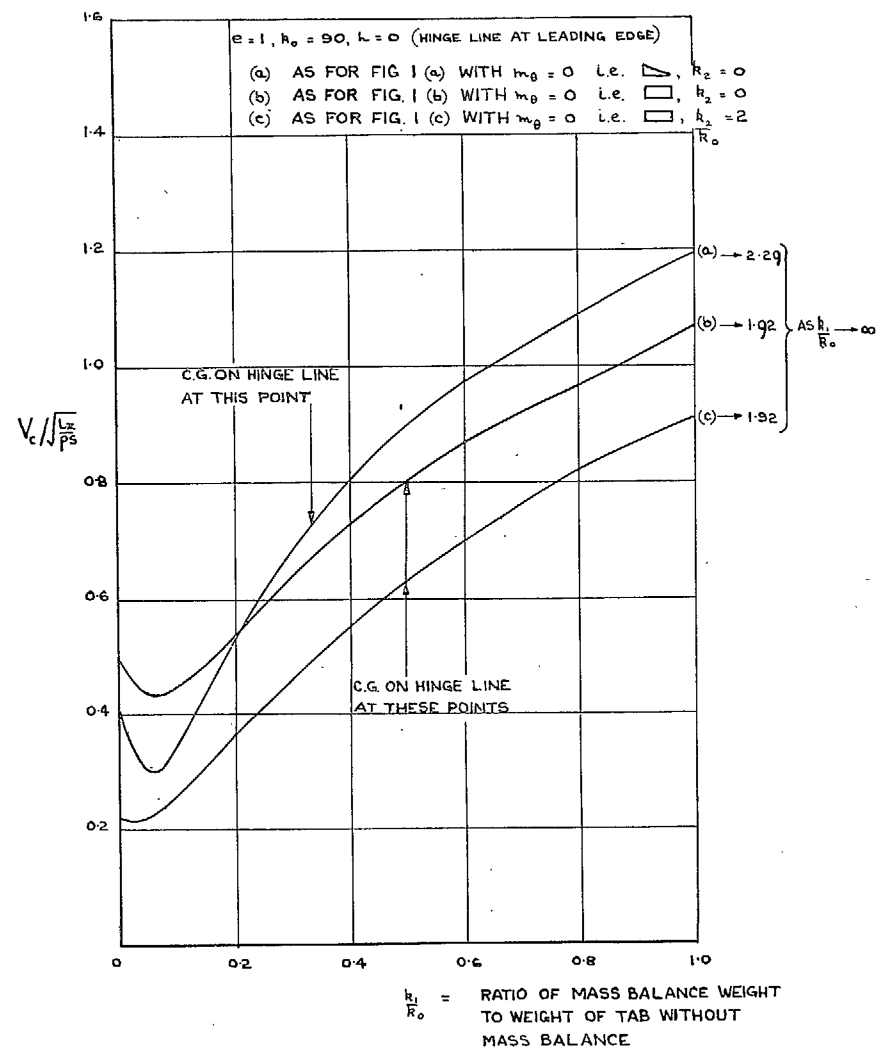

FIG. 2. Variation of Flutter Speed with Mass-balance Weight for $m_\theta = 0$ (Backlash Case).

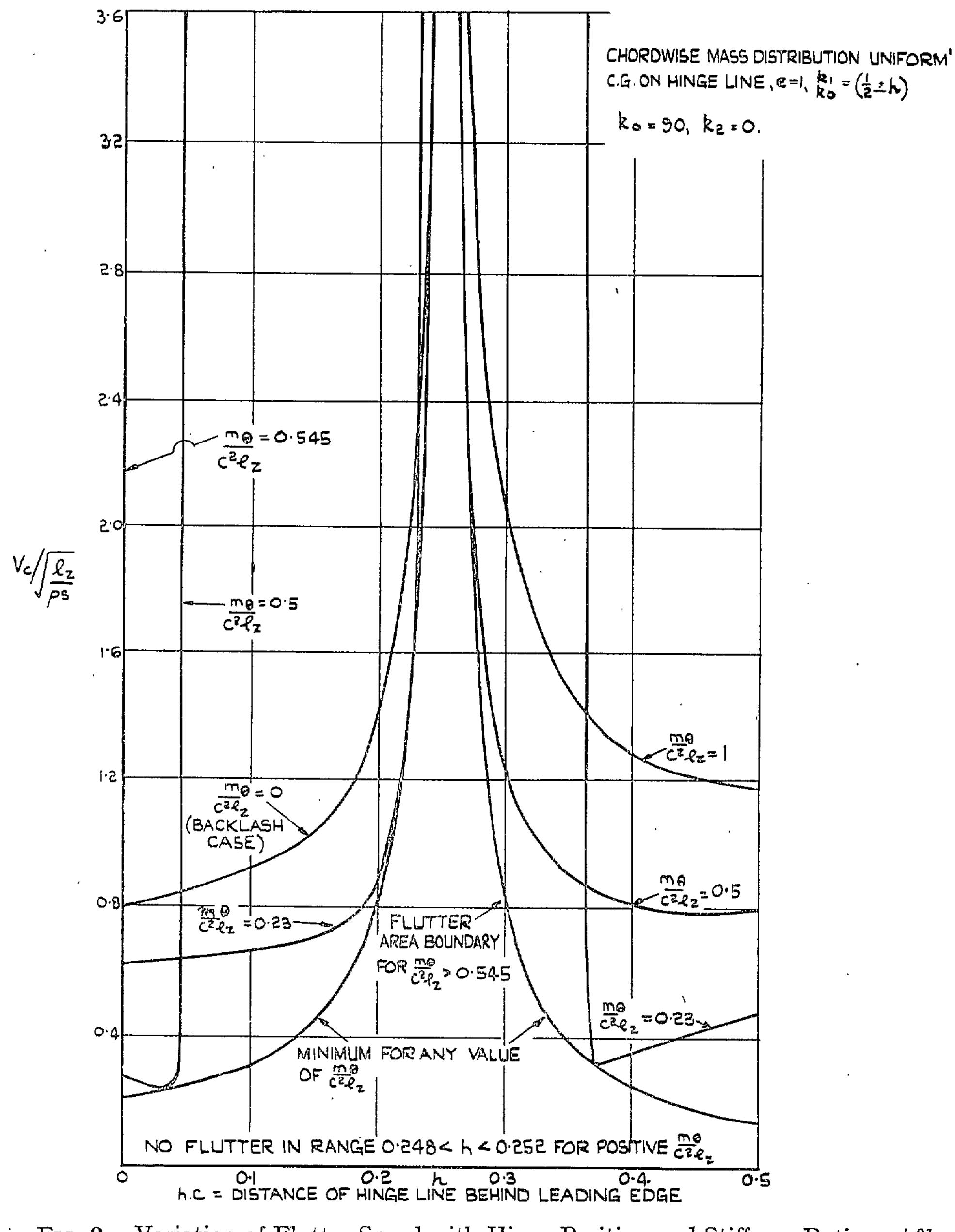

FIG. 3.—Variation of Flutter Speed with Hinge Position and Stiffness Ratio m_θ/c^2l for Mass-balanced Tab (C.G. on hinge line.)

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