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Flexible Mass-Balance Arms and Control-Surface Flutter

By D. Moxon

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Flexible Mass-Balance Arms and Control-Surface Flutter

By D. MOXON

COMMUNICATED BY THE DEPUTY CONTROLLER AIRCRAFT (RESEARCH AND DEVELOPMENT)
MINISTRY OF AVIATION

*Reports and Memoranda No. 3167**
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Summary. This paper records a theoretical investigation into the effect on aileron flutter of flexibility in the aileron mass-balance arm. It is shown that this flexibility can affect both wing-aileron and aileron-tab flutter, but each is affected differently. In wing-aileron flutter, mass-balance arm flexibility gives rise to ternary flutter and has a powerful stabilizing effect when the mass-balance natural frequency approaches the flutter frequency. In aileron-tab flutter, the mass-balance flexibility serves to produce an aileron overtone mode equivalent in effect to a rigidly mass-balanced aileron mode of the same frequency. When this frequency is sufficiently high aileron-tab flutter results. The fundamental aileron mode (the lower frequency normal mode of the aileron and its mass-balance weight) has no significant effect on the flutter.

1. *Introduction.* The results of an investigation following an accident suggested that wing-elevon-tab mass-balance flutter occurred, each mode playing an important, and in some cases necessary, part. In fact, at the actual elevon frequency as measured, wing-elevon-tab flutter could not have occurred had the mass-balance arms been rigid.

An existing official recommendation for mass-balancing states that 'the attachments of the mass-balance to the control surface should be stiff enough to avoid any adverse flexibility effects'. The accident has re-focused attention on the potential danger of flexibility in the mass-balance attachment, and the present analytical investigation was undertaken as a consequence.

The wing chosen was of rectangular shape and it was assumed to deform in a simple arbitrary mode. The aims in the present work were to find and analyse the types of flutter affected by mass-balance arm flexibility and to show the effect of this flexibility on the flutter speed. Unfortunately the wing-elevon-tab mass-balance flutter encountered on the aircraft could not be found: the wing-aileron mass-balance flutter which was found was unaffected by the tab rotation mode. This difference in behaviour may be due to the comparatively small tab in the system chosen for analysis.

Although the results quoted in this paper apply quantitatively to the considered system only, it is thought they will be of qualitative value for other such systems.

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* R.A.E. Tech. Note Structures 231, received 3rd June, 1958.

2. *Details of Investigation.* 2.1. *The Wing.* The hypothetical wing plan-form is shown in Fig. 1. The aileron and tab have no aerodynamic balance; the aileron is statically mass-balanced by a localised mass at its tip. Aileron and tab circuit stiffnesses are entirely independent, as would be appropriate for a trim-tab.

2.2. *The Modes.* The system was assumed to deform in the following four modes:

Mode 1.—Linear torsion of wing about its leading edge* at a frequency of 84 c.p.s.; generalised co-ordinate q_1

$$\alpha = Fq_1 \text{ where } F = y/s .$$

Mode 2.—Aileron rotation at a natural frequency of ω_a c.p.s.; generalised co-ordinate q_2

$$\beta = \beta_0 + (\alpha_0 - \alpha) \text{ or } \beta = q_2 + (1 - F)q_1 .$$

Mode 3.—Tab rotation at a natural frequency of ω_t c.p.s.; generalised co-ordinate q_3

$$\gamma = q_3 .$$

Mode 4.—Mass-balance displacement, natural frequency ω_b c.p.s.; generalised co-ordinate q_4

$$\delta = q_4 = \frac{\text{Displacement of mass-balance relative to aileron}}{\text{Length of mass-balance arm}} ,$$

where

α = rotation of wing at any section
α_0 = rotation of wing at reference section
β = rotation of aileron at any section
β_0 = rotation of aileron at reference section
γ = rotation of tab at any section
δ = angular displacement of mass-balance relative to aileron
y/s = non-dimensional spanwise co-ordinate.

2.3. *Flutter Coefficients.* These were computed in accordance with the usual technique[1]; the simplicity of the assumed modes and plan-form enabled the integration to be done analytically. The two-dimensional aerodynamic derivatives for incompressible flow[2] at a frequency parameter of 1·4 were used in calculating the aerodynamic coefficients.

3. *Theory.* It has been shown in a paper by Williams[3] that flexibility in the mass-balance arm has the same effect as an increase in the mass-balance weight for certain ratios of flutter frequency to mass-balance frequency; the mass-balance weight is thus magnified as a result of flexibility. In this investigation, where the wing mode was linear torsion about the leading edge, an effective increase in mass-balance weight had a stabilizing influence on flutter.

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* Initially it was intended to investigate, in addition, the effect of nodal-line position, nodal lines being assumed at the leading edge, $\frac{1}{4}$ chord and $\frac{1}{2}$ chord. Since the effects of mass-balance flexibility in each case were found to be similar, only the leading-edge case (in which the mass-balance was most effective) was investigated in detail.

If

nominal mass-balance weight is m

effective mass-balance weight is $\overline{m}$

flutter frequency is ω

natural frequency of mass-balance on its arm is ω_b,

then

$$\overline{m} = \frac{m}{1 - \left(\frac{\omega}{\omega_b}\right)^2}. \qquad (1)$$

From equation (1) it is seen that $\overline{m} \to \infty$ as $\omega/\omega_b \to 1$. At the two extremes, $\omega/\omega_b = 0$ and $\omega/\omega_b = \infty$, $\overline{m}$ is equal to m (*i.e.*, rigid mass-balance) and zero respectively. One might think from this that a flexible mass-balance of suitable natural frequency could be used to prevent flutter. Theoretically, it is possible, for a given wing mode and frequency, to decrease the mass-balance weight and rely on the flexibility to stabilize the system: in practice, however, it would be impossible to obtain much benefit in the fundamental mode without inducing flutter at a higher frequency where the effectiveness of the mass-balance weight given by equation (1) would be negative.

4. *Results.* Figs. 2a and 2b both show wing-aileron binary-flutter curves. Fig. 2a shows the variation of flutter speed with aileron natural frequency for an aileron without mass-balance. For aileron natural frequencies greater than 84 c.p.s., there is no wing-aileron flutter: for frequencies less than 84 c.p.s. the system has always two critical flutter speeds for any particular frequency with instability between them.

Fig. 2b also shows the curve of flutter speed plotted against aileron frequency, but for an aileron with static balance, the mass-balance arm being rigid. In this case, the nose occurs at 92 c.p.s., below which, for a particular aileron frequency, the system has a lower and upper critical flutter speed.

Both these graphs will be used to assess the boundary conditions ($\omega_b = 0$ and $\omega_b = \infty$) for a flexible mass-balance.

Figs. 3 and 4 show the variation of flutter speed with mass-balance frequency for various aileron and tab frequencies. The following four cases are represented:

$$\left.\begin{array}{ll} \text{Fig. 3.}\left\{\begin{array}{l} \text{(i) } \omega_a < \omega_t < \omega_w\text{: } \omega_a = 20, \quad \omega_t = 50 \\ \text{(ii) } \omega_a < \omega_w < \omega_t\text{: } \omega_a = 20, \quad \omega_t = 125 \end{array}\right. \\ \text{Fig. 4.}\left\{\begin{array}{l} \text{(iii) } \omega_w < \omega_a < \omega_t\text{: } \omega_a = 100, \omega_t = 200 \\ \text{(iv) } \omega_t < \omega_w < \omega_a\text{: } \omega_a = 100, \omega_t = 50 \end{array}\right. \end{array}\right\} \omega_w = 84.$$

These four cases are thought to be representative of possible practical frequency ratios (Case (iv) is appropriate to a powered control with backlash in the tab circuit). These four cases gave rise to various types of flutter. Cases (i) and (ii) each produced two types of flutter: wing-aileron mass-balance and aileron-tab mass-balance. Case (iii) produced aileron-tab mass-balance flutter only, while case (iv) produced aileron-tab mass-balance and, in addition, wing-aileron-tab flutter which was independent of mass-balance frequency. Each case will now be considered in detail.

4.1. *Low Aileron Frequency* (*Cases* (i) *and* (ii)). (*a*) *Wing-aileron-aileron mass-balance flutter—Regions A and B.* The curves of flutter speed against mass-balance frequency are given in Fig. 3. From the Figure it will be seen that there are two regions of instability: one on the left where $\omega/\omega_b > 1$ and one on the right where $\omega/\omega_b < 1$. In between, where $\omega/\omega_b \to 1$, the mass-balance weight magnification effected by flexibility in the arm approaches infinity; hence the pronounced rise in flutter speed. At this 'peak' the aileron and mass-balance phases are in quadrature. On the left-hand branch the aileron and mass-balance are out of phase; on the right-hand branch they are in phase.

An attempt was made to establish that each point on these two curves was a result of binary flutter, that is, flutter between the wing and an aileron mode, not necessarily the fundamental. For several mass-balance frequencies (ω_b) in Fig. 3, the coupled aileron and mass-balance modes were normalised to give two uncoupled, or normal, modes, one of higher and one of lower frequency than the parent coupled modes. The left-hand branch could be traced very well by quasi-normal-mode flutter calculations (wing and the higher frequency normal mode), thus indicating that each point is essentially a result of binary flutter. The right-hand branch could not be traced in this way. On the left-hand branch it was the higher-frequency normal mode which coupled with the wing to produce flutter: at higher mass-balance frequencies corresponding to the right-hand branch this flutter had disappeared. The lower frequency normal mode when combined with the wing did satisfactorily predict the flutter-speed asymptote. However, this lower-frequency normal mode is very insensitive to changes in ω_b when ω_b is large compared with ω_a as it is on the right-hand branch. As a result of this, the predicted flutter speed from binary calculations remains practically constant ($\omega_b = 80$ c.p.s., $V = 998$ ft/sec; $\omega_b = \infty$, $V = 910$ ft/sec) over the right-hand branch. The right-hand branch cannot therefore be justified on binary considerations and, since it is not a tab effect, it is very probably a result of wing-aileron mass-balance ternary flutter.

A rough estimate of the various forms that the wing-aileron-aileron mass-balance curves assume as ω_a changes can be formed from Figs. 2a and 2b. The left-hand branch of the later flutter curves, such as Fig. 3, has asymptotes ($\omega_b \to 0$) that correspond with Fig. 2a, while the right-hand branch has asymptotes ($\omega_b \to \infty$) that correspond with Fig. 2b. Fig. 2a shows that binary calculations predict that the left-hand branch will 'come in' at higher flutter speeds as the aileron frequency is increased up to a maximum of 84 c.p.s. Above 84 c.p.s. the left-hand branch may vanish or alternatively it may be present in some other form which does not cut the $\omega_b = 0$ axis. On the right-hand branch, the upper and lower asymptotes decrease in flutter speed as ω_a is increased up to a maximum of 92 c.p.s.: above 92 c.p.s. (as at 84 c.p.s. on the left-hand branch) the two asymptotes no longer exist and the right-hand branch has either vanished or it exists in another form without asymptotes.

(*b*) *Aileron-tab-aileron mass-balance flutter—Region C.* Although this type appeared on the simulator as ternary flutter, it was shown to be essentially binary, the aileron and mass-balance modes being combined to give two normal modes the higher-frequency mode of which, when combined with the tab, gave binary flutter in close correspondence with the 'ternary'. Fig. 5 shows the two curves of flutter speed plotted against tab frequency at constant aileron and mass-balance frequencies: one curve is the apparent ternary-flutter curve, the other is the binary curve obtained from the normalised aileron-aileron mass-balance combination and tab. The nearness of the two curves clearly indicates that the 'ternary' flutter was, in fact, binary.

For case (ii) several mass-balance frequencies (ω_b) were selected and the mass-balance mode at these respective frequencies combined with the aileron mode, for which $\omega_a = 20$ c.p.s., to give two normal modes. A curve of flutter speed plotted against aileron frequency ω_a was then worked out for the rigidly mass-balanced aileron-tab case. From this curve it was seen that the flutter shown in Fig. 3 was equivalent to rigid aileron-tab flutter at a rigid aileron frequency equal to the higher frequency of the two normal modes. At the nose of the curve the modified aileron frequency, including the effect of aerodynamic stiffness, is roughly equal to the tab frequency.

Aileron mass-balance flexibility then, in aileron-tab flutter, serves to produce a modified aileron mode equivalent in effect to a high-frequency rigidly mass-balanced aileron mode. When this frequency is sufficiently high aileron-tab flutter results.

4.2. *High Aileron Frequency and Higher Tab Frequency* (*Case* (iii)). This case differs from cases (i) and (ii) in that wing-aileron mass-balance flutter is no longer present; at least, not on the scale of the simulator (up to 1600 ft/sec) and probably not at all (*see* Figs. 2a and 2b).

The aileron-tab mass-balance flutter still exists and probably each point on it could be represented as binary flutter as was done in Section 4.1(*b*).

4.3. *High Aileron Frequency and Low Tab Frequency* (*Case* (iv)). As mentioned previously, this is the 'tab backlash' case. There are two types of flutter; an aileron-tab mass-balance flutter and a wing-aileron-tab flutter occurring at comparatively low airspeed. As can be seen from Fig. 4 it is a very narrow band and the flutter is mild.

5. *Concluding Remarks.* Three types of flutter were encountered: wing-aileron-aileron mass-balance, aileron-tab-aileron mass-balance and wing-aileron-tab. This last type, apart from showing that a flexible mass-balance arm need not necessarily affect all types of flutter, is otherwise of no account in this paper.

In wing-aileron-aileron mass-balance flutter, the plots of flutter speed against mass-balance natural frequency consisted of two branches. On one branch the flutter frequency was greater than the mass-balance frequency and on the other it was less. Where the two frequencies coincided the flexibility was found to have a powerful stabilizing effect. On the former branch each point on the curve could be predicted by binary calculations involving the wing and the higher-frequency normal mode of the aileron and its mass-balance weight; on the latter branch, the flutter appears to be true ternary except at very high mass-balance frequencies.

The other important type, aileron-tab-aileron mass-balance flutter, could be represented as a binary consisting of the tab rotation mode and the higher-frequency mode of the normalised aileron-aileron mass-balance combination. This type of flutter is, in fact, aileron-tab and is born out of a high-frequency aileron mode resulting from flexibility in the arm of the mass-balance.

REFERENCES

No.	*Author*	*Title, etc.*
1	H. Templeton ..	The technique of flutter calculations. C.P. 172. April, 1953.
2	I. T. Minhinnick ..	Subsonic aerodynamic flutter derivatives for wings and control surfaces. A.R.C. 14.228, 14.885. July, 1950.
3	D. Williams ..	Elevator mass-balance in relation to flexibility of the arm and position of fuselage nodal point. R. & M. 2062. Pt. I. June, 1944.

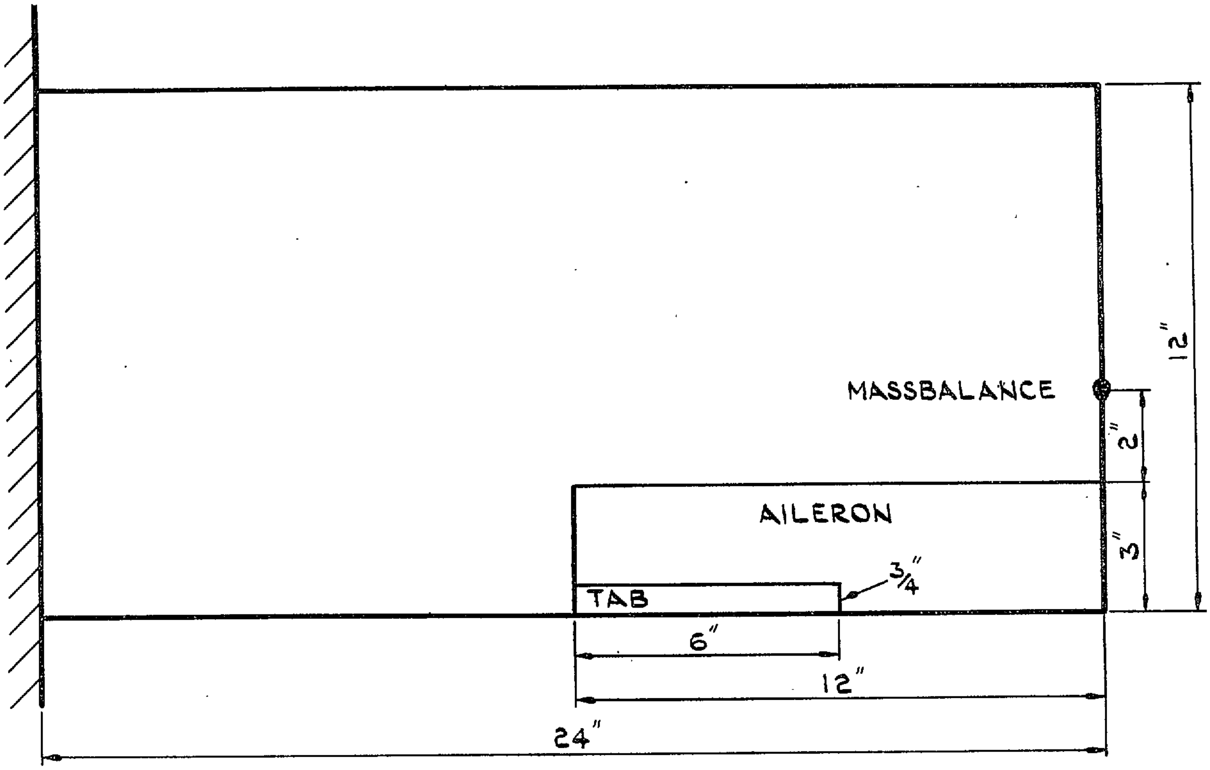
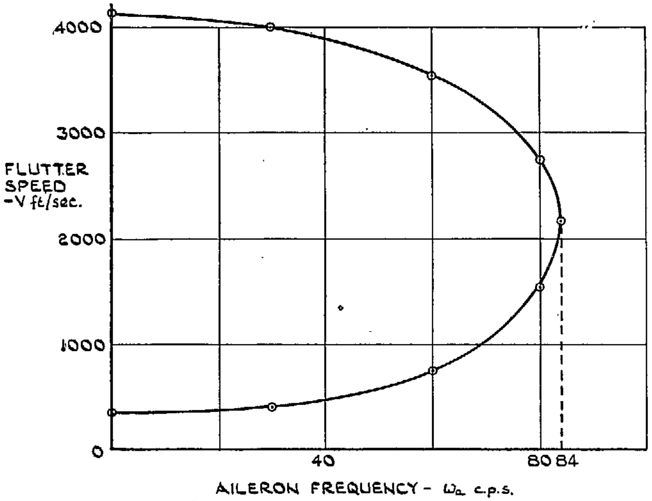
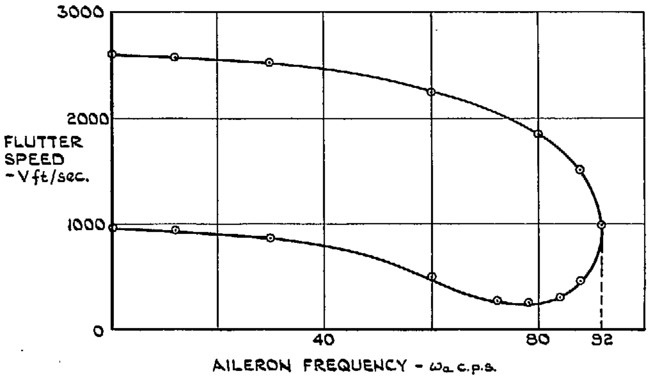


FIG. 1. Wing plan-form.



(a) AILERON WITHOUT MASSBALANCE



(b) AILERON STATICALLY MASSBALANCED (MASSBALANCE ARM RIGID)

FIGS. 2a and 2b. Wing-aileron flutter speed against aileron frequency.

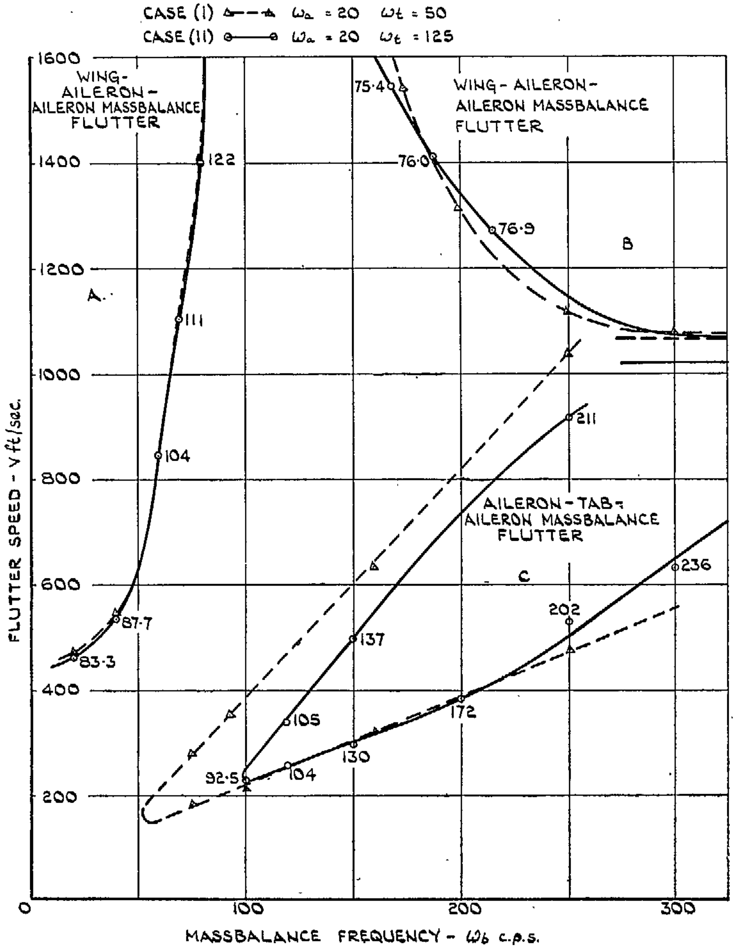


FIG. 3. Variation of flutter speed with mass-balance natural frequency (Cases (i) and (ii)).

(78683) Wt. 54/8210 K.5 9/60 Hw.

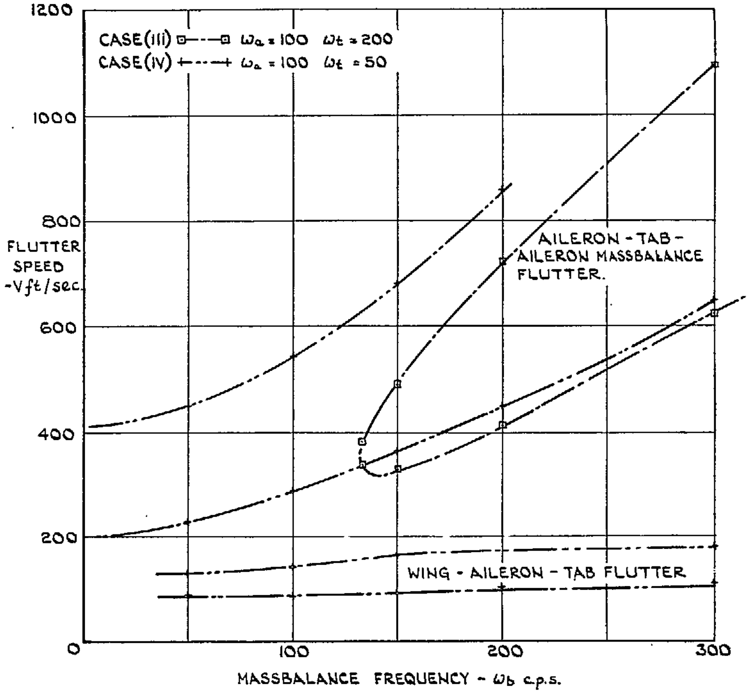


FIG. 4. Variation of flutter speed with mass-balance natural frequency (Cases (iii) and (iv)).

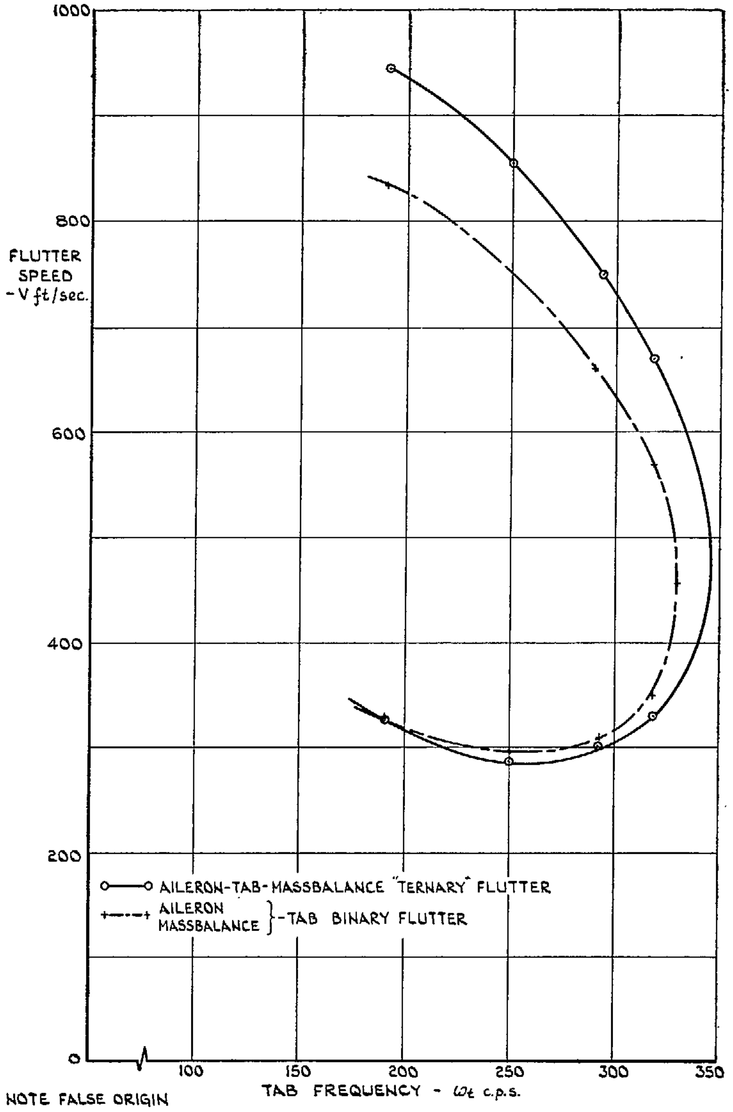


FIG. 5. Variation of flutter speed with tab frequency for constant aileron and mass-balance frequencies.

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