R. & M. No. 3210

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MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

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E. G. BROADBENT, M.A., A.F.R.Ae.S. and MARY CLARKE

LONDON : HER MAJESTY'S STATIONERY OFFICE
1961
PRICE 12*s.* 6*d.* NET

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COMMUNICATED BY THE PRINCIPAL DIRECTOR, SCIENTIFIC RESEARCH (AIR),
MINISTRY OF SUPPLY

Reports and Memoranda No. 3210
January, 1954

Summary.—An account is given of a theoretical flutter investigation in connection with an accident to a *Sea Venom* aircraft. The investigation covers both symmetric and antisymmetric flutter of the tailplane-elevator-tab system. The main (symmetric) calculations include six degrees of freedom, comprising three structural modes and movements of elevator, spring-tab and trim-tab respectively. The parameters that are varied include elevator mass-balance, position and magnitude of mass-balance on each tab independently, structural damping and stiffness of the tab circuits, chord and mass of the trim-tab, and flexibility of the elevator mass-balance attachments. The investigation shows the symmetric flutter to be a probable cause of the accident and confirms the efficacy of the remedial measures adopted, which consisted of modifications to the tab mass-balances combined with a reduction in chord and inertia of the trim-tab. Several points of general interest are discussed.

1. *Introduction.*—In the summer of 1952 an accident to a *Sea Venom* occurred at the start of a high-speed run. It was suggested that flutter might have been the cause, and a theoretical investigation, in which the R.A.E. Flutter Simulator[1] played an important part, was made of this possibility. The present paper describes the investigation. It is concluded that flutter is a likely cause of the accident, and suitable modifications to the aircraft are discussed.

The aircraft differs from the *Venom* Mark 1, on which considerable flight experience has been gained, in having folding wings and an extended nose (being a two seater). The extended nose produced a relatively forward centre of gravity and therefore a more stable aircraft than the *Venom* 1, and this in turn required the use of more powerful tabs on the elevator. The present investigation shows that these larger tabs are probably the main cause of the accident, a conclusion which is strongly supported by the fact that the trim-tab and part of the spring-tab broke away from the aircraft in flight.

The calculations show that a violent form of symmetric flutter involving both tabs could occur at medium to high speeds. The calculated frequency is about 24 c.p.s., so that very high local stresses would be induced. It is logical to suppose that this type of flutter caused one or both elevator mass-balance weights to break away (neither was recovered), as well as the failure of the trim-tab itself. With the elevator unbalanced flutter would certainly persist, and in fact part of the spring-tab broke away later with the aircraft out of control. A diagram of the aircraft is shown in Fig. 1, and of the tailplane, elevator and tabs in Fig. 2 with those of the *Venom* 1 for comparison.

An important feature arising from the calculations is that the two tabs combine to give a much more powerful form of flutter than either tab alone. This would clearly be expected if the tabs were identical with each other, for then the two together would behave as a single tab of twice the size. Usually, however, spring and trim-tabs, even on the same surface, are considered separately, and this is probably justified if the trim-tab frequency is much higher than the important structural frequencies while that of the spring-tab is not. Unfortunately, on the *Sea Venom* the natural frequency of each tab was below that of the tailplane in bending, so that it was not justifiable to treat the two separately, especially in view of the large size of the trim-tab.

The investigation is also of interest in relation to the application of the tab criteria[2]. It is shown that, even without the spring-tab, flutter of the trim-tab could have occurred although this tab was mass-balanced to meet the design requirements as normally applied. The difficulty lies in the fact that in the requirements the tab natural frequency should be at least 50 per cent above the frequency of the relevant main structure mode, but this latter cannot be precisely defined. It has been customary to take it as the relevant fundamental mode, which in this case is that associated with boom bending and has the value 8·25 c.p.s., but the calculations show that it was unsafe to neglect the tailplane bending mode with a frequency of 24·7 c.p.s. An additional feature covered by the investigation is the importance of the flexibility of the elevator mass-balance arms.

Most of the investigation is concerned with the symmetric flutter thought to be the cause of the accident but a limited investigation of the possibilities of antisymmetric flutter is included (Section 3.3). The various stages of the investigation are given in roughly chronological order, as undertaken.

2. *The Calculations Relating to the Accident.*—2.1. *Basic Data.*—2.1.1. *Structural data and degrees of freedom.*—At the time of the accident, resonance tests were scheduled for the *Sea Venom* in connection with the folding wing ; as a result of the accident, the tests were extended to cover the tail in greater detail. Three symmetric modes were selected for the flutter calculation, at frequencies ranging from 8 to 24 c.p.s. The modes are shown in Figs. 3, 4 and 5. Antisymmetric flutter was considered to be less likely ; there were, for example, no signs of elevator torsion in the wreckage, and in addition the antisymmetric modes appeared to be less dangerous. In view of the tab damage, the elevator and tabs clearly had to be included, and the complete calculation thus involved six degrees of freedom. The degrees of freedom are

(1) Mode at 8·25 c.p.s.–boom bending (Fig. 3).
(2) Mode at 21·00 c.p.s.–some boom and tailplane bending with some torsion (Fig. 4).
(3) Mode at 24·7 c.p.s.–tailplane bending (Fig. 5).
(4) Elevator rotation.
(5) Trim-tab angle.
(6) Spring-tab angle.

To simplify the analysis the elevator co-ordinate, q_4, was taken as the elevator angle in space, rather than that relative to the tailplane*, q_5 and q_6 are, however, the tab angles relative to the elevator as normally defined. Thus the displacement of a point on the aircraft is given by the expression

$$\frac{z}{c_r} = f_1 q_1 + f_2 q_2 + f_3 q_3 + \frac{x_\beta}{c_r} q_4 + \frac{x_\gamma}{c_r} q_{5(6)}$$

where z is the displacement of the point

c_r is the tailplane chord (the reference length)

f_1, f_2, f_3 are functions of aircraft position giving the non-dimensional displacement in each of the three normal modes respectively. In accordance with the definition of q_4 these functions are taken to be independent of x (the fore-and-aft co-ordinate) for points on the elevator and tabs and to retain the value appropriate to the elevator hinge line in this region

$q_1 \ldots q_6$ are the six generalised co-ordinates. The co-ordinate q_6 is taken to vanish except for points on the spring-tab ; q_5 vanishes except for points on the trim-tab, and q_4 vanishes except for points on the elevator and the two tabs

x_β is distance aft of the elevator hinge-line

x_γ is distance aft of the appropriate tab hinge-line.

* This does not imply any limitation in the full calculation, but affects the interpretation of any results obtained with q_4 omitted, which implies an unrealistic representation in any case.

The structural inertia coefficients for the Lagrangian equations were then evaluated by standard summations over the aircraft. It was later found that the cross-inertias between the normal modes (a_{12}, a_{13} and a_{23}) were rather large, which may well have been caused by the use of a single exciter at the nose of the aircraft in the ground resonance tests. As tail flutter was being investigated it was thought that the fuselage amplitudes (not to be confused with boom amplitudes) would be exaggerated by this, so they were arbitrarily reduced by a factor of 0·75. This resulted in more favourable products of inertia, as shown in Table 1.

TABLE 1

	$\frac{a_{12}}{\sqrt{(a_{11}a_{22})}}$	$\frac{a_{13}}{\sqrt{(a_{11}a_{33})}}$	$\frac{a_{23}}{\sqrt{(a_{22}a_{33})}}$
Before amplitude reduction ..	0·267	0·197	0·205
After amplitude reduction ..	0·118	0·109	0·065

It is usual to assume that products of inertia between measured resonance modes are acceptable if

$$\frac{a_{rs}}{\sqrt{(a_{rr}a_{ss})}} < 0 \cdot 1 \,. \qquad \ldots \quad (1)$$

In this case the modified values of a_{12} and a_{13} still do not quite meet this criterion, but no further refinement was attempted.

In evaluating the inertia coefficients allowance was made for varying several of the mass-balance weights, as will be apparent from the results given later. The elastic coefficients for the normal modes and the two tabs were obtained from relations of the type (using capital letters for dimensional coefficients).

$$E_{rr} = \omega_r^{\,2} A_{rr} \qquad \ldots \quad (2)$$

where ω_r is the natural frequency of mode r. The elastic coefficient for the elevator and the cross-stiffnesses between it and the tabs were derived from the follow-up ratio of the spring-tab and the gearing of the trim-tab*.

A major uncertainty was presented by the spring-tab circuit. This, moving rigidly, was over 50 times the inertia of the tab itself, mostly as a result of the control column. The spring, moreover, is preloaded. A resonance test on the tab (elevator locked) showed a very flat peak at 6¼ c.p.s., and this was the only resonance which could be associated with the tab. At this frequency the motion seemed to be largely confined to the local tab linkage and the spring-box (whether or not the preload was taken up). The tab coefficients were therefore based on this frequency and the inertia estimated from what evidence there was for the circuit motion (assumed to be entirely local). This resulted in a total inertia coefficient $\hat{A}_{66}$ of 1·5 times that of the tab alone (the circumflex is used to denote that the aerodynamic contribution is not included) ; appreciable structural damping (10 per cent of critical) was included. The authors are aware that this treatment of the spring-tab circuit appears to involve some inconsistencies, but it was thought to be the most realistic. The nominal follow-up ratio (with the preload taken up) is 3·3, but at flutter frequencies a value of zero was thought to be more appropriate in view of the behaviour of the circuit at resonance. During the calculations, both the trim-tab gearing and the spring-tab follow-up ratio were varied through a wide range and appeared to have a negligible effect on the flutter characteristics. In the circumstances the flutter curves obtained from the calculation are thought to be qualitatively reliable.

* The trim tab was designed to be used as a geared tab also, but the standard gearing was zero. By some error the tab was geared to a slight degree of anti-balance at the time of the accident. This is not regarded as significant.

2.1.2. *Aerodynamic data.*—The aerodynamic data were derived following the suggestions of Minhinnick[3]. The aerodynamic stiffness derivatives were assumed constant with frequency and based on static values supplied by the firm. The damping coefficients were obtained in the main by deriving factors[3] to apply to the two dimensional values but some values were available by direct calculation for a rectangular wing of aspect ratio 4, which is roughly representative of the *Sea Venom* tailplane. Some of the damping derivatives could thus be obtained in more than one way by making different assumptions ; but the difference was found to have little effect on the answer. The aerodynamic inertias were allotted 80 per cent of their full theoretical values. The aerodynamic forces on the wing were included for the second mode only ; their contribution in the other modes was thought to be negligible.

2.1.3. *Preparation of simulator coefficients.*—The aerodynamic coefficients were calculated in the form

$$\rho V^2 s c_r^2 (\bar{a}_{rs}\lambda^2 + b_{rs}\lambda + c_{rs}) q_s \quad \ldots \quad (3)$$

for the rth equation, where

- ρ is the air density
- V is the true forward speed
- s is the tailplane span between booms
- c_r is the tailplane chord
- λ is $i\nu = i\omega c_r / V$
- ν is the frequency parameter
- ω is the flutter frequency

and $\bar{a}_{rs}$, b_{rs} and c_{rs} are the aerodynamic inertia, damping and stiffness coefficients.

The structural inertia coefficients were therefore made non-dimensional and added to the aerodynamic inertias,

$$\hat{a}_{rs} = \frac{\hat{A}_{rs}}{\rho s c_r^4} \quad \ldots \quad (4)$$

and

$$a_{rs} = \hat{a}_{rs} + \bar{a}_{rs} \, . \quad \ldots \quad (5)$$

The elastic stiffness coefficients were also made non-dimensional, but were written in the form

$$\left(\frac{V_0}{V}\right)^2 e_{rs} = \frac{E_{rs}}{\rho V^2 s c_r^2} \quad \ldots \quad (6)$$

where V_0 is a suitable reference speed, and was taken as 1000 ft/sec. The flutter equations can now be written

$$[a\lambda^2 + b\lambda + c + e/v^2][q] = 0 \quad \ldots \quad (7)$$

$$\text{with } v = V/V_0 \, .$$

For solution by the flutter simulator, the coefficients for a typical element of the matrix need to be in the form[1],

$$a'\ddot{q} + b'v\dot{q} + (c'v^2 + e')q \quad \ldots \quad (8)$$

and the simulator flutter frequency should be about 1 radian per second.

Transposition of equation (7) to the form required by (8) is very simple ; multiplying through by v^2 we can write, for a typical element,

$$a\ddot{q} + bv\dot{q} + (cv^2 + e)q \quad \ldots \quad (9)$$

which is of identical form to (8) and has a frequency of $\omega c_r/V_0$, which is proportional to the flutter frequency but is likely to be less than unity. In fact it was found most suitable to double the frequency of (9) by writing

$$\left.\begin{aligned} a' &= a/4 \\ b' &= b/2 \end{aligned}\right\} \quad \ldots \quad (10)$$

so that the relation between the simulator frequency (written as $\bar{\nu}$ since it is a slightly modified form of ν, the frequency parameter) and the flutter frequency is

$$\left.\begin{aligned} &\bar{\nu} = 2\omega c_r/V_0 \\ &\text{or, numerically,} \\ &\omega = 20\cdot777 \times 2\pi\bar{\nu} \end{aligned}\right\} \quad \ldots \quad (11)$$

The coefficients were then scaled by rows and columns to numbers not exceeding 1110 (the maximum available on the simulator) but as near to it as possible. In doing this the column factors were

$$1, 1, 1, 7\cdot833, 15\cdot985, 36\cdot760 \quad \ldots \quad (12)$$

so that any measured amplitude ratios have to be multiplied by the proportions (12) in order to refer to the original co-ordinates. The complete matrix of scaled coefficients for the 'standard case', *i.e.* the condition at the time of the accident, is given in the Appendix, together with the important variations representing the various stages discussed below.

2.2. *Results Including the Variation of Elevator Mass-balance.*—At the time when the investigation was started it was thought possible that the aircraft had lost an elevator mass-balance weight as a result of the catapult launching (the mass-balance weight being underslung), so that elevator mass-balance was the first variable chosen. The amount actually fitted to the elevator was 40 lb (although 48 lb is standard). Flutter was not expected in this condition, as it was known that the elevator-tab binaries 4–5 and 4–6 (*see* Section 2.11) were stable, and it was likely that the tailplane-elevator binaries 1–4, 2–4 and 3–4 would also be stable (even with 40 lb mass-balance the elevator C.G. is well ahead of the hinge line). The reason for the elevator mass-balance being underslung was that on an early *Vampire* flutter occurred involving considerable fore-and-aft motion of the (then) high tailplane. The *Venom* resonance tests, however, showed no mode of this type.

As expected, the tailplane-elevator binaries were stable, but the full senary calculation gave flutter over the speed range 362 ft/sec to 1100 ft/sec (*see* Fig. 6) and at a frequency of 23·9 c.p.s. ($\bar{\nu} = 1\cdot15$). The flutter was, moreover, of a violent form showing a clearly marked change from stability to flutter and back again at the two critical speeds. The flutter seemed to be hardly affected by changes of mass-balance, as shown in Fig. 6, but for small values of mass-balance a new form of flutter occurred simultaneously at a lower frequency. At $M = 24$ lb for example, the flutter starts at 382 ft/sec with a frequency of 24·9 c.p.s., but stops at 1280 ft/sec with a frequency of 10·8 c.p.s. The high frequency form of flutter appeared to die out at about 1100 ft/sec in line with the right-hand curve of Fig. 6. At zero mass-balance violent flutter occurs throughout the speed range, with mostly a high frequency predominating.

The result shown in Fig. 6 provides a theoretical explanation of the accident, in that flutter is predicted above an airspeed of 360 ft/sec on the aircraft as flown. In what follows consideration is given to the form and violence of the flutter, to the effect of varying tab mass-balance, and to a check of the theoretical prediction by comparison with flight experience on a similar aircraft (the *Venom* 1).

2.3. *Form and Violence of the Flutter.*—The simulator gives directly a measure of the importance of the different degrees of freedom, by showing the different amplitudes. It has often been objected that this will be unreliable because of the large scaling factors used. Sometimes the result is unreliable, but not usually because of the scaling process ; the scaling is such as to make the 'forces' in each equation of the same order, so that in general the importance of the different degrees of freedom can be gauged much more easily from the amplitude ratios on the simulator than from those of the original generalised co-ordinates. In the present problem, for example, the simulator usually showed the largest amplitudes at flutter on the tabs, so that if the original co-ordinates (in which the scaling factors (12) were omitted) had been used all the other types of motion would have seemed non-existent by comparison.

In the standard condition (elevator mass-balance 40 lb) flutter occurred at the high frequency (23·7 c.p.s.) and the significant degrees of freedom appeared to be 3, 5 and 6 ; *i.e.* a form of tailplane bending-tab flutter was taking place. The flutter continued to behave as though of this form, for it was later shown that the inertia couplings a_{35} and a_{36} (together, of course, with a_{53} and a_{63}) were important terms, and by changing these the flutter was most easily overcome. The complete picture, was, however, not as simple as these results seemed to show, for with only degrees of freedom 3, 5 and 6 no flutter was possible ; degree of freedom 4 (the elevator) was also necessary.

At this stage in the investigation it was thought that the flutter predicted by calculation was more violent than could have happened in practice, for it was found in the calculations that flutter with either tab alone also occurred. The aircraft with trim-tab alone corresponded to the *Venom* 2 on which no trouble had been experienced, but on further consideration it was decided that too little flight experience existed on the *Venom* 2 with extended chord tab* for any deduction as to its immunity from flutter to be sound. The *Sea Venom* with spring-tab alone was at first thought to be equivalent to the *Venom* 1, but this was not so as the spring-tab on the *Venom* 1 is smaller than that on the *Sea Venom*.

It was therefore decided to obtain a quantitative measure of the violence of the flutter. This was done by finding how much structural damping in the tab degrees of freedom was necessary just to eliminate flutter at the different speeds, and the results are shown in Fig. 7. The abscissa gives the numerical value of the direct-damping coefficient concerned (d_{55} or d_{66}) which must be added to the coefficients given in the Appendix to represent a condition of no flutter. For the full calculation, with both tabs present, the increments in d_{55} and d_{66} were made equal to each other ; this was somewhat arbitrary in that the two tabs were not allotted the same fraction of critical damping (appropriate to ground conditions) as each other, but to have done so would in any case have been rather artificial because of the low elastic stiffness of the spring-tab. The main conclusion to be drawn from Fig. 7 is quite clear : that the two tabs together give rise to a much more violent form of flutter than either tab by itself. In fact more than three times as much damping must be applied to each tab in order to prevent flutter as is necessary for either tab alone with the other locked.

2.4. *Effect of Tab Mass-balance.*—In view of the large tab amplitudes it was thought that changes of tab mass-balance might be beneficial. To check this the effect of increasing the trim-tab mass-balance was investigated ; this increase has the effect of reducing the inertia coupling between the tab and each of the other degrees of freedom, of which tailplane bending was most important in the type of flutter encountered. If tab mass-balance is increased too far, however, it is known (*see* Ref. 2 for example) that a different form of flutter commonly known as 'ternary tab flutter' can occur, in which the tailplane and, more especially, the elevator, have large amplitudes whereas the tab moves little although being a vital degree of freedom. This ternary flutter was always found in the present calculations when overbalance of the tabs was investigated. With one exception it was associated with the boom-bending mode (mode 1) and therefore occurred with a much lower frequency than the flutter discussed above (Section 2.3).

* The extension to the trim-tab chord on the *Venom* 2 was deleted after a little flying.

The result of this variation in trim-tab mass-balance is given in Table 2, and plotted in Fig. 8.

TABLE 2

Mass-balance on trim-tab (lb)	0	0·8	Amount fitted, 1·625	2·4	3·2	4·0
Lower critical speed	<200	326	362	390	436	560
Frequency	23·9	23·3	23·9	24·1	23·9	24·3
Upper critical speed	1,690	1,284	1,100	902	950	>2,198
Frequency	32·0	27·2	27·0	26·8	9·3	15·6

Critical speeds are quoted in ft/sec. Frequencies in c.p.s.

A small increase in balance weight is seen to be beneficial and reduces the range of instability. Larger increases, however, bring in the new form of flutter involving mode 1 at much lower frequency and with a much greater elevator amplitude and smaller tab amplitude, although the tab degree of freedom is still necessary to the flutter. It is apparent that the flutter is too persistent for the two forms to be separated out by tab mass-balance alone.

2.5. *Determination of a Safe Datum in Relation to Established Flight Experience.*—The attempt made to determine a satisfactory flutter-free condition is described in the next Section, but at the same time it was thought to be important to try and establish how much improvement in flutter characteristics was necessary. It was, by now, realised that the quinary calculations 12345 and 12346 did not correspond to reality either on the *Venom* 1 or (in effect) on the *Venom* 2 (*see* Section 2.3). To obtain a datum which was known to correspond to safety in flight, therefore, a senary calculation was made on the *Venom* 1 on exactly the same lines as that for the *Sea Venom*. The difference in tail configuration between the two aircraft is given in Fig. 2. If this calculation had shown the *Venom* 1 to flutter, then the results from the *Sea Venom* calculations could have been assumed to be pessimistic, and a correction factor could have been deduced. In practice, however, the calculation showed the *Venom* 1 to be stable at all speeds, and while this result was certainly encouraging it implied at the same time that complete immunity from a calculated flutter condition had to be achieved on the *Sea Venom*.

3. *Investigation of a Cure.*—The search for a cure was considerably influenced by the fact that the aircraft was in production, and therefore the modifications had if possible to be of a type that could be introduced quickly without greatly interrupting the production programme. The most natural improvement, for example, would have been to redesign the trim-tab operating mechanism to give a very high tab frequency, and the trim-tab could then be dismissed as a separate degree of freedom. In the circumstances this was not practical, and even a moderate stiffening of the circuit could not easily be achieved as there were no obvious weak points.

3.1. *Changes in Tab Size.*—The pronounced difference between the results of calculations on the *Sea Venom* and *Venom* 1 clearly shows that any reduction in tab size would have a relatively large beneficial effect. The first step in this direction was to investigate the effect of reducing the trim-tab chord to the *Venom* 1 value (*see* Fig. 2). As flight tests on *Venom* 2's showed the elevator control to be satisfactory, without the extension, this modification was made without question, but the improvement in flutter characteristics, although considerable, was not as great as was hoped. The calculated effect of this reduction in chord of the trim-tab is shown in Fig. 7. A further reduction in size of the trim-tab by cutting down the span was considered to be possible in an emergency, but was most undesirable ; much the same was true of the spring-tab. In fact these further reductions in size were found to be unnecessary.

3.2. *Changes in Tab Mass-balance.*—Increase in trim-tab mass-balance was found to have much the same effect for the trim-tab with reduced chord as for the trim-tab with extended chord. Small increases were beneficial, but before the high frequency flutter was eliminated the low frequency flutter was introduced. In Fig. 8 a comparison of the effectiveness of trim-tab mass-balance is given for the two sizes of tab.

These investigations into the effect of mass-balance clearly indicated the need to find a form of balance which would prove effective for the high frequency flutter, without precipitating the other form. The only possibility was to assume that the product of inertia between tab and tailplane bending was the important parameter (as seemed reasonable) and to mass-balance accordingly. This involved concentrating the tab mass-balance near to the aircraft centre-line and it was assumed to be concentrated at the position of the existing weight there. The effect of this was very powerful, as shown in Fig. 9, where it can be seen that if all the trim-tab mass-balance is placed at the centre-line end of the tab the flutter curves with and without the trim-tab locked are practically identical. At the time this was thought to be the best that could be hoped for in the way of mass-balance on the trim-tab for the modes considered, and it was assumed (rightly) that if centre-line mass-balance cured the trim-tab's contribution to the flutter, a similar modification to the spring-tab should eliminate the flutter altogether. There is, however, an obvious drawback to putting all the tab mass-balance on the centre-line : it is the worst position possible for antisymmetric flutter. Antisymmetric elevator-tab flutter can only occur through elevator torsion, but in this case the elevator torsional natural frequency of 20·95 c.p.s. is not very different from the symmetric frequency of tailplane bending, so the possibility of trouble could not be ruled out. It was therefore decided to make a calculation of the possibilities of antisymmetric flutter. This investigation will now be briefly described, but the outcome was not very conclusive on account of the apparently inadequate data.

3.3. *The Check Calculation on Antisymmetric Flutter.*—The accuracy of this calculation was impaired by the fact that the ground resonance data showed only one mode where there should have been two. Had the calculation assumed greater importance than it actually did in the final decision, a further experimental investigation might have been necessary.

3.3.1. *Basic data.*—The ground resonance tests showed only two modes in the practical frequency range that involved large tail amplitudes. The first of these was primarily antisymmetric vertical bending of the booms, with consequent rolling of the tailplane, at a frequency of 8·4 c.p.s. The second was the elevator torsion mode at 20·95 c.p.s., but unfortunately this mode included considerable wing motion. It seems likely that in reality the aircraft has two resonant modes near together in frequency, each involving elevator torsion and wing motion, with the phase of these two constituents reversed as between one mode and the other. As only one of these two modes was recorded in the ground resonance tests considerable doubt exists as to whether the whole or none of the recorded wing motion should be included, or whether some compromise should be struck. Had both modes been available they could each have been included in full, with reasonable hope of obtaining the correct answer. In fact, solutions were obtained with the wing motion both included and excluded but its effect was so powerful that the significance of the antisymmetric calculations is still in doubt. The four degrees of freedom used were

(1) Mode at 8·4 c.p.s.–boom bending.

(2) Mode at 20·95 c.p.s.–elevator torsion.

(3) Trim-tab angle.

(4) Spring-tab angle.

As an experiment the calculation was in one case expanded to a quinary by splitting mode (2) into an aircraft mode and an elevator torsion mode, and using the two parts as separate degrees of freedom. This is not justified, however, and the results were similar to those of the quaternary with wing terms neglected.

The aerodynamic derivatives used in this calculation were the same as those used in the symmetric case. The torsional mode of the elevator, which was not measured in detail, was assumed to be linear along the span, but, as in the symmetric case, the tabs were assumed to be rigid in torsion. The tab restraints (giving rise to the elastic coefficients) were assumed to be the same as in the symmetric case.

3.3.2. *Results from the antisymmetric calculations.*—Calculations were made (on the simulator) of the variation of critical flutter speed with mass-balance placed at the boom end of each tab ; mass-balance at the centre-line end merely increases the tab inertia and was in practice found to have a slightly unfavourable effect as expected. The simulator showed the first mode to be quite ineffective, and the calculation could, with equal accuracy, have been reduced to the ternary (2), (3) and (4). The elevator torsion, however, was clearly capable of promoting flutter, and the degree with which it did so was dependent on the allowance made for the motion of the rest of the aircraft in the mode. With no allowance made for this motion considerably more mass-balance is needed to eliminate flutter than was actually fitted, even though the mass-balance is placed in its most favourable position at the boom-ends of the tabs. The results are plotted in Fig. 10, from which it can be seen that the lower critical speeds are absurdly low. With full allowance made for the aircraft amplitudes in the mode at 20·95 c.p.s. the corresponding curve to that shown in Fig. 10 is completely absent. This calculation was so stable that there can be no doubt, on balance, that the aircraft as flying at the time of the accident was not in danger from antisymmetric flutter. It is also clear, however, that in view of the uncertainties in this calculation it would have been unwise to worsen the antisymmetric flutter characteristics. The decision was therefore taken to leave the existing mass-balance on the tabs unchanged, but to experiment with additional masses added at the centre-line end of the tabs. Since this appeared to offer a satisfactory solution, no further work was carried out on the antisymmetric flutter problem, *e.g.* in the way of clearing up the position as regards the ground resonance test results.

3.4. *Further Investigations on the Effect of Tab Mass-balance.*—The symmetric flutter calculations were then pursued along the lines of the compromise just mentioned. The results are given in Fig. 11, in which critical flutter speed is plotted against the trim-tab mass-balance additional to that already fitted, and placed near the aircraft centre-line. As this work was done with a view to modifying the aircraft, all these curves relate to the trim-tab with reduced chord. The different curves are for different conditions of mass-balance on the spring-tab, and again the amounts are additional to the standard balance fitted and are near the aircraft centre-line.

In each case the flutter is divided into two areas by the curves of Fig. 11, one corresponding to the high-frequency flutter of the type believed to have caused the accident and the other, apart from one exception, the low-frequency flutter of the type brought on by over mass-balance of the trim-tab. For the standard mass-balance on the spring-tab the flutter curve starts (for no extra trim-tab weight) with a band of flutter from 365 ft/sec to 985 ft/sec. These speeds do not correspond exactly with those shown in Figs. 7 and 8, as the standard amount of elevator mass-balance (48 lb) was used for this later calculation (*see* Section 2.2). As trim-tab mass-balance is increased the curve narrows, rapidly at first, and finally closes up showing that the trim-tab when well mass-balanced helps to prevent spring-tab flutter, for with the trim-tab locked a high frequency flutter band exists from 565 to 850 ft/sec (Fig. 7). A gap of no flutter then extends for about 0·35 lb additional trim-tab mass-balance beyond which the low frequency flutter is introduced at higher speeds. In one case only (that for standard spring-tab mass-balance) the new branch of flutter remains at the high frequency ; in all the cases covering additional spring-tab mass-balance the new branch occurs at the low frequency. Even when it does assume the high frequency involving mode 3 (*see* Section 2.1.1) the two types of flutter are superimposed, and at the upper critical speed it is the low-frequency type involving mode 1 which prevails.

Increase in spring-tab balance weight has the effect of increasing the gap between the two branches of the curve, so that with suitable values of spring-tab mass-balance a gap of just over

0·5 lb can be obtained. The high-frequency band cannot be entirely eliminated, which suggests that the spring-tab cannot be made to have as favourable an effect on the trim-tab flutter as the trim-tab has on the spring-tab flutter. The most favourable gap between the curves is obtained with an extra 1·15 lb of mass-balance on the spring-tab, and then the optimum condition is obtained with an extra trim-tab balance weight of 0·5 lb. This condition was then put forward as a theoretical solution of the problem. Unfortunately it was found in practice that the size of the gap was not large by comparison with the balancing errors that might be expected in production. To improve matters the firm then designed a lighter trim-tab which has the same external dimensions as the previous tab (with reduced chord) but lower inertia, and, incidentally, a higher natural frequency. The effectiveness of this modification was checked by further calculations to be discussed in Section 3.6. The results in the next section represent a digression into the effects of the circuit parameters which were varied and can conveniently be described at this stage.

3.5. *The Importance of the Stiffness and Inertia of the Tab Circuits*.—The main investigation here was concerned with the effect of increasing the stiffness of the trim-tab circuit. It has been mentioned earlier that considerable stiffening was not a very practical modification, but the results were obviously of general interest and some stiffening of the circuit was considered possible. It is convenient to give at the same time the results of some variations of inertia and stiffness in the spring-tab circuit which were carried out because of the uncertainty about the original assumption.

3.5.1. *Variation of trim-tab circuit stiffness*.—The results are shown in Fig. 12. The curve labelled $e_{55} = 380$ corresponds to the standard value of the circuit stiffness. The flutter curve for the trim-tab locked is also given, and it is to be expected that as the trim-tab circuit stiffness is increased from 380 the flutter curve will contract and eventually approach this curve for the trim-tab locked. It can be seen that this does happen, but even for $e_{55} = 1110$ (about three times the standard value) the flutter curve is considerably worse than that for the trim-tab locked. This result illustrates the fact that a major modification to the trim-tab circuit would be needed to destroy the active participation of this tab in the flutter. Fig. 12 also shows the effect of reducing the trim-tab frequency to zero. In this condition, as would be expected, the possibilities of flutter are more widespread, but the lower critical speed is, rather surprisingly, higher than that for the standard case.

In practice the improvement obtained by increased tab circuit stiffness as shown by these results was too poor for any modifications to be considered worthwhile. This would not have been true if the flexibility had been largely caused by a single weakness that could easily have been remedied.

3.5.2. *Variation of spring-tab circuit stiffness and inertia*.—To allow for the effect of a greater value of the spring-tab circuit inertia the values of a_{66} and e_{66} were doubled, thus keeping the same spring-tab frequency. The change in flutter speeds produced was small; the lower critical speed being reduced by 4 per cent and the upper critical speed by 8 per cent. The conclusion reached from this was that even if the initial assumptions were appreciably wrong the final conclusion was not likely to be seriously affected.

Another contribution from the spring-tab circuit which was investigated qualitatively was that arising from a connecting rod filled with lead. In the early *Vampire* design this lead had acted as part of the elevator mass-balance, and with the conversion to a spring-tab circuit, as on the *Sea Venom*, the weighted rod was retained although it no longer had any direct mass-balancing effect. In fact the rod has an under-balancing effect on the spring-tab statically although it does not affect the product of inertia between the tab and elevator as it is situated in the starboard boom. Furthermore, the flexibility of the circuit between this rod and the tab will be such as to change the effect of the rod considerably (the original assumptions were that this rod was inoperative at the spring-tab natural frequency). In this qualitative investigation a variable gearing between the motion of the rod and rotation of the spring-tab was assumed, and flutter speeds were obtained as the value of the gearing was increased from zero. A small increase of gearing showed little effect, but for larger values the band of flutter increased in severity. It was therefore decided to remove the lead filling in production.

3.6. *Calculations on the Trim-Tab with Reduced Inertia.*—Estimates of the inertia of the newly designed trim-tab were made by the firm, and readily introduced into the previous flutter calculations. The arm of the mass-balance weight was not decided at this stage, so that arrangements were made to vary this parameter as well as the mass-balance itself. The results of the calculation are given in Fig. 13 where the critical flutter speed is plotted against the length of mass-balance arm for three different values of mass-balance. The values corresponding to static balance are shown in each case. It will be seen that with this new lighter trim-tab no flutter occurs on the side of tab underbalance, *i.e.*, the type of flutter believed to be responsible for the accident has been completely eliminated. After these calculations were completed, a suitable practical configuration was designed by the firm. This consisted of a mass of $\frac{3}{4}$ lb on an arm 1·3 in. fitted at each end of the trim-tab, thus giving roughly static balance, the tab C.G. being 0·04 inches aft of the tab hinge line. This final design does not fit precisely on to any of the curves shown on Fig. 13, but it evidently provides a large safety margin. At the same time it was found inconvenient to mass-balance the spring-tab unsymmetrically, so in practice the extra 1·15 lb was distributed uniformly over the span of the spring-tab. The effect of this can be seen by referring to Fig. 11. Instead of giving exactly the curve corresponding to 1·15 lb added mass-balance on the spring-tab, the true curve will be the same as this for the right-hand branch but will correspond to about 1·0 lb added to the spring-tab for the left-hand branch*, *i.e.*, just a little worse than the curve drawn for 1·15 lb added. This shows that the adverse effect of distributing the extra spring-tab balance weight uniformly is very small and will not perceptibly alter the margin indicated by Fig. 13.

In the last resort, therefore, no use has been made of the device for improved mass-balance on the tabs by biasing the weight towards the centre-line. This is because once the effort of putting into production a lighter trim-tab had been faced the extra refinements of mass-balance distribution proved to be unnecessary. The improvement in inertia was from 0·1118 lb ft² to 0·0394 lb ft².

3.7. *The Effect of Flexibility of the Elevator Mass-balance Arms.*—At the stage reached in Section 3.6 the theoretical investigation appeared to have been completed with satisfactory results, but the authors thought that one further feature should be investigated. This concerned the effect of the flexibility of the elevator mass-balance arms. There was no reason to suppose that this effect should be worse on the *Sea Venom* than on the *Venom* 1, in fact rather the contrary as the frequency ratio mass-balance weight/tab was lower on the *Venom* 1 than the *Sea Venom*, but this parameter was known to have a powerful effect on tab flutter. It is well known that as long as the mass-balance natural frequency is higher than the flutter frequency, flexibility increases the efficiency of the mass-balance ; on the other hand if the flutter frequency is the higher the mass-balance weight's effectiveness is completely reversed so that its contribution to the relevant product of inertia is unfavourable.

For the *Sea Venom* the extra degree of freedom for flexibility of the elevator mass-balance weights was introduced in place of degree of freedom (2), the normal mode at 21·00 c.p.s. (Section 2.1.1), which had shown little effect on the flutter. The mass-balance frequency was varied in these calculations and the effect was investigated for three conditions : the *Sea Venom* as it was at the time of the accident ; the modified *Sea Venom* as described in Section 3.5 ; and on the *Venom* 1. As a result of the accident the *Venom* elevator mass-balance arms were stiffened to give an estimated (symmetric, vertical) frequency of about 50 c.p.s. compared with a previous value of 35 c.p.s. The results of the calculations are given in Figs. 14 and 15. Fig. 14 shows the effect on the *Sea Venom* at the time of the accident ; flutter frequencies are shown along the curve. It will be noted that this result conforms to the general rule given above ;

* This interpolation is based on the product of inertia a_{36}.

as the mass-balance frequency is reduced the severity of the flutter falls off, and the main branch disappears altogether before the frequency ratio is reversed. Flutter was, however, found to occur at high speeds throughout the range of mass-balance frequencies, the speed falling rapidly with frequency.

Fig. 15 shows the interesting result of including the mass-balance flexibilities on the *Venom* 1 and modified *Sea Venom*—two cases giving no flutter with rigid balance arms. In each case a high-frequency flutter is introduced (higher than the highest natural frequency even allowing for aerodynamic stiffness on the *Venom* 1) so that the mass-balance frequency is in the dangerous region below the flutter frequency. The flutter speeds obtained in this calculation (Fig. 15) are high, and because of the generally pessimistic nature of the assumptions made should probably be even higher, so that these results are not considered to be of practical interest on the *Venom*. Fig. 15 does, however, demonstrate a possibility that is of considerable academic interest, and provides the principal reason for including this section.

4. *Conclusions.*—Before summarising the detailed results of this investigation some remarks on the use of the Flutter Simulator may be of interest. It is clear that such a vast quantity of work could not have been undertaken at all without the use of the simulator or some form of high-speed computing equipment, and in practice the simulator proved extremely suitable for all the variations covered. The progress of the investigation was, however, to some extent shaped by the availability of the simulator, and by the urgency with which the results were required. The history of this investigation has been presented in roughly chronological order so as to bring out this effect. The graphs of flutter speed against tab damping, for example, would never have been obtained but for the simulator on which the variation of structural damping is particularly simple.

The main factual conclusions relating to the *Sea Venom* are:—

(1) Symmetric flutter of the *Sea Venom* involving tailplane bending, elevator, trim-tab and spring-tab rotations, was possible in a violent form at the time of the accident.

(2) Increased mass-balance of the tabs is beneficial for this form of flutter but introduces a lower frequency form involving boom bending.

(3) Suitable modifications were found to be

(3.1) Trim-tab chord reduced.

(3.2) Trim-tab inertia reduced.

(3.3) Trim-tab statically balanced.

(3.4) Spring-tab mass-balance increased.

thus giving about the same margin of stability as on the *Venom* 1.

Some general points of interest are:—

(1) Where possible for flutter investigations the technique of comparison with calculations for a similar aircraft, known to be satisfactory, is to be recommended.

(2) Two tabs can be much more dangerous together than either taken alone, especially if both have natural frequencies below that of the important structural mode.

(3) Tailplane bending, at least, must be considered in the elevator tab criteria.

(4) Unsymmetric spanwise distribution of tab mass-balance weights may improve safety margins, but the antisymmetric possibilities of flutter should be considered before adopting any such configuration.

(5) In possible cases of tab flutter the effect of control surface mass-balance flexibility must be carefully considered : it is not sufficient to ensure that the frequency of the mass-balance weights is higher than that of the important structural modes.

Acknowledgement.—The authors are indebted to the de Havilland Aircraft Company for supplying all the basic information (weight data, estimates of static aerodynamic coefficients and ground resonance modes), and for assisting with some of the computational work. They are also indebted to Miss E. V. Hartley for helping with the operation of the simulator.

Addendum.—Since the main text of this report was written, the modifications enumerated in Section 4, items 3.1 to 3.4 inclusive, have been incorporated in a *Sea Venom* aircraft. Flight tests were carried out on this aircraft with full instrumentation, and under careful examination for any near approach to flutter. In fact no trace of low damping was found at speeds up to 500 knots, but at this stage the tab arrangement was changed to be the same as that of the *Venom* 1, for reasons other than flutter, and this configuration is now standard.

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APPENDIX

Tables of Flutter Coefficients

1. *Introduction.*—The following tables show the effect produced on the flutter coefficients by a change in the physical properties of the aircraft, *e.g.*, a comparison of coefficients is given for a change in elevator mass-balance, etc. The coefficients are given in the form as finally scaled for the simulator. The constant scale factors are

$$V_0 = 1000 \text{ ft/sec}$$

$$\text{simulator frequency} = \text{full-scale frequency} \div (2\pi \times 20 \cdot 777).$$

The derivation of the frequency factor $(2\pi \times 20 \cdot 777)$ is explained in Section 2.1.3 of the main text.

2. *Summary of coefficients quoted.*—The following list gives a guide to the tables below, indicating the principal variant.

Table I—standard
(Figs. 6 and 7) .. .. Coefficients for aircraft as flying at the time of the accident. The elevator mass-balance is 40 lb in these coefficients.

Table II—elevator mass-balance
(Fig. 6) .. .. .. Inertia matrix for an elevator mass-balance of 48 lb. Comparable with Table I.

Table III—trim-tab mass-balance
(Fig. 8) .. .. .. Inertia matrix for zero trim-tab mass-balance (also comparable with Table I where the trim-tab mass-balance = 1·625 lb).

Table IV .. .. .. Coefficients for *Venom* 1 calculation.

Table V—trim-tab chord
(Fig. 7) .. .. .. Coefficients for the *Sea Venom* with reduced chord trim-tab, elevator mass-balance = 40 lb. Comparable with Table I.

Table VI—trim-tab mass-balance (new tab).
Effect on 5th row and column of Table V of changing the trim-tab mass-balance from 1·625lb to 2·4 lb.

Table VII
(Fig. 10) .. .. .. Coefficients for antisymmetric calculation with contributions from the elevator only included in the elevator torsion mode (second degree of freedom).

Table VIII .. .. .. Coefficients for antisymmetric calculation with contributions from the whole aircraft included in the elevator torsion mode. Comparable with Table VII.

Table IX—elevator mass-balance
(Fig. 11) .. .. .. Inertia matrix for the *Sea Venom* with reduced chord trim-tab. Elevator mass-balance = 48 lb. Comparable with Table V.

Table X—localised trim-tab mass-balance
(Fig. 11) .. .. .. Inertia terms changed from the values in Table IX by adding 0·5 lb to the inboard mass-balance weight on the trim-tab.

Table XI—localised spring-tab mass-balance
(Fig. 11) .. .. .. Inertia terms changed from Table IX by adding 0·5 lb to the mass-balance weight on the inboard end of the spring-tab.

Table XII—trim-tab inertia
(Fig. 13) .. .. .. Inertia matrix for the lighter trim-tab finally fitted. This compares with Table V.

Table XIII—trim-tab mass-balance arm
(Fig. 13) .. .. .. Inertia matrix for the lighter trim-tab for a change in length of arm of the trim-tab mass-balance. Comparable with Table XII.

Table XIV
(Fig. 14) .. .. .. Fresh inertia terms in the second row and column representing the displacement of the elevator mass-balance weights relative to the elevator.

Although several sets of coefficients were worked out for different values of each parameter varied in order to obtain the graphs shown, only one set is quoted for each parameter in the tables that follow for reasons of space. With the exception of trim-tab mass-balance arm (Table XIII), the coefficients change in a linear manner with all the parameters, so that these tables are sufficient for comparison. Where the coefficients are too small to be inserted on the simulator they are quoted as zero ; coefficients which are absolutely zero are indicated by a blank space.

3. *Table of Coefficients.*

TABLE I

Scaled coefficients for aircraft as flying at time of accident

Degrees of freedom :—

(1) boom bending at 8·25 c.p.s.

(2) tail mode at 21·0 c.p.s.

(3) tailplane bending at 24·7 c.p.s.

(4) elevator rotation

(5) trim-tab angle

(6) spring-tab angle

		1	2	3	4	5	6
1	a	1067	−549	117	−14	1	1
	b	78	−116	−10	83	−29	−43
	c	23	−87	−2	408	220	291
	e	168					
2	a	−29	1100	−16	3	0	0
	b	−2	31	6	−7	1	2
	c	1	−30	2	−28	−18	−25
	e		1090				
3	a	85	−222	785	37	−1	−1
	b	−8	86	116	−64	20	37
	c	−3	32	35	−302	−167	−265
	e			1110			
4	a	−54	250	200	842	12	8
	b	3	5	−2	103	20	13
	c	−22	102	31	293	477	514
	e						
5	a	106	−222	−152	248	224	
	b	11	−20	−12	124	119	
	c	−12	59	18	249	1110	
	e					132	
6	a	56	−111	−70	118		312
	b	−4	20	6	50		89
	c	−8	40	14	88		1110
	e						31

$d_{66} = 20$

The flutter speeds obtained with these coefficients are shown on Fig. 7 together with the effect of varying the tab damping.

The effect of change in elevator mass-balance may be gauged by comparing the inertia coefficients of Table I (mass-balance = 40 lb) with those for a mass-balance of 48 lb given below. 48 lb is the weight now in use on the aircraft. The graph of critical flutter speed against elevator mass-balance is given in Fig. 6.

TABLE II

Elevator mass-balance = 48 *lb* (*Inertia matrix*)

1084	−584	93	−29	1	1
−31	1104	−13	5	0	0
67	−185	810	53	−1	−1
−112	373	282	949	12	8
106	−222	−152	248	224	
56	−111	−70	118		312

Similarly, change in trim-tab mass-balance is represented by comparison between the (a's) of Table I (tab mass-balance = 1·625 lb) with those for no tab mass-balance, which are given below.

TABLE III

Trim-tab mass-balance = 0 (*Inertia matrix*)

1064	−543	119	−18	3	1
−28	1083	−16	4	0	0
87	−226	782	40	−2	−1
−70	327	214	823	18	8
207	−371	−256	369	187	
56	−111	−70	118		312

The scaled coefficients for the *Venom* 1 calculation, which follow, may also be compared with Table I. The *Venom* 1 was found to be stable at all speeds by the simulator, whereas the *Sea Venom* as represented by the coefficients of Table I was found to flutter between the speeds of 362 and 1100 ft/sec (see for example, Fig. 7 at zero tab damping).

TABLE IV

Scaled coefficients for Venom 1

		1	2	3	4	5	6
1	a	1086	−558	124	−31	0	1
	b	89	−122	7	96	−57	−47
	c	26	−94	5	475	388	331
	e	171					
2	a	−29	1099	−18	4	0	0
	b	−2	35	7	−8	3	3
	c	1	31	2	−31	−35	−32
	e		1110				
3	a	88	−239	683	36	1	−1
	b	2	90	148	−72	49	45
	c	0	30	47	−348	−357	−328
	e			1110			
4	a	−92	237	151	805	8	5
	b	1	8	0	82	16	14
	c	−16	76	23	233	670	577
	e						
5	a	6	14	27	65	452	
	b	−2	10	3	30	82	
	c	−5	23	8	56	1110	
	e					665	
6	a	27	−53	−41	56		118
	b	−2	12	4	34		82
	c	−5	27	10	65		1110
	e						40

$d_{66} = 20$

Coefficients for the *Sea Venom* with reduced trim-tab chord are given below in Table V. These may not be compared directly with Table I as the coefficients concerning the trim-tab directly (the fifth row and column), being all reduced by this reduction in chord, are scaled with a larger factor in Table V than in Table I. The remainder of the coefficients are scaled with the same factors and may be compared.

TABLE V

Reduced chord trim-tab

Trim-tab mass-balance = 1·625 lb
Spring-tab mass-balance = 2·30 lb
Elevator mass-balance = 40 lb

		1	2	3	4	5	6
1	a	1067	−549	117	−14	0	1
	b	78	−117	−10	83	−38	−43
	c	25	−97	−2	392	255	291
	e	168					
2	a	−29	1100	−16	3	0	0
	b	−2	31	8	−7	0	2
	c	1	−29	2	−26	−20	−25
	e		1090				
3	a	85	−222	785	37	−1	−1
	b	−8	87	117	−64	27	37
	c	−3	37	41	−288	−194	−265
	e			1110			
4	a	−64	191	165	825	6	8
	b	1	9	0	81	12	13
	c	−18	86	26	232	504	514
	e						
5	a	15	−81	−87	150	420	
	b	−5	26	−8	70	89	
	c	−13	61	19	138	1110	
	e					380	
6	a	56	−111	−70	118		312
	b	−4	20	6	51		89
	c	−8	40	14	88		1110
	e						31

$d_{66} = 20$

The results using these coefficients are comparable with those obtained from Table I and are shown in Fig. 7 (variation of tab damping). The effect of increasing the trim-tab mass-balance on this tab (with no extension) may be seen by comparing Table VI with Table V (inertia matrix).

The principal change to the coefficients is to the fifth row and column (*i.e.* those arising specifically from the trim-tab) and the comparison for these coefficients only is given.

TABLE VI

Trim-tab mass-balance = 2·4 *lb* (*Inertia matrix*)

−76	76	−12	41	−1 0 0 2 471	

TABLE VII

Scaled coefficients for antisymmetric calculation on the Sea Venom

Degrees of freedom :—

(1) boom bending at 8·4 c.p.s.
(2) elevator torsion at 20·95 c.p.s. taking the elevator motion only
(3) trim-tab angle
(4) spring-tab angle

Elevator mass-balance = 48 lb
mass-balance on inboard end of trim-tab = 0·8125 lb
mass-balance on inboard end of spring-tab = 1·15 lb
mass-balance on outboard end of trim-tab = m_5
mass-balance on outboard end of spring-tab = m_6

$m_5 = 0{\cdot}8125$ lb $\quad m_6 = 1{\cdot}15$ lb

		1	2	3	4
1	a	998	1	0	0
	b	26	4	2	−1
	c	−17	23	−9	3
	e	163			
2	a	229	716	−6	2
	b	32	108	−12	3
	c	80	308	−494	140
	e		728		
3	a	−29	−130	367	
	b	−20	−61	78	
	c	−37	−120	969	
	e			340	
4	a	378	286		314
	b	40	117		89
	c	75	230		1110
	e				31

$d_{44} = 20$

Results obtained using these coefficients are shown in Fig. 10 at a mass-balance value of 1 (see note on Fig. 10). The effect of completely including the elevator torsion mode in the antisymmetric calculation may be gauged by comparing Table VIII with Table VII in which only the contributions directly relating to the elevator were included.

TABLE VIII

Elevator mass-balance = 48 lb

Trim-tab mass-balance = 1·625 lb

Spring-tab mass-balance = 2·3 lb

Antisymmetric coefficients with allowance made for the amplitudes of the whole aircraft in deriving the structural inertia and stiffness coefficients of the mode at 20·95 c.p.s.

		1	2	3	4
1	a	998	412	0	0
	b	26	1	2	−1
	c	−17	8	−9	3
	e	163			
2	a	137	980	0	0
	b	0	0	0	0
	c	0	0	0	0
	e		996		
3	a	−29	−44	367	
	b	−20	−20	78	
	c	−37	−40	969	
	e			340	
4	a	378	95		314
	b	40	39		89
	c	75	77		1110
	e				31

$d_{44} = 20$

This calculation gave a stable result.

The effect of increasing the mass-balance on the inboard end of the trim-tab may be seen by comparison of the two sets of figures below. The first table (IX) is the inertia matrix for the case with reduced trim-tab chord, an elevator mass-balance of 48 lb, and the basic amount (1·625 lb) of trim-tab mass-balance ; and Table X shows the effect of increasing the inboard balance weight by 0·5 lb. The inertia coefficients of Table IX differ from those of Table V in that the elevator mass-balance is now increased to 48 lb.

TABLE IX

1084	−585	93	−32	1	1
−31	1104	−13	4	0	0
67	−185	810	47	−1	−1
−123	313	247	936	6	8
15	−81	−87	150	420	
56	−111	−70	118		312

TABLE X

			—30	0	
			4	0	
			45	0	
—118	299	238	942	3	
—43	55	11	69	452	

The sixth row and column are not affected by this change, and the 1–3 block of coefficients are altered only by a negligible amount.

Increasing the spring-tab mass-balance at the inboard end of the tab results in the coefficients of Table XI. The fifth row and column are not affected by this change, and this table may be directly compared with Table IX, which represents the standard case of mass-balance.

TABLE XI

Increase in spring-tab inboard mass-balance = $0 \cdot 5$ *lb*

			—30		0
			4		0
			45		—1
—116	299	238	941		6
36	—66	—41	91		318

The reason that $\frac{1}{2}$ lb spring-tab mass-balance weight has a much smaller effect than $\frac{1}{2}$ lb trim-tab mass-balance weight is that the mass-balance arm is much less. The results of these variations in inboard mass-balance weights are shown in Fig. 11.

The only change made in the coefficients of Table V by fitting a lighter trim-tab is to the inertia matrix which is given below in Table XII. The spring-tab mass-balance used in this calculation was $1 \cdot 15$ lb (standard) on the outboard end of the tab, and $2 \cdot 3$ lb on the inboard end. The mass balance on the trim-tab is $0 \cdot 8125$ lb on each end.

Tables XII and XIII are for the arm of the trim-tab mass-balance first $0 \cdot 1$ ft (which is approximately standard) and then zero.

TABLE XII

Inertia matrix (*mass-balance arm* = $0 \cdot 1$ *ft*)

1083	—573	94	—33	0	0
—30	1075	—13	4	0	0
68	—186	810	46	—1	0
—127	316	247	924	3	4
19	—75	—74	77	177	
16	—21	—8	65		324

TABLE XIII

Inertia matrix (mass-balance arm = 0)

			−32	2	
			4	0	
			46	−1	
−125	313	246	929	10	
164	28	−178	257	116	

The values given in Table XII may be compared approximately with the inertia matrix of Table V which gives corresponding values for the trim-tab with reduced chord (the position of the C.G. of the trim-tab mass-balance is about 1-in. ahead of the hinge-line in both cases, and the mass-balance weights are the same). These coefficients (above) gave stable results, but increasing the length of arm gave flutter speeds which are shown in Fig. 13.

The effect of displacements of the elevator mass-balance weights relative to the elevator was investigated by repeating the calculation, omitting the mode at 21·0 c.p.s., and including displacements of the elevator mass-balance as the second degree of freedom. Changes in the second row and column (the aerodynamic terms in the second degree of freedom being zero) are as given below in Table XIV.

TABLE XIV

(*Inertia matrix*)

	16				
502	191	−713	925		
	−16				
	111				

$e_{22} = 0 \cdot 4432\omega^2$ where ω is the frequency of the mass-balance arm in c.p.s. These coefficients replace the second row and column in Table I.

The results obtained from these coefficients may be seen in Fig. 14 where the stiffness of the arm of the mass-balance (e_{22}) has been varied.

Similar values were used to obtain the curves of Fig. 15.

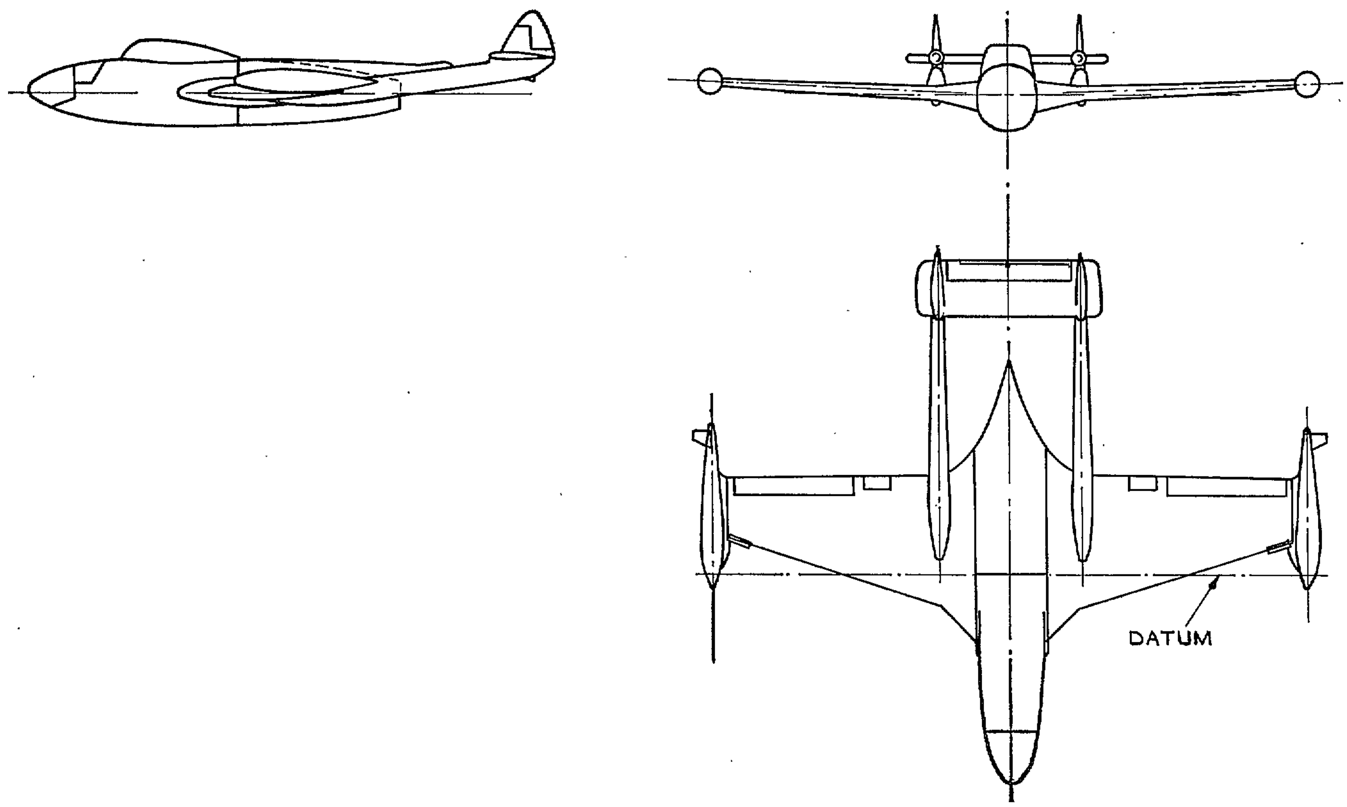

FIG. 1. *Sea Venom.*

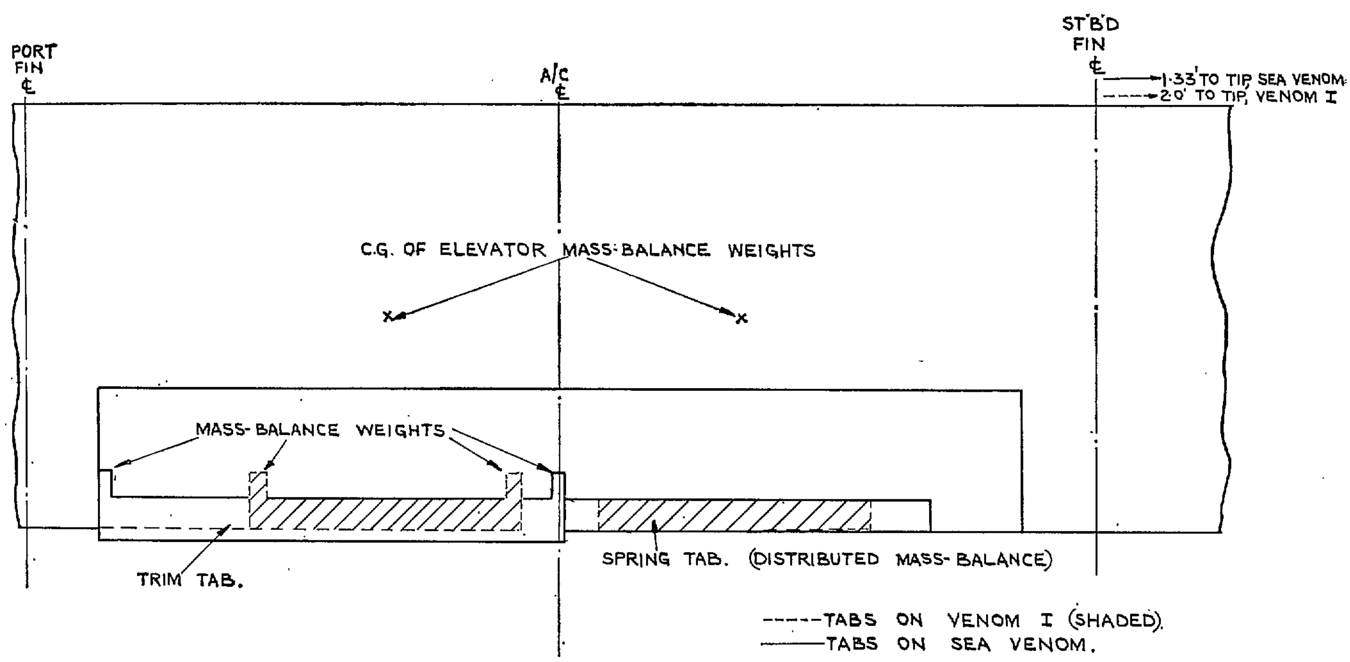

FIG. 2. Tailplane showing comparison of *Sea Venom* with *Venom* 1.

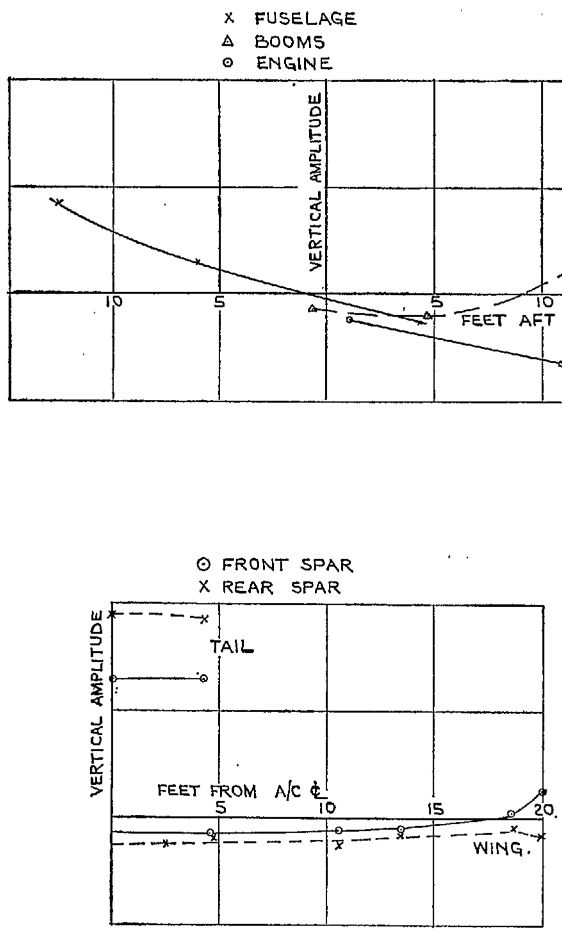

FIG. 3. *Sea Venom* symmetric ground resonance mode at 8·25 c.p.s. Vertical excitation at nose. Full internal fuel and forward tip-tank full.

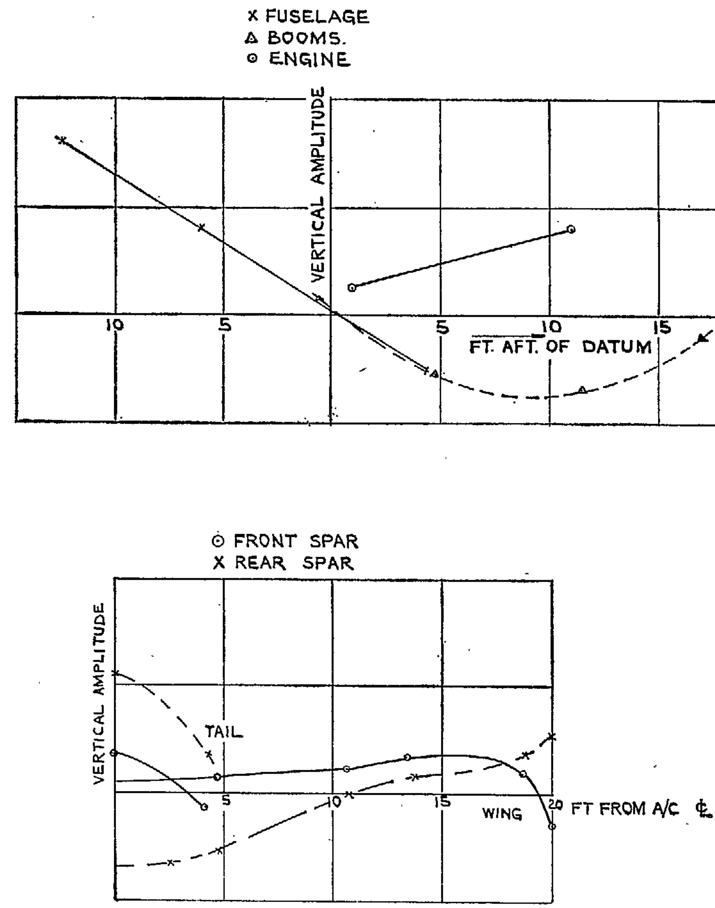

FIG. 4. *Sea Venom* symmetric ground resonance mode at 21·0 c.p.s. Vertical excitation at nose. Full internal fuel and forward tip-tank full.

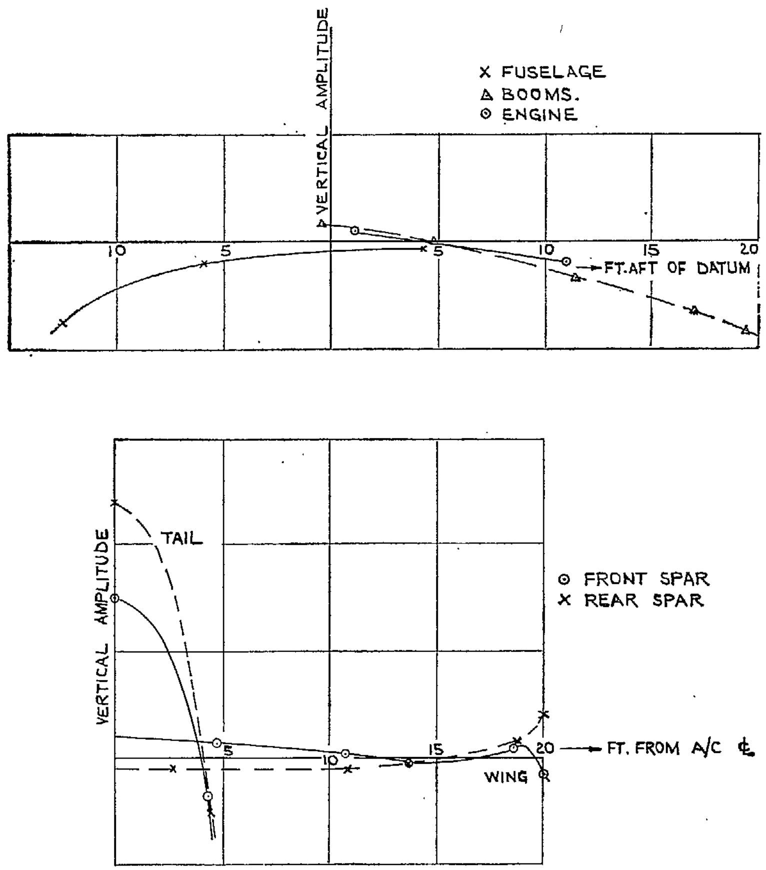

FIG. 5. *Sea Venom* symmetric ground resonance mode at 24·7 c.p.s. Vertical excitation at nose. Full internal fuel and forward tip-tank full.

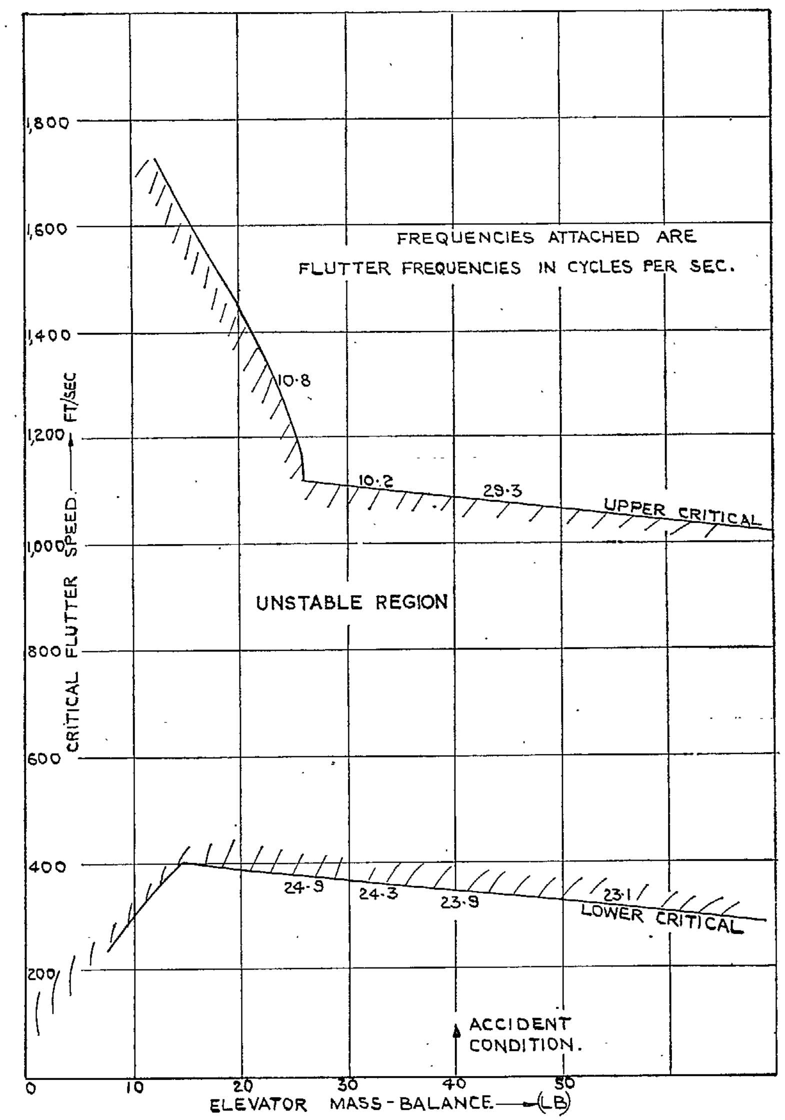

FIG. 6. Variation of flutter speed with elevator mass-balance.

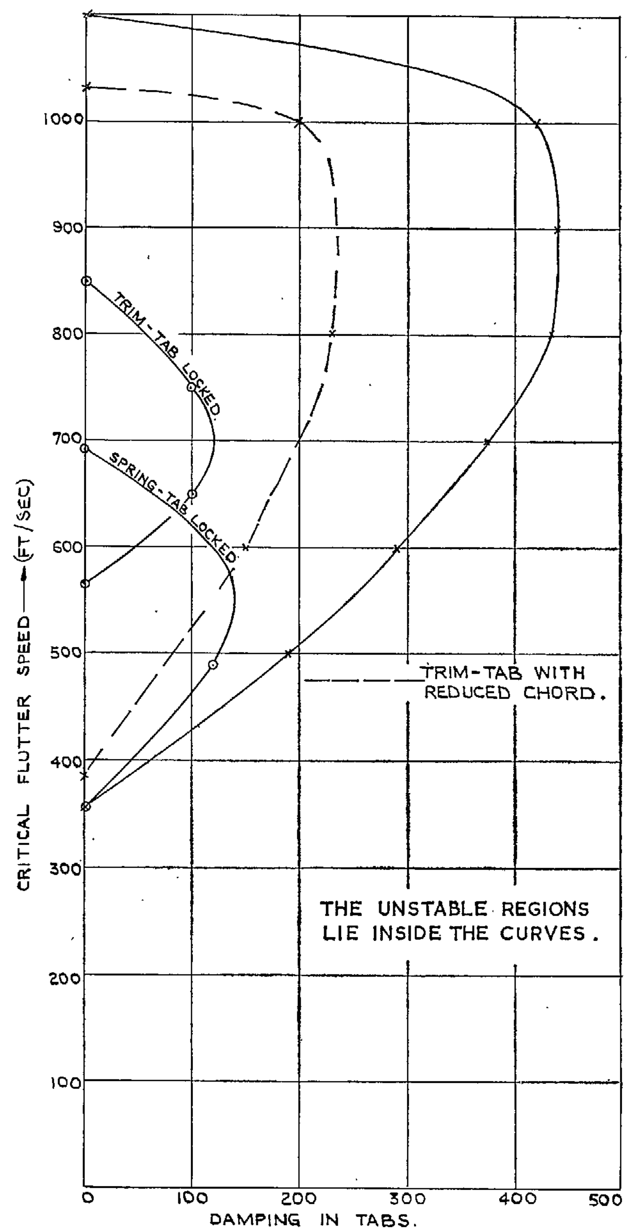

FIG. 7. Flutter speed *vs.* tab damping.

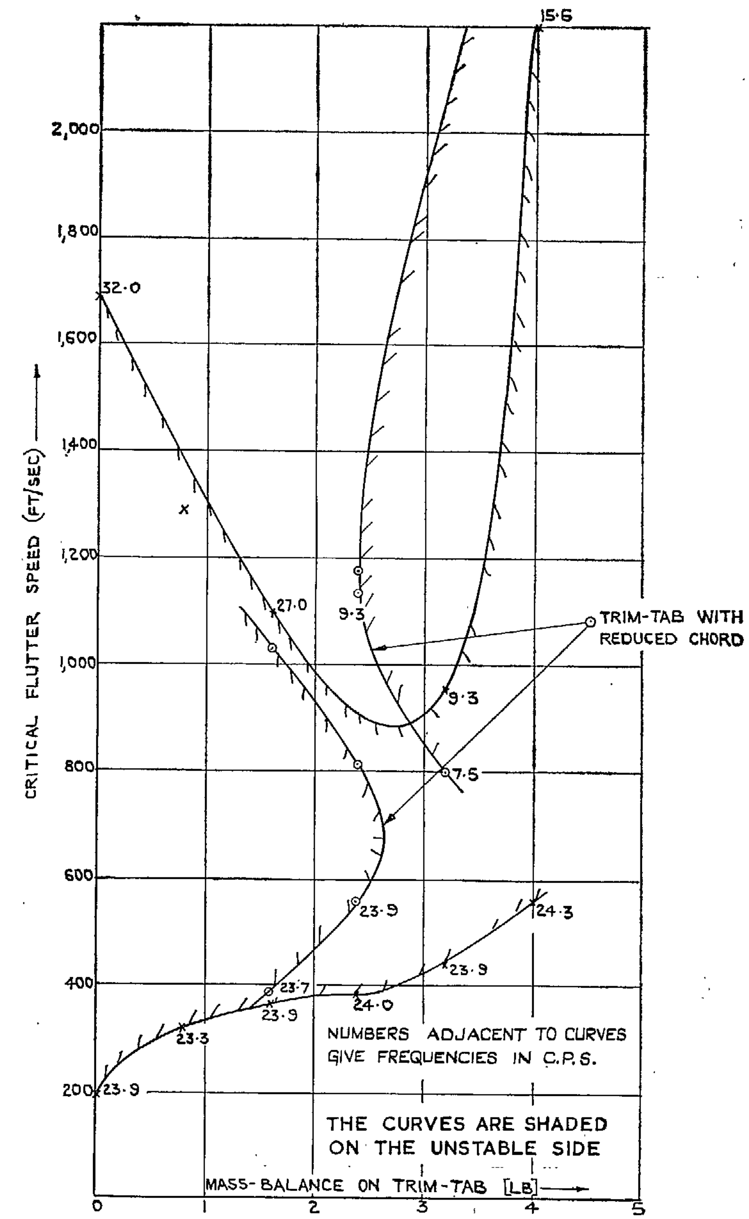

FIG. 8. Flutter speed *vs.* mass-balance on trim-tab.

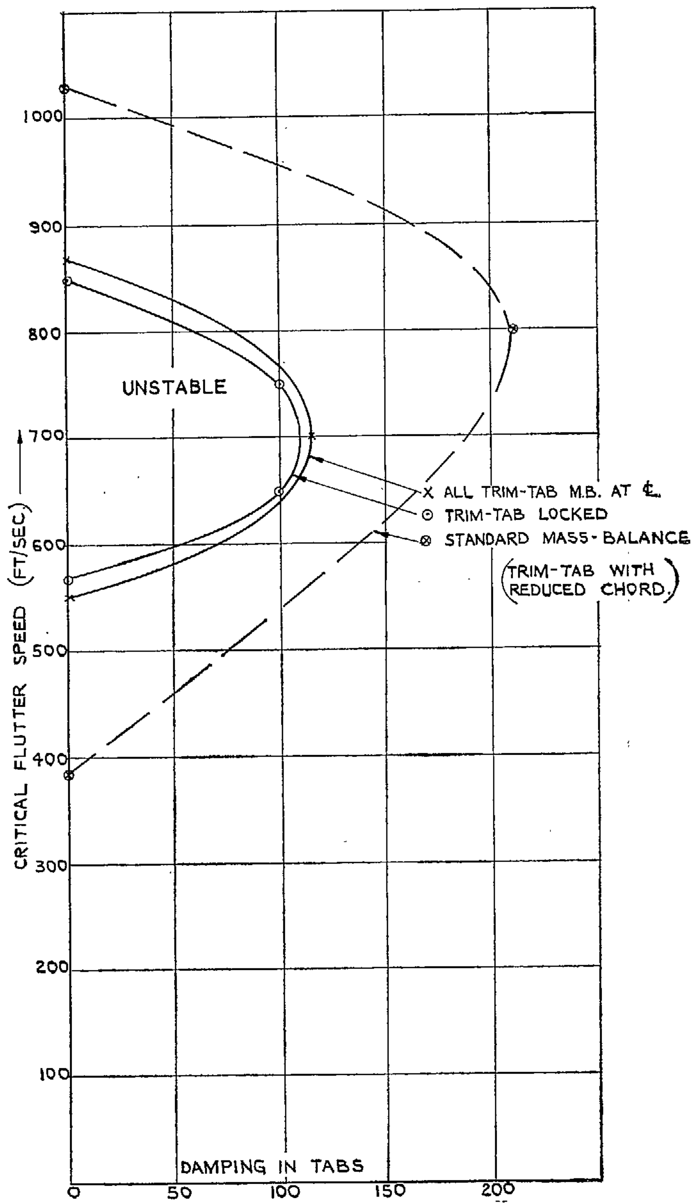

FIG. 9. Effect of placing trim-tab mass-balance on centre-line.

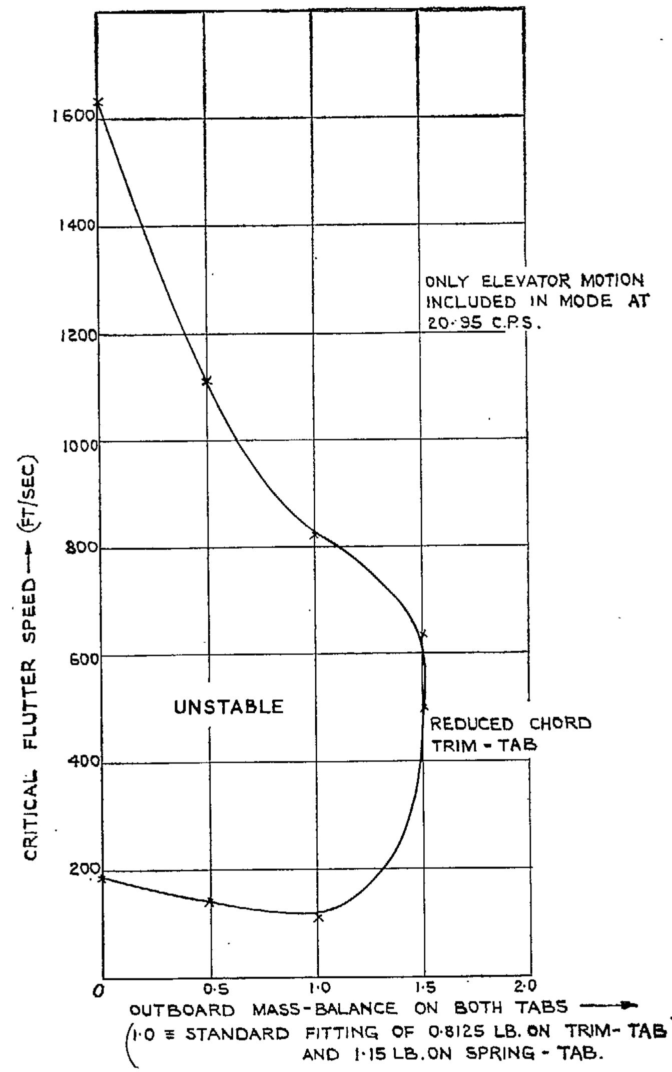

FIG. 10. Flutter speed *vs.* outboard mass-balance on both tabs. Antisymmetric case.

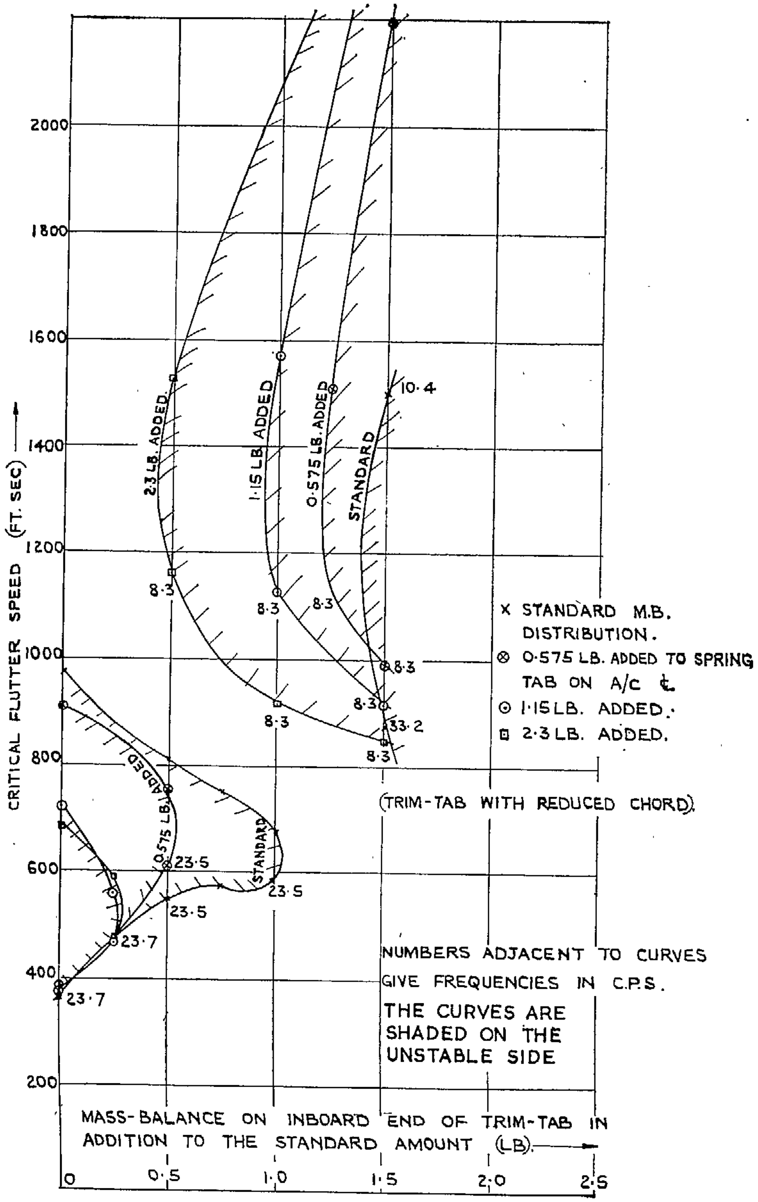

FIG. 11. Flutter speed *vs.* trim-tab mass-balance on centre-line of aircraft.

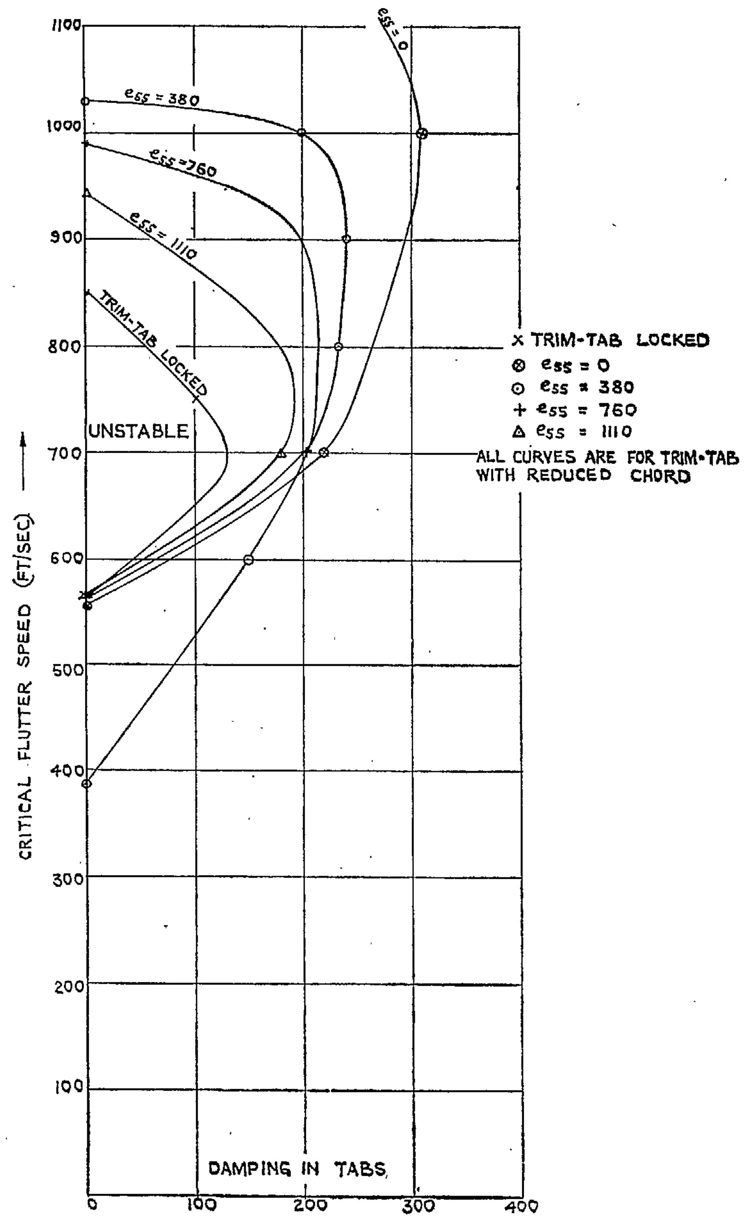

FIG. 12. Flutter speed *vs.* damping in tabs for various tab circuit stiffnesses.

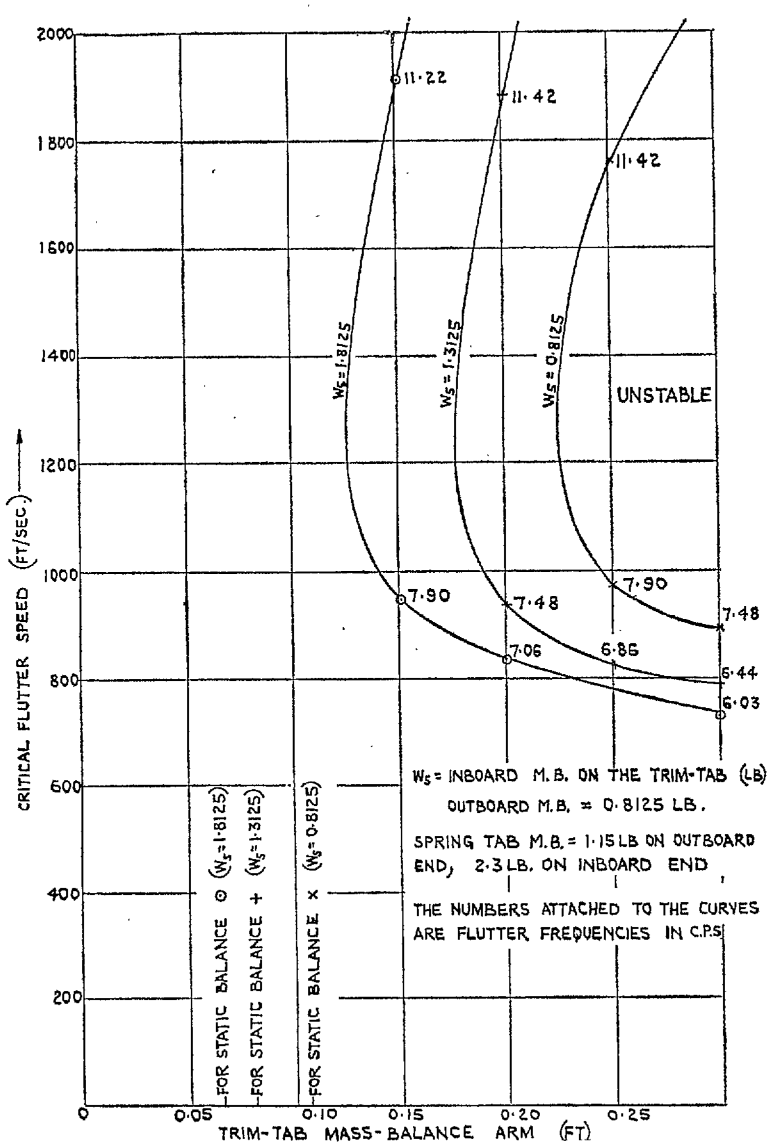

FIG. 13. Flutter speed *vs.* length of trim-tab mass-balance arm. Lighter trim-tab.

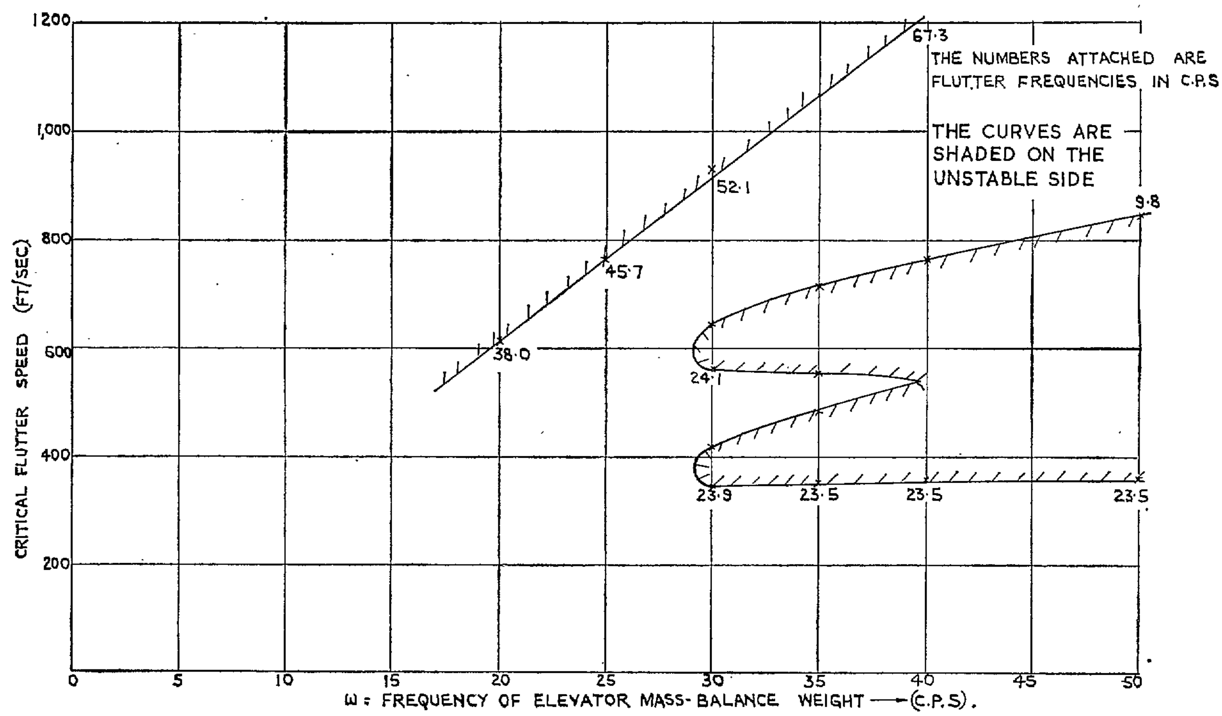

FIG. 14. Flutter speed *vs.* frequency of elevator mass-balance weight. Extended chord trim-tab.

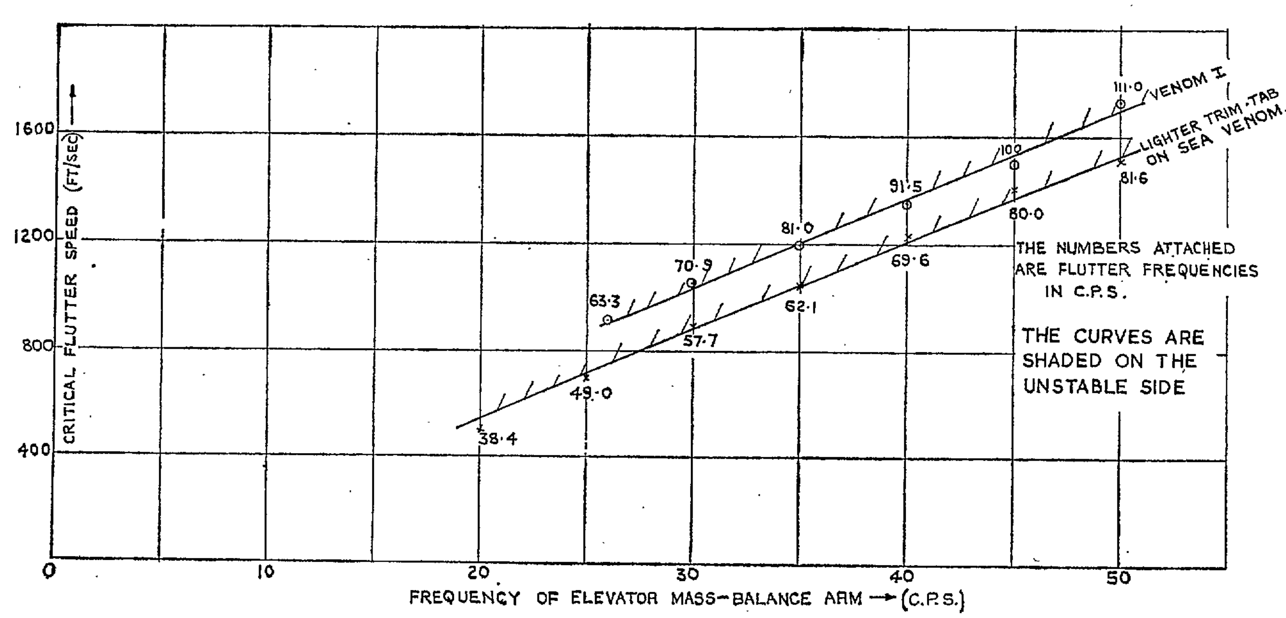

FIG. 15. Flutter speed *vs.* frequency of elevator mass-balance weight. *Venom* 1 and *Sea Venom* with lighter trim-tab.

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