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Summary.—Wind-tunnel tests to determine the flutter characteristics of a model wing, carrying a localised mass, are described. The investigation covers the effects of wing sweepback, and of the magnitude and position of the localised mass. Consideration is also given to the effects of pitching radius of gyration and aerodynamic shape. The mass values used vary from 0·13 to 1·17 times the wing mass. The test results indicate that the parameters that have the greatest effect on critical flutter speed are mass value, spanwise and chordwise position of the localised mass, and wing sweepback. Radius of gyration and aerodynamic shape of the localised mass are found to be secondary in their effects.

It was found that the flutter speed of a wing could be considerably increased or decreased by attaching a localised mass; under certain conditions the flutter speed could be more than doubled.

A number of different forms of flutter were obtained in the tests, and the values of the parameters at the transition from one form of flutter to another provide the main guide to the flutter characteristics of a wing carrying a localised mass.

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1. *Introduction.*—Experimental investigations of the flutter characteristics of model wings carrying localised masses† have been undertaken both in this country and elsewhere in the past. Generally speaking, these investigations were directed either towards establishing the behaviour of actual aircraft under particular loading conditions, or providing checks on theoretical investigations. Although these tests produced much valuable information, it was felt that there was a need for a more comprehensive experimental investigation covering a wide range of mass loadings and variation of wing sweepback. This report describes such an investigation concerned with the effect of a localised mass on the flutter of swept-back wings with fixed roots. It is intended to extend the work later to wings with symmetric body freedoms.

The tests described in this report were made on a half-span model in a low-speed wind tunnel. A new technique has been used for the application of the localised masses, enabling a much larger number of tests to be made than would have been possible with the methods of earlier experimental work. The localised-mass parameters that have been independently varied are the magnitude of the mass, its radius of gyration, and its spanwise and chordwise positions on the wing. Effect of change of aerodynamic shape has been considered, and the wing sweepback angle has also been varied.

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† The term 'localised mass' defines a mass that is localised to the extent that its moment of inertia about a longitudinal axis through its centre of gravity is small compared with its moments of inertia about lateral and vertical axes through its centre of gravity. The 'position' of the mass is defined as the position of its centre of gravity; the inertial parameters of significance in the present context are then the mass position, the mass value, and the pitching moment of inertia.

Wide variations of flutter speed occurred within the testing range, and a number of different forms of flutter were encountered. The results show generally that the flutter characteristics of a wing are likely to be modified considerably by the addition of a localised mass. They also give some indication of the types of loading that are favourable or unfavourable with respect to wing flutter.

2. *Localised-Mass Technique.*—A number of special problems arise in the flutter testing of a wind-tunnel model carrying a large localised mass. The first of these is the problem of overcoming the gravitational force acting on the localised mass. In low-speed wind-tunnel work, the stiffnesses of the model wings are so low that it is usual to mount the wing vertically in the tunnel, in order to avoid large static displacements under gravity. If a wing of low stiffness carries a heavy localised mass at an outboard section, the gravitational force on the mass may seriously overload the wing in an oscillating condition and produce structural failure. Another problem is that of producing a large number of localised masses of a standard aerodynamic shape. A comprehensive investigation can involve the testing of some hundreds of combinations of mass and position. If the masses are to be attached directly to the wing, and each mass is to have a standard fairing, the design and production becomes a major problem in itself.

A method of testing has been devised that largely overcomes the problem of gravitational forces, and which, in the present tests, involved the making of only a small number of directly applied localised masses. In its simplest form the method consists of attaching a mass, or number of masses, to the wing by two freely jointed parallel rods. Fig. 1 shows the arrangement for a wing mounted vertically in an open-jet wind tunnel. The load to be applied consists of masses clamped to a bar AA′. Two parallel rods CC′ and DD′ join the bar to the wing section BB′, and are freely jointed at C, C′, D and D′. It can be seen that any movement of the section BB′ in pitch, or normal translation, is exactly reproduced in the bar AA′ ; masses at any points P or Q on the loading platform thus exert the same inertia forces on the wing section as would be exerted by the same masses at the corresponding points P′ or Q′. It may be noted that masses on the loading platform are equivalent to the same masses at the corresponding points on the wing section only for motion in pitch and normal translation, and only if the rods are parallel. For wind-tunnel testing, the connecting rods are made sufficiently long for the loading platform to be outside the air stream, and the loading platform is suspended by long wires arranged to prevent fore and aft movement of the loading platform and to provide a low-frequency pendulum support.

In the present tests, a remote-loading rig of the type described has been used extensively. The problem of large gravitational forces on the model, associated with large localised masses, is overcome, since the only gravitational forces acting on the model are those resulting from the support of the connecting rods. Moreover, all inertia loads can be applied to a particular wing section with a constant aerodynamic interference, represented by the connecting rods. A further advantage of this method of remote loading is that it provides a safety device against flutter failure of the model, since the loading platform can be held by the operator, thus locking the wing at the loading section.

3. *Model and Test-Rig Details.*—3.1. *Model Wing.*—A root-to-tip model wing of wood and silk construction was used (Fig. 2). The model was made to the same design as that used in previous wind-tunnel flutter tests[1]. In the standard condition, the wing span (root to tip) was 36 in., and a single spar of spruce at 30 per cent chord was swept back at an angle of 23 deg. Spruce ribs, $\frac{3}{8}$ in. thick, were glued to the spar one inch apart, and were fitted with built-in lead weights to give an inertia axis for the wing at 43 per cent chord. The leading and trailing edges of the wing were stiffened with paper glued to the ribs, but a small unstiffened section was left between each rib to avoid increasing the wing torsional stiffness appreciably. The ribs were covered with silk doped with a solution of Vaseline in chloroform. Balsa-wood blocks were fitted to the wing at the root, and could be removed when larger angles of sweepback were required. Alternative angles of sweepback of 13, 33 and 43 deg were obtained by rotating the wing about the main support point, which was located $3\frac{3}{4}$ in. below the root chord. Sets of holes were drilled in the

ribs at 0·25, 0·5, 0·75 and 0·95 span, to provide two attachment points in the line of flight at each of the four sweepback angles. These holes were used for attaching the connecting rods described in Section 2. The loading section at 0·95 span is referred to as the 'tip' section throughout the report. The wing was mounted vertically in the Royal Aircraft Establishment 5-ft Open-Jet Wind Tunnel, and the wing root rigidly held. A flat plate at the wing root acted as a reflector for the half-wing model, to simulate the symmetric-flow condition.

3.2. *Remote-Loading Rig.*—The rig for applying localised masses was made as light as possible; the mass and moment of inertia of the rig represented the minimum localised mass that could be applied to the wing by remote loading. The connecting rods, which were 47 in. long, were round Duralumin tubes of $\frac{5}{8}$-in. outside diameter. The ends of the tubes attached to the wing were fitted with universal joints; the ends attached to the loading platform were fitted with ball races which restricted movement of the loading platform to the plane of the rods. Each rod together with end fittings weighed 0·6 lb. The loading platform was 27·7 in. long and weighed 0·26 lb. The connecting rods were attached to it at equal distances on each side of the midpoint. The total weight of the rig was thus 1·46 lb and the moment of inertia (in the wing pitching sense) was 18·90 lb in.^{2} for the tip attachment, and 27·06 lb in.^{2} for the 0·25, 0·5 and 0·75 span attachments. The difference is due to the connecting rods being closer together at the tip than at the other loading positions. To obtain appreciable variation of the centre-of-gravity position in the chordwise direction it was necessary to attach a sliding weight of at least 1 lb to the loading platform, bringing the total weight to 2·46 lb. The natural frequency of the rig on its supporting wires was less than 0·5 c.p.s.

3.3. *Direct-Loading Rig.*—In order to investigate the effect of localised masses of smaller mass and moment of inertia than could be obtained by remote loading, a rig was made for direct attachment to the wing. This consisted of a flat strip of metal fixed to the wing externally, forming a base plate to which additional weights could be bolted. No form of aerodynamic fairing was fitted. In each set of tests an inertia condition that could be reproduced on the remote-loading rig was tested, and it was found that the flutter speeds for the two rigs were the same.

3.4. *Aerodynamic Shapes.*—Light balsa-wood shapes, representing aircraft fuel tanks, were made for use at the 0·5 span and tip attachment points. Two shapes of tank, representing forward and aft underslung loads, were used at each spanwise position. Details of their dimensions in relation to the wing section at the attachment points may be seen in Figs. 3 and 4. The shapes were attached to the wing on the surface opposite to the connecting rods; identical inertia loads were obtained with and without aerodynamic effect by transferring the shape from the wing to the loading platform.

4. *Range of Tests.*—4.1. *Mass Loadings.*—The investigation of the effect on the wing flutter characteristics of variations of the inertia parameters of a localised mass is divided into four parts:

Part I.—Detailed variation of chordwise and spanwise position of large localised masses having a constant pitching radius of gyration.

Part II.—A limited variation of chordwise and spanwise position of small localised masses having a constant pitching radius of gyration.

Part III.—Variation of pitching radius of gyration of a large localised mass at a number of chordwise and spanwise positions.

Part IV.—Variation of mass with constant pitching moment of inertia at a number of chordwise and spanwise positions.

The details of these tests are given below:

Part I.—The three mass values chosen for the detailed chordwise and spanwise investigation were 4·46, 3·46, and 2·46 lb. These values represent 117, 91 and 64 per cent of the bare wing mass outboard of the wing root at 23 deg sweepback. The pitching radius of gyration in each case was 6·08 in. (45 per cent of the wing mean chord). Each mass was tested at each of the four spanwise sections, 0·25 span, 0·5 span, 0·75 span, and at the wing tip, and at a number of chordwise positions at each spanwise section. The limit of chordwise variation of the position of the localised mass was determined by the length of the loading platform ; for the two larger masses the range extended from 7 in. aft of the wing spar to 5 in. forward, and for the smaller mass from 5 in. aft to 3·5 in. forward. About six chordwise positions were chosen at each spanwise station. The tests were made at the four angles of wing sweepback, 13, 23, 33 and 43 deg.

Part II.—Localised masses directly attached to the model were used for the small mass values, which were 2·46, 1·23 and 0·5 lb. These represent 64, 32 and 13 per cent of the bare wing mass. The radius of gyration of each mass was 6·08 in. (45 per cent of the wing mean chord), as in Part I of the tests. The results are directly comparable, therefore, and since the 2·46-lb mass was used in each part a comparison could be made of the results obtained from the two loading systems. The chordwise and spanwise positions at which these masses were tested were restricted to those that would provide the most useful information. At each spanwise section, three chordwise positions were tested, forward of the spar, on the spar, and aft of the spar. At 23-deg sweepback (the wing standard condition) the tests were made at all four spanwise sections ; the 0·5-span section was also investigated at 13, 33 and 43-deg sweepback, and the tip section at 13 and 43-deg sweepback.

Part III.—With a localised mass of 4·46 lb (117 per cent of the bare wing mass) the radius of gyration was varied from 3·5 in. to 6·08 in. (26 to 45 per cent of the wing mean chord). These tests were made at the 0·5-span and tip sections at all four angles of sweepback. Two chordwise positions were investigated at the tip section, and one at the 0·5-span section.

Part IV.—Variation of mass was investigated for a localised mass having a constant moment of inertia of 42 lb in.^{2}. The mass was varied from 1·96 to 4·46 lb (51 to 117 per cent of the bare wing mass), the corresponding variation in radius of gyration being from 4·6 to 3·1 in. (34 to 23 per cent of wing mean chord). The chordwise, spanwise and wing-sweepback variations for these tests were the same as in Part III.

4.2. *Aerodynamic Shapes.*—The effect of aerodynamic shape was examined at the 0·5-span and tip sections only. At each section a chordwise traverse of a localised mass of 4·46 lb and 165 lb in.^{2} moment of inertia was made, with and without the shape attached to the wing. Of the two shapes available (Types I and II (Figs. 3 and 4)), Type I was used for chordwise positions aft of the spar, and Type II for chordwise positions on and forward of the spar. No attempt was made to provide a rolling moment of inertia representative of that arising in practice with an underslung fuel tank ; the actual rolling moment of inertia of the balsa models was thought to be sufficiently small to be neglected.

5. *Test Results.*—The tests involved in Parts I and II of the mass-loading investigation (see Section 4.1) constitute the great majority of all the tests made. It is convenient to present the results of these particular tests under the headings of mass loading at each of the four spanwise sections considered (Sections 5.1 to 5.4 below). Parts III and IV of the mass-loading investigation and the investigation of aerodynamic-shape effect (Section 4.2) are then described under further separate headings (Sections 5.5 to 5.7 below).

5.1. *Localised Masses at the Tip.*—The effect of varying the localised mass position chordwise is shown in Figs. 5 to 8, for masses of 4·46, 3·46, and 2·46 lb and for wing sweepback angles of 13, 23, 33 and 43 deg. Two types of flutter occur for each mass-sweepback condition. The flutter associated with aft positions of the localised mass involves flexure and torsion of the wing in the fundamental modes, and considerable movement of the localised mass occurs. It will be convenient to refer to this flutter as type A flutter. The flutter that occurs with forward positions of the localised mass is characterised by flexural overtone and torsional overtone modes of the wing, with very little movement of the mass. This type of flutter will be referred to as type B flutter. For a mass well aft of the wing spar the flutter is of type A, and the flutter speed and frequency are below those of the bare wing. The flutter speed falls as the localised mass is moved forward, but after reaching a minimum at a chordwise position slightly aft of the spar, the flutter speed rises rapidly until at a critical value of chordwise position the flutter abruptly changes to type B flutter. The flutter speed at this transition is above that of the bare wing, and the frequency of type B flutter is considerably higher than the bare wing flutter frequency. Type B flutter occurs for all chordwise positions of the localised mass forward of the transition position, and the critical flutter speed and frequency remain approximately constant.

The curves of Figs. 5 to 8 are all of similar shape, but there are some differences of detail. The effect of increasing sweepback is to raise the flutter speeds for both type A and type B flutter. The frequency of type B flutter also increases with increasing sweepback. The effect of sweepback on the chordwise position of the transition points is to move the points forward as the sweepback is increased.

The tests with masses of 1·23 and 0·5 lb at the wing tip may be considered in conjunction with the tests with larger masses, and curves of flutter-speed variation with mass at constant radius of gyration for wing sweepback angles of 13, 23 and 43 deg are shown in Fig. 21. At each sweepback angle the effect of mass variation is shown for chordwise positions 3 in. forward and aft of the spar, and on the spar. As an example, at 23-deg sweepback, with the localised mass on the spar, the flutter at low mass values is of type A. As the mass is increased the flutter speed falls initially, reaches a minimum when the mass is just over 1 lb, then rises until a critical mass is reached at which transition to type B flutter occurs. The flutter speed then remains constant for masses greater than the mass at transition. When the localised mass is forward of the spar, the transition occurs at a lower mass value, and when the localised mass is aft of the spar the transition (if it occurs at all) is at a mass value outside the range of the present tests. At 13-deg and 43-deg sweepback the effect of mass is similar to its effect of 23-deg sweepback, but the transitions occur at different values of the mass ; the greater the angle of sweepback, the larger the mass value at the transition for a given chordwise position of localised mass.

5.2. *Localised Masses at* 0·75 *Span*.—The variation of flutter speed with chordwise position of masses of 4·46, 3·46 and 2·46 lb (Figs. 9 to 12) is similar for all the mass and sweepback combinations. The flutter obtained over the range tested is entirely type A flutter, and the flutter-speed curves resemble those obtained in the corresponding region with localised masses at the tip. Minimum flutter speeds occur when the mass is near the spar ; the flutter speed rises gradually when the mass is moved aft, but rises very rapidly when the mass is moved forward. It is probable that transition to an overtone type of flutter still occurs, but at speeds that are above the limiting working speed (about 220 ft/sec), which was determined by the danger of skin ballooning on the wing. In one or two cases in which the speed was taken fairly high, there were definite indications of an approach to an overtone type of flutter.

Increase of sweepback results in an increase of flutter speed for the same position of localised mass, but the increase is approximately in proportion to the increase of bare wing flutter speed with sweepback. The results shown in Figs. 9 to 12 indicate that the chordwise position at which the sharp increase in flutter speed occurs, moves forward as the angle of sweepback is increased, and also as the mass value is reduced. These variations follow the same trends as the variations in transition point for a localised mass at the tip (Section 5.1).

The flutter frequencies are slightly higher than those obtained with the same masses at the tip. The frequency rises as the mass approaches the spar, and falls as the mass is increased.

The variation of flutter speed with mass is shown in Fig. 23. The curves were obtained for one angle of sweepback (23 deg) and three chordwise positions of the localised mass (3·5 in. forward and aft of the spar, and on the spar). For all three chordwise positions the flutter speeds fall initially as the mass is increased from zero. The speeds remain below the bare wing speed, and are practically constant for the two aft chordwise positions when the mass is further increased, but for the forward chordwise position, further increase of mass results in a sharp rise of flutter speed.

5.3. *Localised Masses at* 0·5 *Span.*—The characteristic curves of flutter speed and frequency variation with chordwise position for mass values of 4·46, 3·46 and 2·46 lb are shown in Figs. 13 to 16. The same general trends occur as with the masses at the tip and at 0·75 span. If the mass is aft of the spar, type A flutter is obtained, with a minimum critical speed when the mass is near the spar. The flutter speed then rises rapidly when the localised mass is moved forward until transition to an overtone type of flutter again occurs. The type of overtone flutter is, however, different from that occurring with a mass at the tip ; it is characterised by only slight movement of the mass and of the wing inboard of it, the main motion being in the wing outboard of the mass. Its general appearance is, in fact, similar to a fundamental type of flutter of the outer part of the wing. For convenience, this flutter is referred to as type C flutter. It is similar to type B flutter, of course, in that the mass is more or less stationary, and the difference in the mode arises from the difference in spanwise position of the mass. The frequency is again higher than that of the bare wing flutter.

For this type C flutter the flutter speed and frequency vary with sweepback in the same way as for the bare wing, but the rate of variation of flutter speed is rather greater. The tests made to investigate the effect of mass and its chordwise position on the type C flutter were not extensive but in Fig. 13 it will be seen that the flutter speed appears to be unaffected by chordwise position of the mass and rises slightly as the mass is reduced. At the other sweepback angles, type C flutter was obtained for only one mass value, for which, however, no change in flutter speed was found when the chordwise position was varied.

With 23-deg sweepback of the wing, and a localised mass of 4·46 lb, a detailed investigation of type A flutter speed close to the transition was made (Fig. 14). It was found that when the chordwise position of the mass was 1·0 in. forward of the spar an upper and a lower flutter speed could be obtained. Although this was the only case where two flutter speeds were measured, it indicates that the flutter-speed curve for type A flutter may be of a loop form. However, the rate of increase of flutter speed near the transition is generally so rapid that for practical purposes the flutter-speed curve may be assumed to rise vertically in this region.

Increase of wing sweepback and decrease of mass result in the chordwise position of the mass at transition moving in a forward direction ; the effect is thus similar to that obtained with localised masses at the tip and 0·75-span sections.

Fig. 22 shows the variation of flutter speed with mass for three chordwise positions at each sweepback angle of the wing. In all the diagrams the flutter speeds fall as the mass is increased from zero, and only rise again for the chordwise positions 3·5 in. forward of the spar. With the localised mass on, and 3·5 in. aft, of the spar, the flutter speeds fall gradually as mass is increased. With the mass in the forward position, transition to type C flutter is obtained at mass values dependent on the sweepback.

5.4. *Localised Masses at* 0·25 *Span.*—With masses 4·46, 3·46 and 2·46 lb (Figs. 17 to 20) the flutter is of type A except for the largest mass at 13, 23 and 33-deg sweepback, when type C flutter is obtained with the mass well forward of the spar. The absence of type C flutter at mass values below 4·46 lb, and at 43-deg sweepback with all mass values tested, indicates that the effect of mass and sweepback on the transition is similar to the effect with localised masses at the outboard sections.

The flutter speeds for type A flutter are below the bare wing flutter speed when the localised mass is aft of the spar, except for the largest mass at 43-deg sweepback of the wing : in this case the flutter speed is slightly higher than that of the bare wing when the localised mass is well aft. The variation of flutter speed with chordwise position of the mass seems to differ somewhat from the curves obtained for masses at the outboard stations. The range of flutter speed is not great, and the occurrence of a minimum value, which is characteristic of the flutter curves for localised masses at the outboard sections, is not evident in Figs. 17 to 20. The frequency curves of Figs. 17 to 20 indicate a slight increase of frequency for mass positions close to the spar.

The variation of flutter speed with mass at 23-deg sweepback is shown in Fig. 23. Here the transition occurs at a mass value greater than the maximum tested and apart from an increase of flutter speed as the transition is approached, the speeds are close to that of the bare wing for the other chordwise positions and mass values.

5.5. *Variation of Radius of Gyration with Constant Mass.*—Figs. 24 and 25 show the effect of varying radius of gyration with a constant mass (4·46 lb) at two chordwise positions at the tip section, and at one chordwise position at the 0·5-span section. With the mass at either of the two positions aft of the spar, the flutter is, throughout, type A flutter ; with the mass forward of the spar (tip section only) the flutter is, throughout, type B flutter. Increase of radius of gyration produces a decrease of type A flutter speed, but little change of frequency. Variation of radius of gyration has very little effect on the type B flutter.

5.6. *Variation of Mass with Constant Moment of Inertia.*—The test results for independent variation of mass with constant moment of inertia, are given in Figs. 26 and 27. At 0·5 span an increase in mass produces a roughly linear increase in the type A flutter speed, and a linear decrease in frequency, the variation in both speed and frequency being comparatively small. At the tip, a similar effect occurs with the type A flutter (mass aft of the spar), but variation of mass has almost no effect on the type B flutter (mass forward of the spar).

5.7. *Aerodynamic Shapes.*—The results of the aerodynamic-shape tests are shown in Figs. 5 to 8 and 13 to 16. The tests were made with a localised mass of 4·46 lb and radius of gyration 6·08 in. The underslung shape (type I) was fitted to the wing for localised mass positions aft of the spar, and the forward underslung shape (type II) for positions on and forward of the spar.

The flutter speeds and frequencies are shown in comparison with the corresponding values obtained without the shape. These tests were made only at the 0·5-span and tip sections. In general, the aerodynamic effect is small and somewhat inconsistent ; there is a greater change in flutter speed than in frequency in all cases. At the tip sections, the aerodynamic effect is to change the chordwise position of the transition but the effect is small at all sweepback angles. The tests at 0·5 span did not give sufficiently consistent results to enable any generalisation to be made.

6. *Discussion.*—The results of the tests described in this report form a general guide to the flutter characteristics of wings carrying localised masses. They may be of help in deciding upon the most favourable size and position of expendable store on particular aircraft, and also in the special cases of expendable stores (such as fuel tanks) that may vary in mass during flight. In this discussion, therefore, the ways in which the test results may be applied to full-scale flutter problems are examined, with particular attention to the limitations that must be imposed upon such application.

6.1. *The Overtone Forms of Flutter.*—Two forms of overtone flutter have been obtained with forward chordwise positions of a localised mass. Type B flutter, associated with a localised mass near the wing tip, is characterised by a nodal line at the localised mass section while the greatest amplitudes of oscillation occur at the mid-span sections in both flexure and torsion. With type C flutter, the localised mass is only slightly displaced and the flutter may be described as fundamental type flutter of the wing outboard of the mass, the sections inboard having relatively small amplitudes.

Fig. 30 shows the flutter speeds of the overtone types of flutter for the four sweepback angles. These speeds are independent of the localised mass value and of its chordwise position, but are dependent on its spanwise position (*see* Section 5). It will be recollected (*see* Section 5.2) that with a localised mass at 0·75 span no overtone flutter was obtained over the range tested. This range included a speed of 210 ft/sec at 13-deg sweepback, and this fact has been used in drawing the curves of Fig. 30. It is very likely, of course, that with a mass at 0·75 span the overtone flutter would be neither type B nor type C, since there is a change from the one to the other in taking a mass from the tip to the 0·5-span section ; it would in fact probably involve motion of the wing both inboard and outboard of the relatively stationary mass.

An attempt has been to estimate the type C flutter speeds, on the basis that this flutter is primarily fundamental flutter of the wing outboard of the mass, by applying an approximate formula for flutter speed[2, 3, 4] to this portion of the wing, assumed rigidly fixed at the mass. Estimated values for 23-deg sweepback, shown in Fig. 30, are consistently lower than the measured values, the difference varying from 3 per cent with the mass at the root to 7 per cent with the mass at 0·5 span. As the mass is taken further outboard the difference between these estimated values and the actual values probably becomes much greater, consistant with the view that over this region the overtone flutter changes from the type C flutter. It may be concluded, however, that with a mass within the inboard half of the wing a reasonable (and conservative) estimate of the overtone flutter speed can be obtained on the above basis.

Flutter speeds for type B flutter (mass at the tip) cannot be estimated so easily, since the flutter mode is not of a form to which any existing formula could be applied. However, since the flutter mode in this case appears to be compounded primarily of the fundamental bending and torsion modes of the wing when rigidly held at root and tip, a simple two-degrees-of-freedom calculation using these modes might be expected to give a reasonable approximation to the measured results.

A point of particular significance from these tests is that there appears to be a spanwise position of localised mass at which a peak value of overtone flutter speed is obtained. For the present model wing this optimum position appears to be at about 0·75 span, and the corresponding overtone flutter speed is at least two and a half times the bare wing flutter speed. This optimum position will almost certainly depend on the flexural/torsional stiffness ratio for the wing, but for most practical designs it seems probable that the optimum position will be in this region. This characteristic may be of paramount importance in the design of very thin wings, where the avoidance of wing flutter may be the critical factor in the design. It may, in fact, be more economical to install a localised mass at the optimum position rather than to achieve the overall wing stiffness required to give a satisfactory bare wing flutter speed.

6.2. *The Boundaries between Fundamental and Overtone Flutter.*—Examination of the test results shows that the chordwise position of the mass at which transition from fundamental to overtone flutter occurs varies with the mass value (at constant radius of gyration), spanwise position of the mass, and wing sweepback. Over the range tested, the transition appears to be relatively unaffected by independent variations of mass and pitching moment of inertia of the mass (*see* Section 6.4). The locus of the transition point is shown in Figs. 28 and 29, directly in terms of mass value and chordwise position, for masses up to 117 per cent of the wing mass. The curves have been drawn for all combinations of spanwise position of the localised mass and wing sweepback in order to present as full a picture as possible, although this has resulted in considerable extrapolation for the localised masses at 0·25 span. The chordwise positions at transition were obtained by extrapolation of the flutter speed curves of Figs. 5 to 23 where the actual transition had not been obtained.

The shape of all the curves of Figs. 28 and 29 is similar, but the transition point for a given mass value varies considerably with spanwise position, and to a lesser extent with wing sweepback. Let us consider in detail the transition curve for a localised mass at the tip when the wing sweepback is 23-deg. If the mass is equal to the wing mass, the transition occurs at a chordwise position of the mass just aft of the spar by an amount which is 0·02 times the wing mean chord ; if the mass is placed forward of this position overtone flutter will occur, and if it is placed aft of it, fundamental (type A) flutter will occur. If the mass is reduced to 0·8 of the wing mass, the transition point occurs on the spar. As the mass is further reduced so the transition point moves forward. The limiting case is when the mass is zero, and in this condition the flutter must be of the fundamental type for all chordwise positions. The curve must therefore tend to an infinite value of forward chordwise position as the mass tends to zero. This curve shape is characteristic of the curves obtained in the other conditions of wing sweepback and mass spanwise positions. Increase of sweepback results in a forward movement of the position of the transition point. Inboard movement of the localised mass also moves the transition point forward, and this shift increases rapidly when the inboard spanwise sections are reached.

The significance of the transition curves of Figs. 28 and 29 may be stated as follows. The transition curve represents not only a change from one form of flutter to another, but also a dividing line between critical flutter speeds on one side (the fundamental flutter region) that are in general lower than the bare wing flutter speed, and on the other side (the overtone flutter region) that are higher than the bare wing flutter speed. Although it is possible to obtain flutter speeds in the fundamental flutter region above that of the bare wing, this generalisation is convenient and fairly realistic.

In the design of aircraft wings it is desirable that any localised mass should increase rather than decrease the wing flutter speed, and this can be achieved if the configuration is located within the overtone flutter region. Some qualitative requirements for this condition are of interest, as follows :

(*a*) A larger mass is required at inboard sections than at outboard sections

(*b*) A more forward position of the mass is required with large sweepback than with small sweepback

(*c*) A more forward position of the mass is required at inboard sections than at outboard sections.

The first two of these requirements are in keeping with structural and aerodynamic requirements for the aircraft. From the structural viewpoint it is easier, generally speaking, to carry large masses inboard than outboard ; from the aerodynamic stability viewpoint, localised masses are generally mounted further forward on highly swept-back wings than on slightly swept-back wings.

The third requirement may, however, conflict with aerodynamic stability requirements, and it may be that at inboard sections the position and localised mass value required to ensure overtone flutter are outside practical limits.

6.3. *The Positional Effect of a constant Localised Mass.*—Although the values of flutter speed of the model are of secondary importance in comparison with the flutter boundaries discussed in Section 6.2, it is interesting to examine the order of flutter speed obtained when a given mass is placed at any position on the wing. In Fig. 31 contour lines are shown for a localised mass equal to 117 per cent of the wing mass, and having a radius of gyration 45 per cent of the wing mean chord, the wing sweepback being 23-deg. The contours are lines of constant flutter speed and are spaced at intervals of 10 per cent of the bare wing speed. The shaded parts of the diagram show the area in which the localised mass may be placed to give a flutter speed in excess of the bare wing speed. The diagram indicates clearly the areas of the wing that give the highest and lowest flutter speeds for this particular mass. The former are the areas in which the overtone forms of flutter may occur ; the lowest flutter speeds occur when the localised mass is just aft of the spar and between 0·25 and 0·75 span. In this area the critical speeds may be as low as 60 per cent of the bare wing speed.

6.4. *Independent Variations of Radius of Gyration and Mass.*—The effect of varying radius of gyration with a constant mass has been described in Section 5.5 and is shown in Figs. 24 and 25. In none of the test conditions have very large changes in flutter speed occurred, nor have transitions from one form of flutter to another taken place. These facts indicate that radius of gyration does not have a great effect on the position of the transition point. What effect there may be is certainly of minor importance compared with the effect of mass with a constant radius of gyration. Variation of radius of gyration, with constant mass, is one that is unlikely to occur in practice.

The variation of mass with constant moment of inertia (Section 5.6 ; Figs. 26 and 27) is also unlikely to occur in practice since it involves simultaneous variation of both mass and radius of gyration. The investigation was included in the present tests for the sake of completeness ; the effect on flutter speed is rather less than the effect produced by variation of radius of gyration alone, but it is impossible to draw any definite conclusion from the results because of the simultaneous variation of the mass and radius-of-gyration parameters.

6.5. *The Flutter Problems of Expendable Stores.*—In assessing the flutter characteristics of wings carrying expendable stores it may be necessary to consider more than one inertia-loading condition. This will be necessary in the case of fuel tanks that are emptied progressively, and in which the reduction of mass may be accompanied by a change in the centre-of-gravity position of the load. The present tests indicate that at nearly all positions of a localised mass on a wing, there is some mass value for which the flutter speed is lower than the flutter speed of the bare wing. In general, for the wing tested, minimum flutter speeds were associated with localised masses between 0·2 and 0·5 of the wing mass. Moreover, the area of the wing in which localised masses may be attached so that the flutter speed obtained is above that of the bare wing, is rapidly reduced as the mass is reduced. Whilst there is no simple way of determining the localised-mass condition giving the lowest flutter speed, it should be borne in mind that this speed may be as low as 0·5 of the bare wing flutter speed.

6.6. *The Effect of Aerodynamic Shape.*—The small effects on flutter speed of the addition of comparatively large shapes to the wing are unexpected. In steady-flow aerodynamics the addition of quite small shapes to the wing tip can produce large changes in aerodynamic characteristics. The fact that similar changes have not occurred during the present tests cannot be taken as sufficient evidence for a general assumption that flutter speeds are little affected by external wing shapes. Some American work, in fact, shows that considerable changes in flutter speed may occur. The attachment of large bomb cocoons of unorthodox shape to wings is a development that may require investigation from the flutter viewpoint.

6.7. *The Method of Test.*—The method of remotely applying localised masses to a wing, which has been extensively used in the present tests, has produced only minor difficulties of technique. The greatest restriction imposed by the method is that the inertia of the rig itself limits the minimum inertial condition of localised mass. Efforts to reduce the structure weight by using lighter connecting rods were found to be impossible, since the light rods themselves oscillated at moderate tunnel speeds. It was thought that the flow pattern over the wing might be improved by fairing the connecting rods, but in practice the rods were found to be subject to considerable lift forces if faired, and under fluttering conditions the rig was difficult to control. The advantages of the rig, however, were firstly the ease with which a mass and moment-of-inertia condition could be obtained, secondly, the speed at which localised-mass conditions could be varied (thus indirectly increasing the accuracy with which a particular investigation could be made), and thirdly the reduction of the risk of wing damage or failure from excessive oscillation, since the loading platform could be readily held to prevent oscillation.

6.8. *General.*—In assessing the value of the present tests the limitations of the work should be borne in mind. The main limitation is that all the tests have been made on one wing, and that changes in flutter characteristics that may occur as a result of variations in the wing parameters have not been investigated. Although the model is representative of current design in plan-form, stiffness and inertia distribution, the test results could not be said to apply in detail to the behaviour of any other wing under localised-mass loading. Undoubtedly, however, the results form a general guide to the behaviour of wings of current design, and indicate the trends that occur with certain important variations in the localised-mass parameters. It is also thought that any future investigation into the effects of wing parameter variations could be concentrated upon the localised-mass parameters that in the present series of tests are shown to be of major importance.

7. *Conclusions.*—(1) The effect of a localised mass on the flutter characteristics of a wing with fixed root has been found to be mainly dependent on four parameters : (i) spanwise position of the mass, (ii) chordwise position of the mass, (iii) mass value (with constant pitching radius of gyration) and (iv) angle of sweepback of the wing.

(2) Three types of flutter have been encountered as a result of varying the above parameters. These are :

(i) Flutter involving mainly the fundamental modes of the wing-mass combination (Type A).

(ii) An overtone type of flutter, which occurs only with the mass at the wing tip, involving very little movement of the tip, with flexural and torsional displacements of the wing between root and tip (Type B).

(iii) An overtone type of flutter, which occurs with the mass at an inboard section, involving mainly the fundamental modes of the wing outboard of the mass, with very little movement of the wing at, and inboard of, the mass (Type C).

(3) For all chordwise positions of the mass well aft of the spar type A flutter occurs, and the flutter speeds are generally below that of the bare wing. If the mass is moved forward, the flutter changes abruptly to one of the overtone forms. The overtone flutter speeds are above that of the bare wing.

(4) The chordwise position of the mass at which transition from type A flutter to overtone flutter takes place moves forward with decrease of mass, increase of wing sweepback, or movement of the mass inboard.

(5) A conservative estimate of the type C flutter speeds may be obtained by assuming the wing fixed at and inboard of the mass and applying the formula of Molyneux[2, 3, 4] to the portion of the wing outboard of the mass.

(6) The highest flutter speeds occur with a mass at three-quarters span and well forward, and the lowest with a mass at between half and three-quarters span and slightly aft of the wing spar. These speeds may be 2·5 and 0·5 times the bare wing flutter speed respectively. The highest flutter speed is achieved with a mass of about 0·3 or more of the bare wing mass.

(7) For almost every position of a localised mass on a wing there is some mass value for which the flutter speed is lower than the flutter speed of the bare wing. In the present tests this value was generally between 0·2 and 0·5 of the wing mass.

(8) The aerodynamic effect of the fuel-tank shapes tested is small and indeterminate.

Acknowledgements.—The author acknowledges the assistance given throughout the tests by Mrs. E. B. Broadbent and Mr. K. G. Fonteneau.

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No.	*Author*	*Title, etc.*
1	D. R. Gaukroger	Wind-tunnel tests on symmetric flutter of swept-back wings, including the tailplane effect. R. & M. 2911. April, 1952.
2	W. G. Molyneux	The flutter of swept and unswept wings with fixed root conditions. R. & M. 2796. January, 1950.
3	W. G. Molyneux, F. Ruddlesden and P. J. Cutt.	Technique for flutter tests using ground launched rockets, with results for unswept wings. R. & M. 2944. November, 1951.
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TABLE 1

Inertia Conditions of Localised Masses

Parameter variation	Mass (lb)	M.I. (lb in.^{2})	$\frac{\text{Mass}}{\text{Wing mass}}$	$\frac{k}{\text{Wing mean chord}}$
Mass with constant radius of gyration . .	4·46	165	1·17	0·45
	3·46	128	0·91	0·45
	2·46	91	0·64	0·45
	1·23	45·5	0·32	0·45
	0·5	18·5	0·13	0·45
Radius of gyration with constant mass . .	4·46	30 to 165	1·17	0·10 to 0·45
Mass with constant moment of inertia . .	1·96 to 4·96	42	0·51 to 1·30	0·34 to 0·21

Wing Details

Weight of wing outboard of wing root at 23-deg sweepback = 3·81 lb

Weight of wing including wing root block at 23 deg = 5·02 lb

Frequency of first normal mode (fundamental flexure) = 3·9 c.p.s.

Frequency of second normal mode (overtone flexure) = 11·4 c.p.s.

Frequency of third normal mode (fundamental torsion) = 15·3 c.p.s.

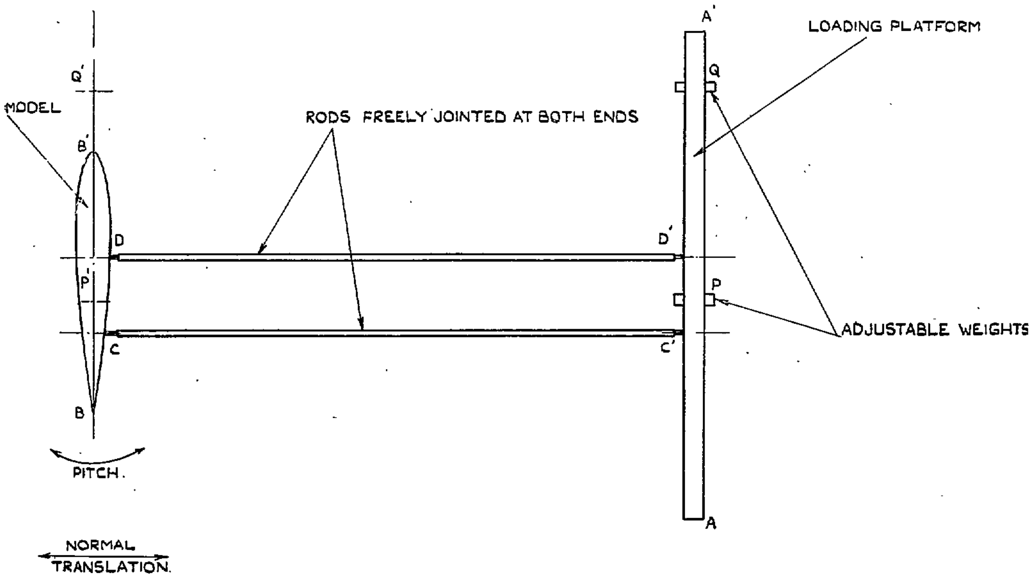


Fig. 1. Method of applying inertia loads.

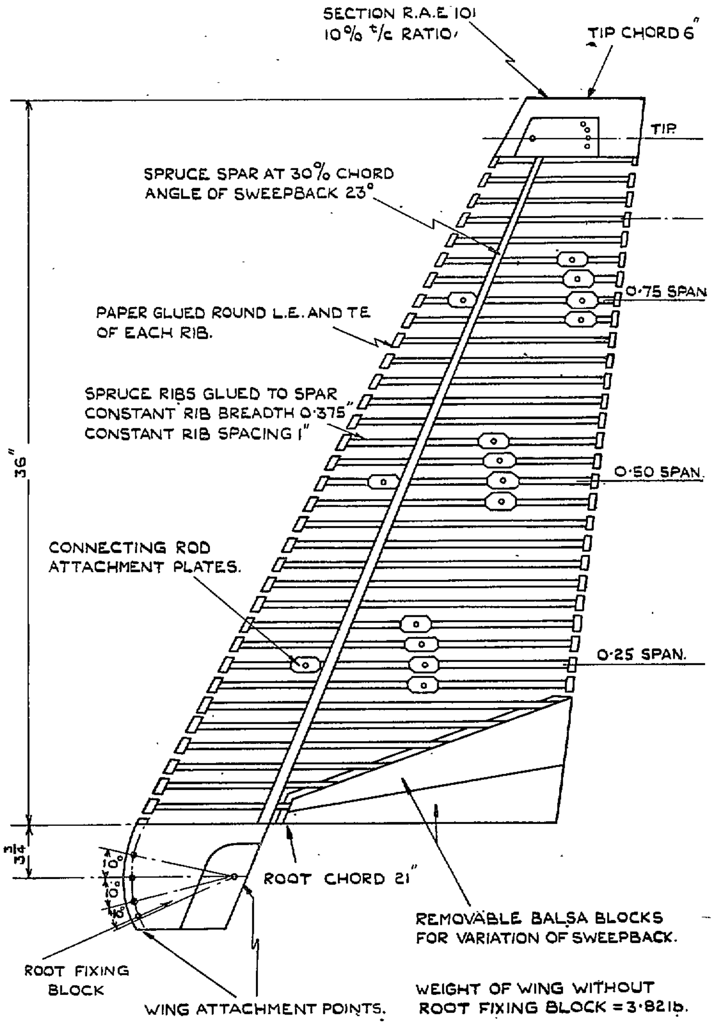
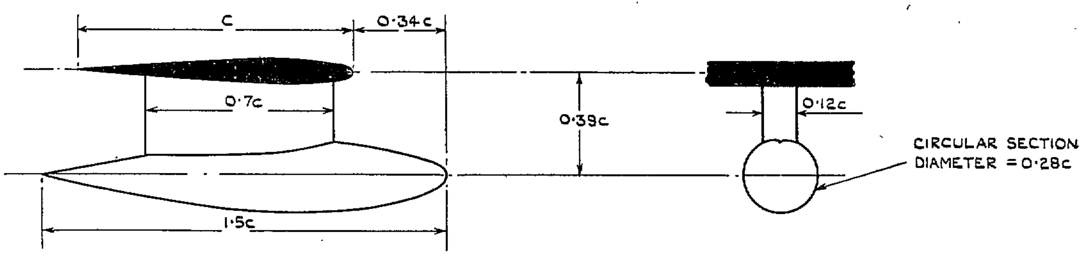
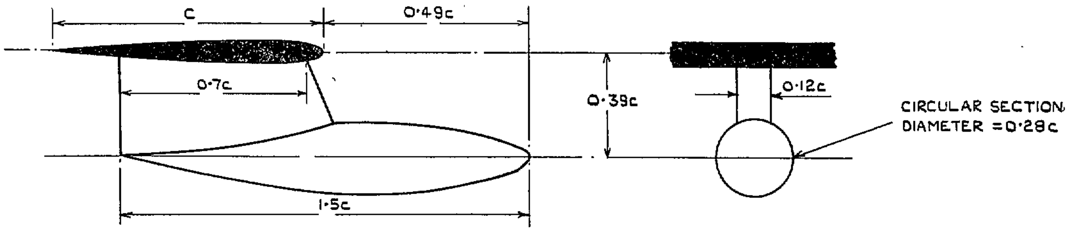


Fig. 2. Model-wing details.

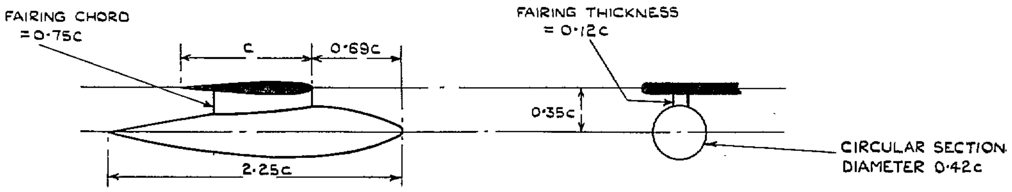


UNDERSLUNG POSITION — TYPE A.

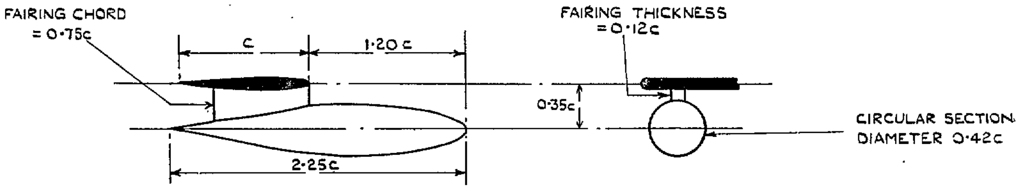


FORWARD UNDERSLUNG POSITION — TYPE B

FIG. 3. Aerodynamic shapes at half-span section.



UNDERSLUNG POSITION — TYPE A.



FORWARD UNDERSLUNG POSITION — TYPE B.

FIG. 4. Aerodynamic shapes at tip section.

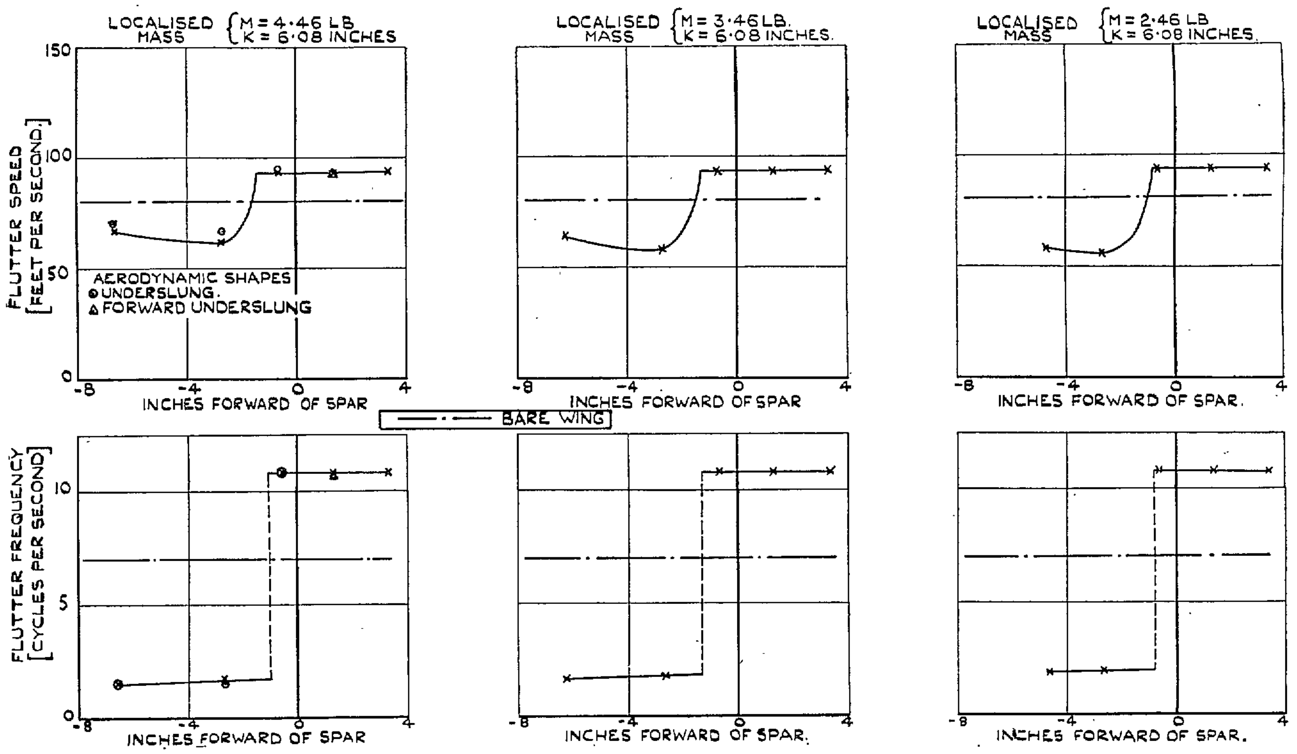


Fig. 5. The effect of chordwise position of a localised mass at the tip (13-deg sweepback).

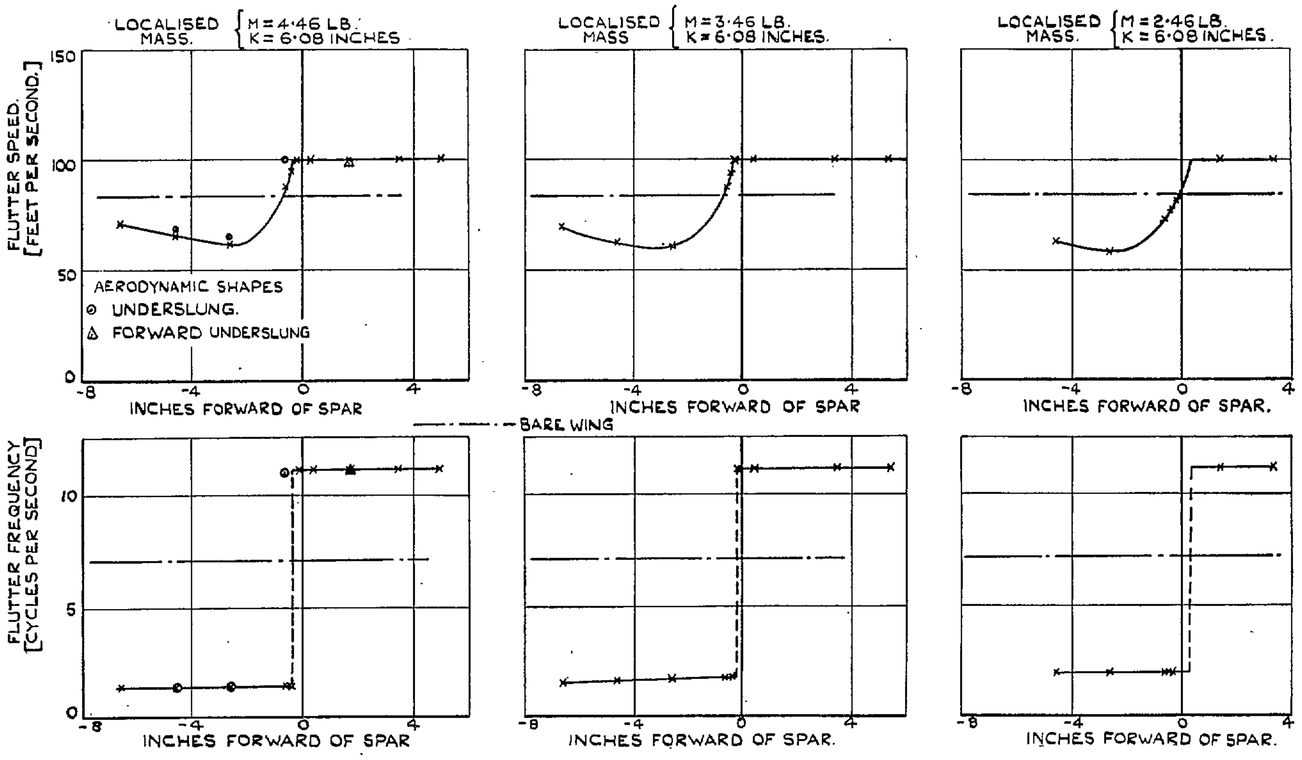


Fig. 6. The effect of chordwise position of a localised mass at the tip (23-deg sweepback).

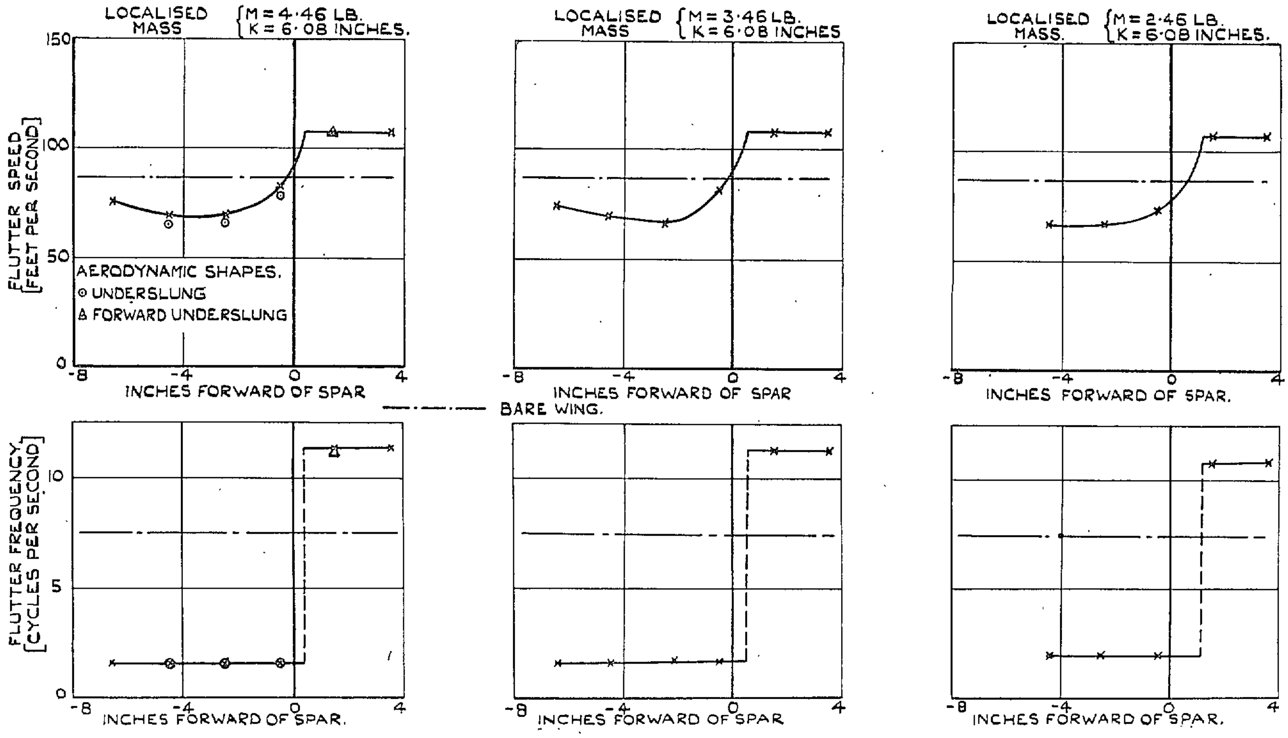


FIG. 7. The effect of chordwise position of a localised mass at the tip (33-deg sweepback).

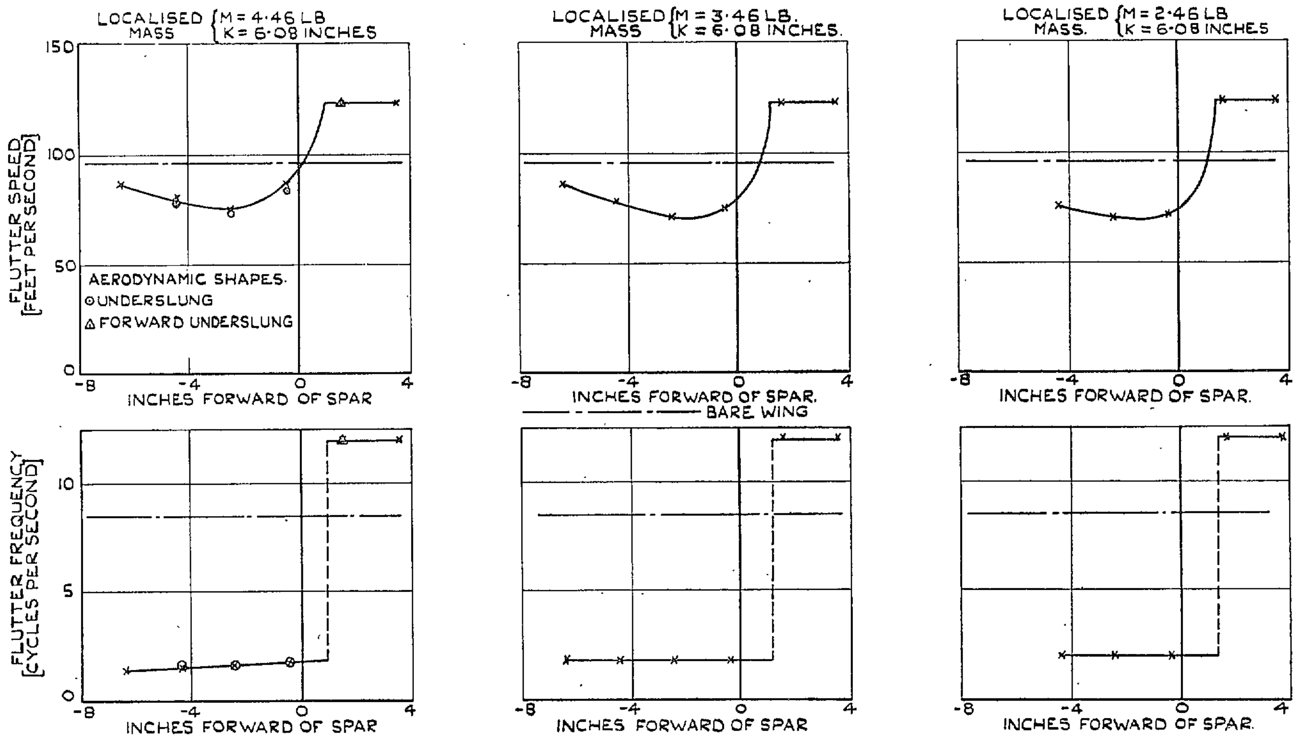


FIG. 8. The effect of chordwise position of a localised mass at the tip (43-deg sweepback).

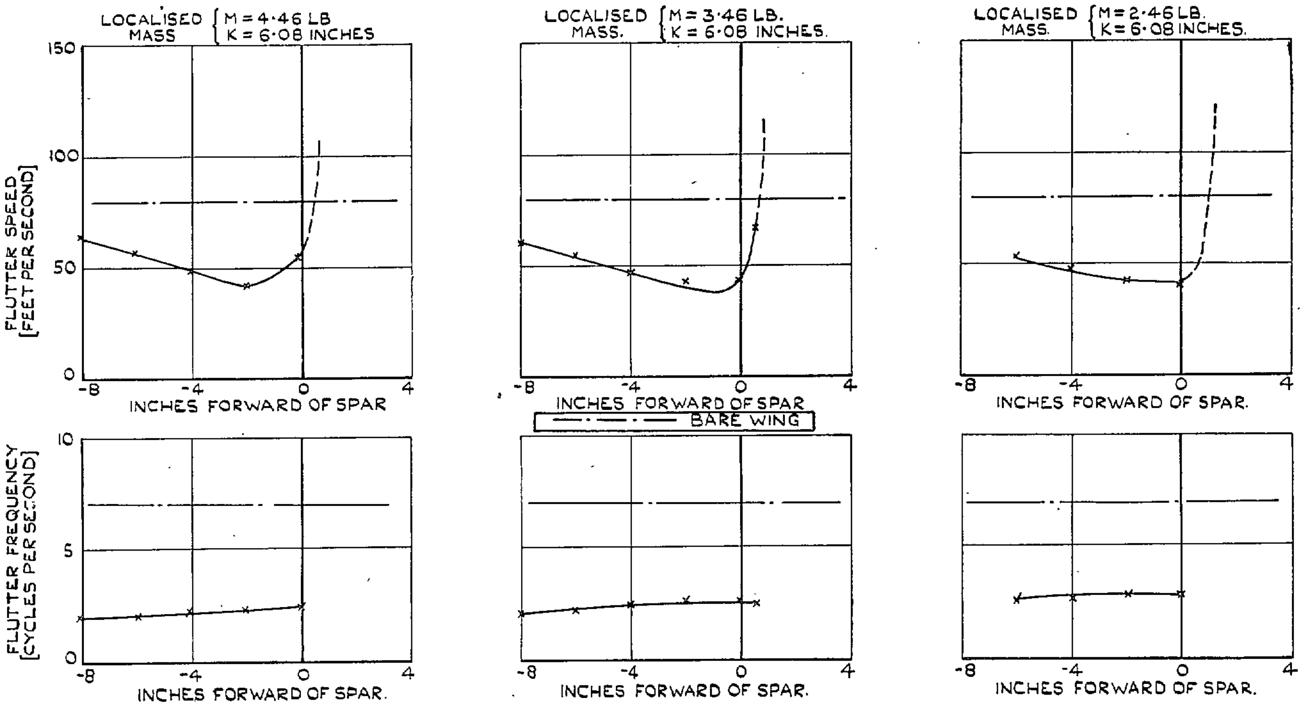


FIG. 9. The effect of chordwise position of a localised mass at 0·75 span (13-deg sweepback).

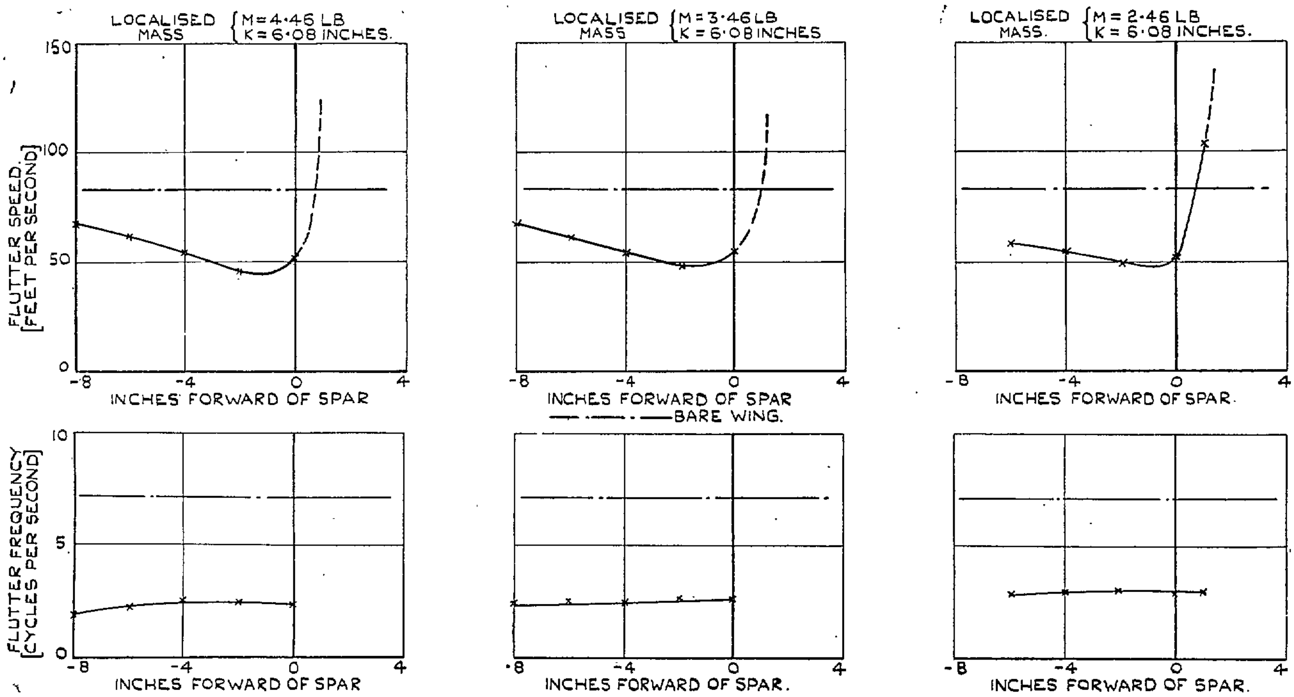


FIG. 10. The effect of chordwise position of a localised mass at 0·75 span (23-deg sweepback).

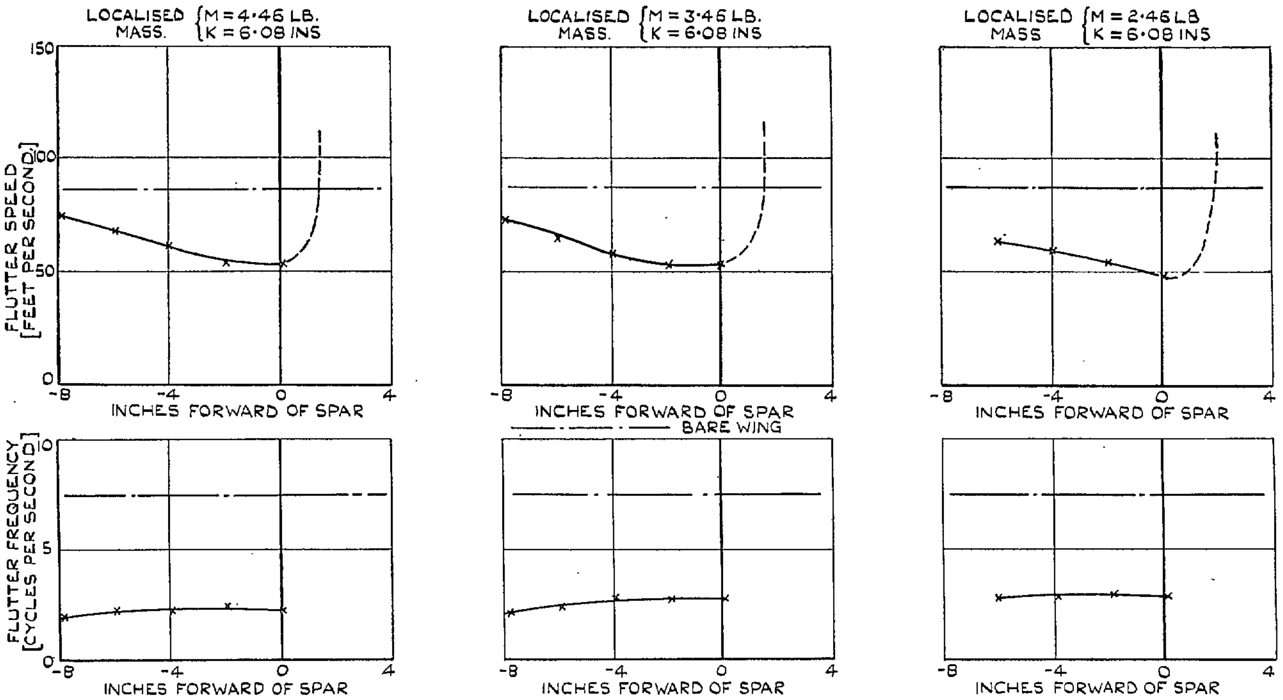


Fig. 11. The effect of chordwise position of a localised mass at 0·75 span (33-deg sweepback).

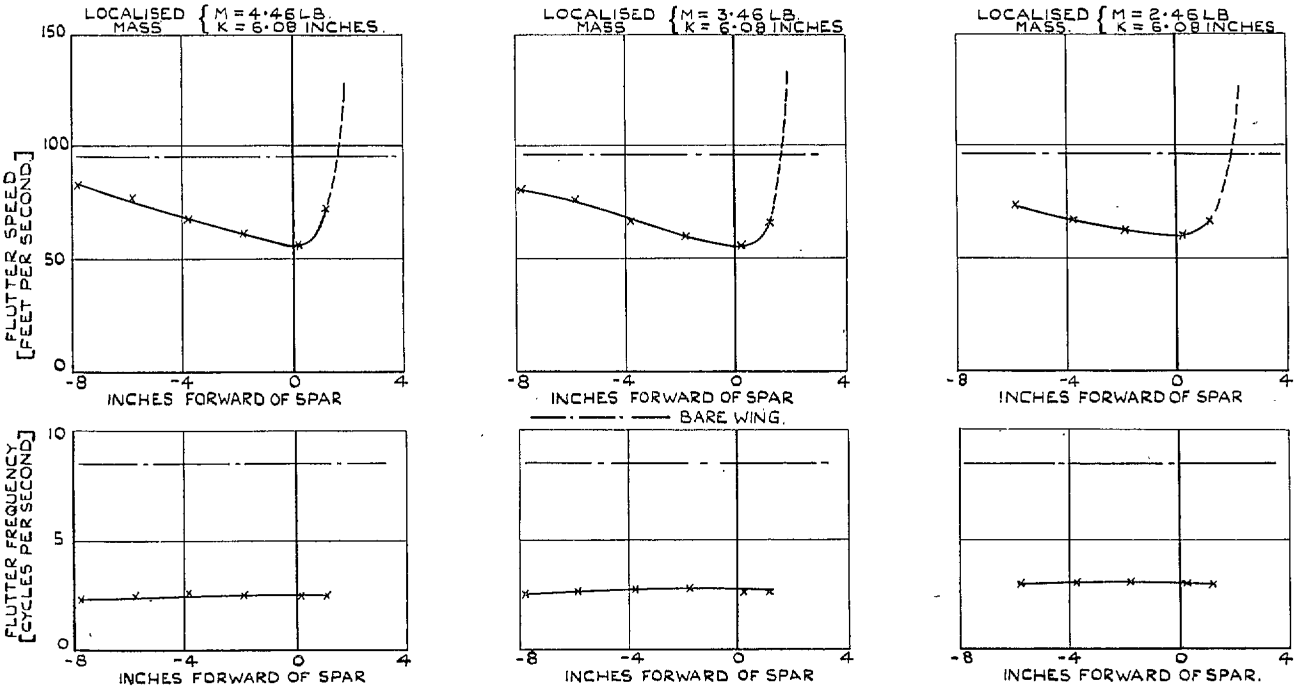


Fig. 12. The effect of chordwise position of a localised mass at 0·75 span (43-deg sweepback).

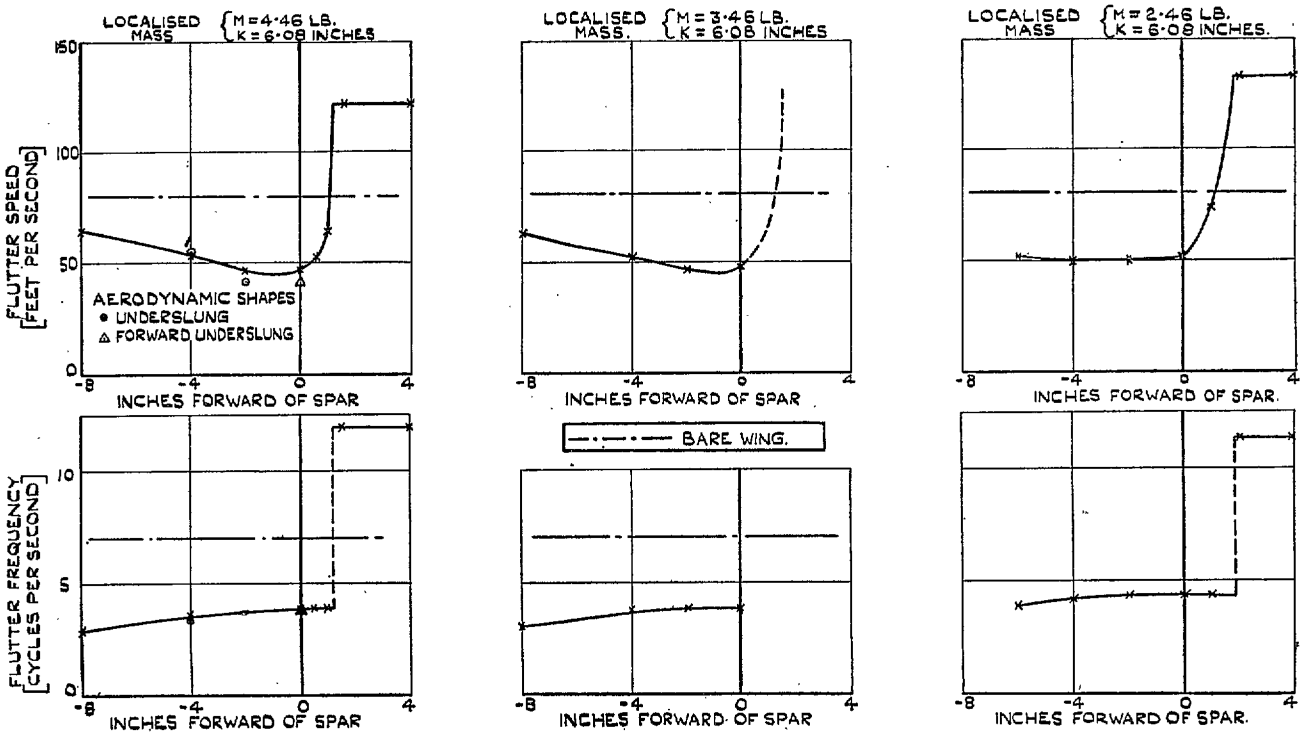


Fig. 13. The effect of chordwise position of a localised mass at 0·5 span (13-deg sweepback).

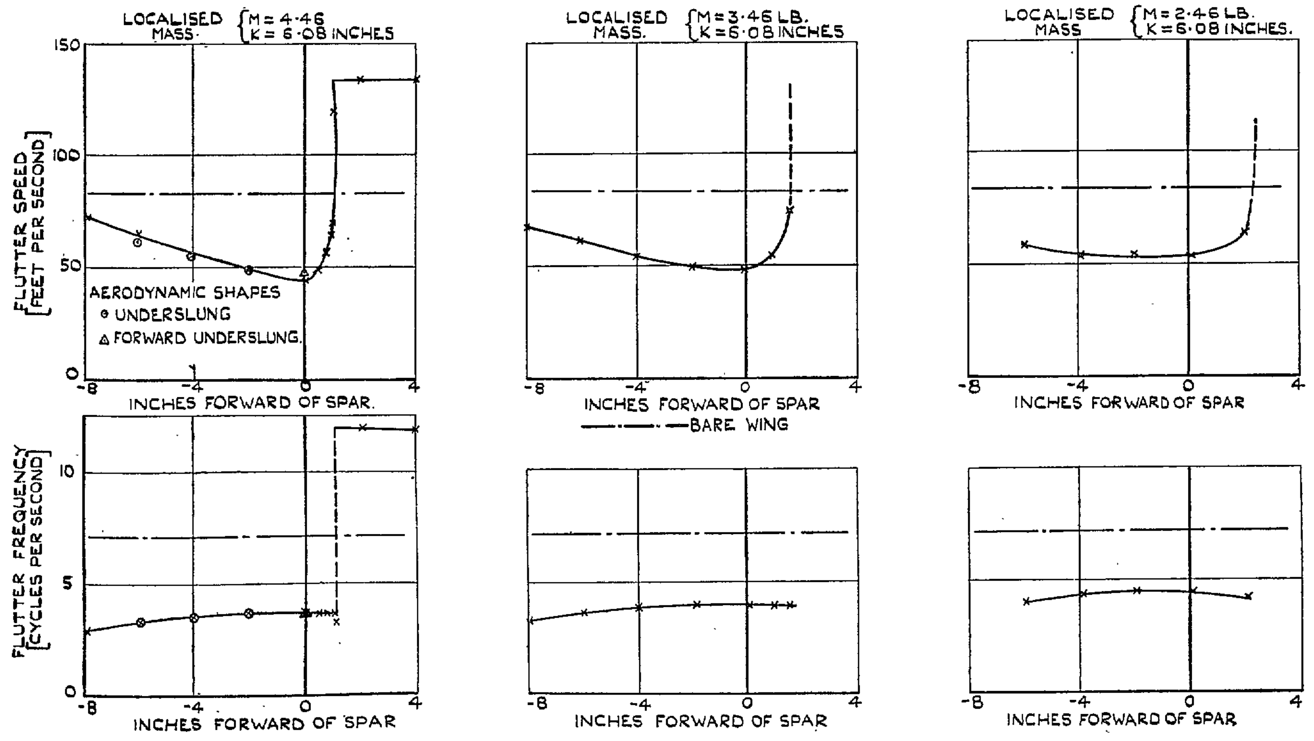


Fig. 14. The effect of chordwise position of a localised mass at 0·5 span (23-deg sweepback).

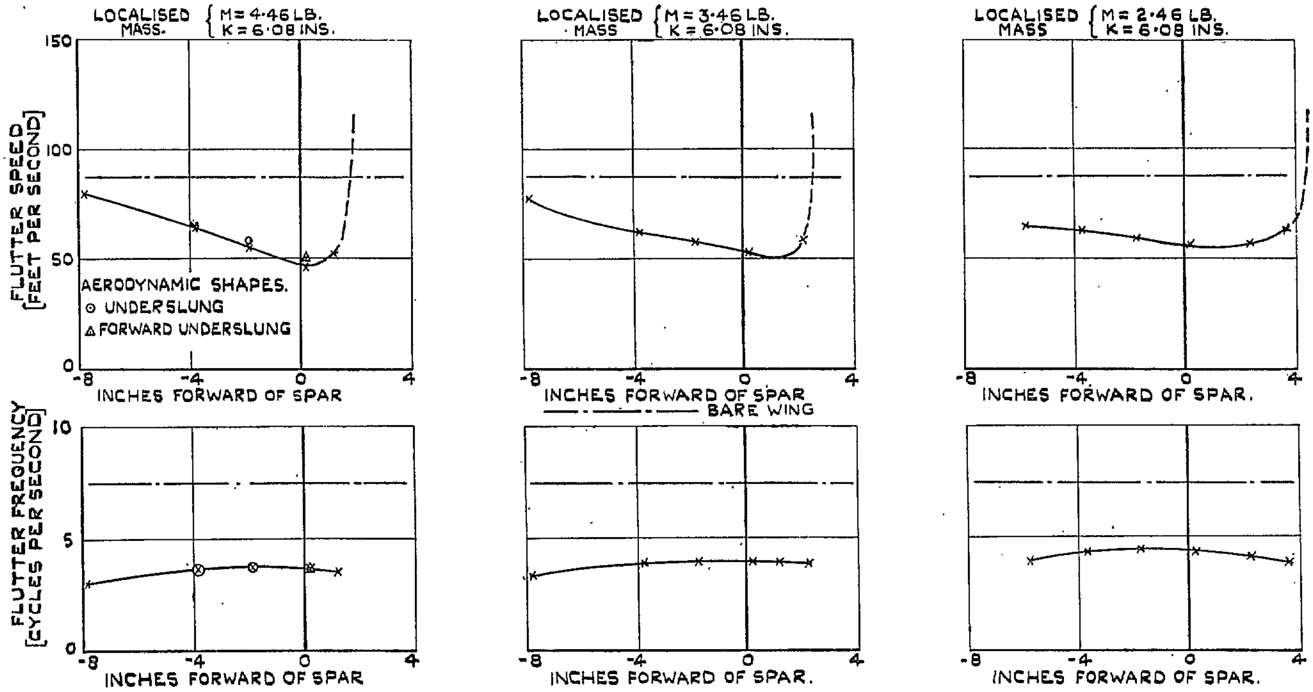


Fig. 15. The effect of chordwise position of a localised mass at 0·5 span (33-deg sweepback).

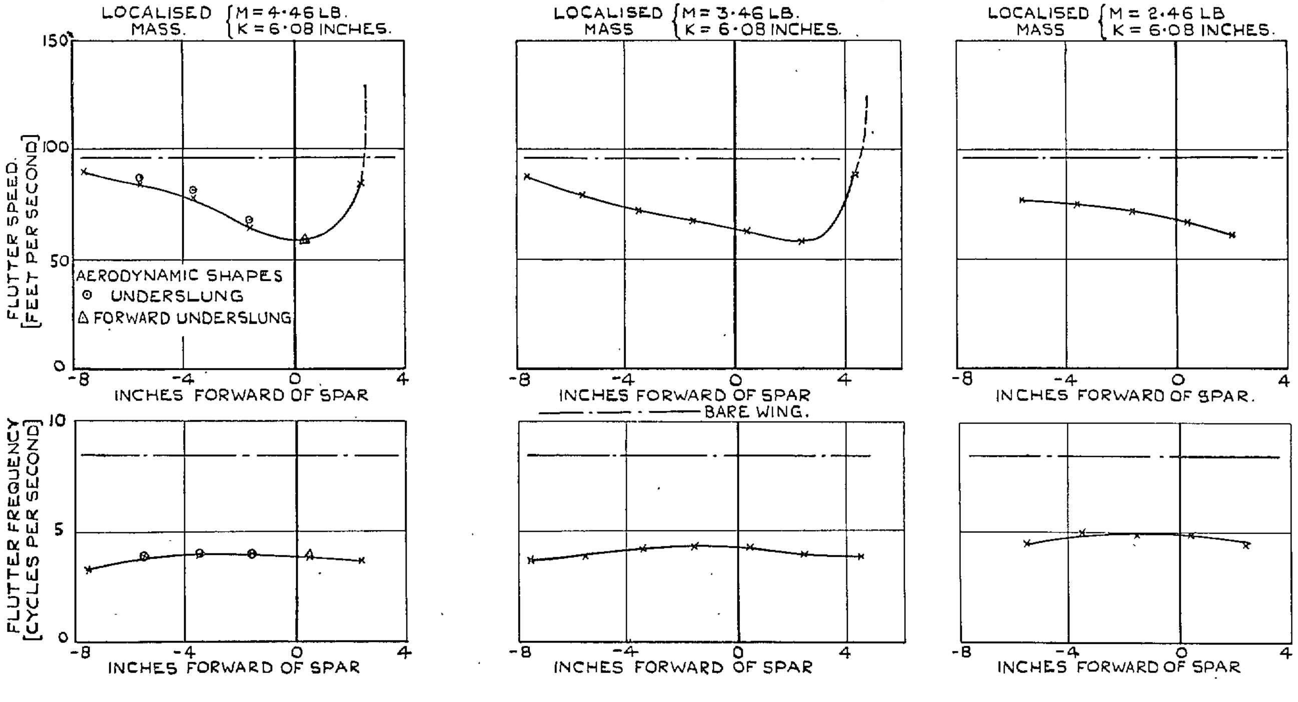


Fig. 16. The effect of chordwise position of a localised mass at 0·5 span (43-deg sweepback).

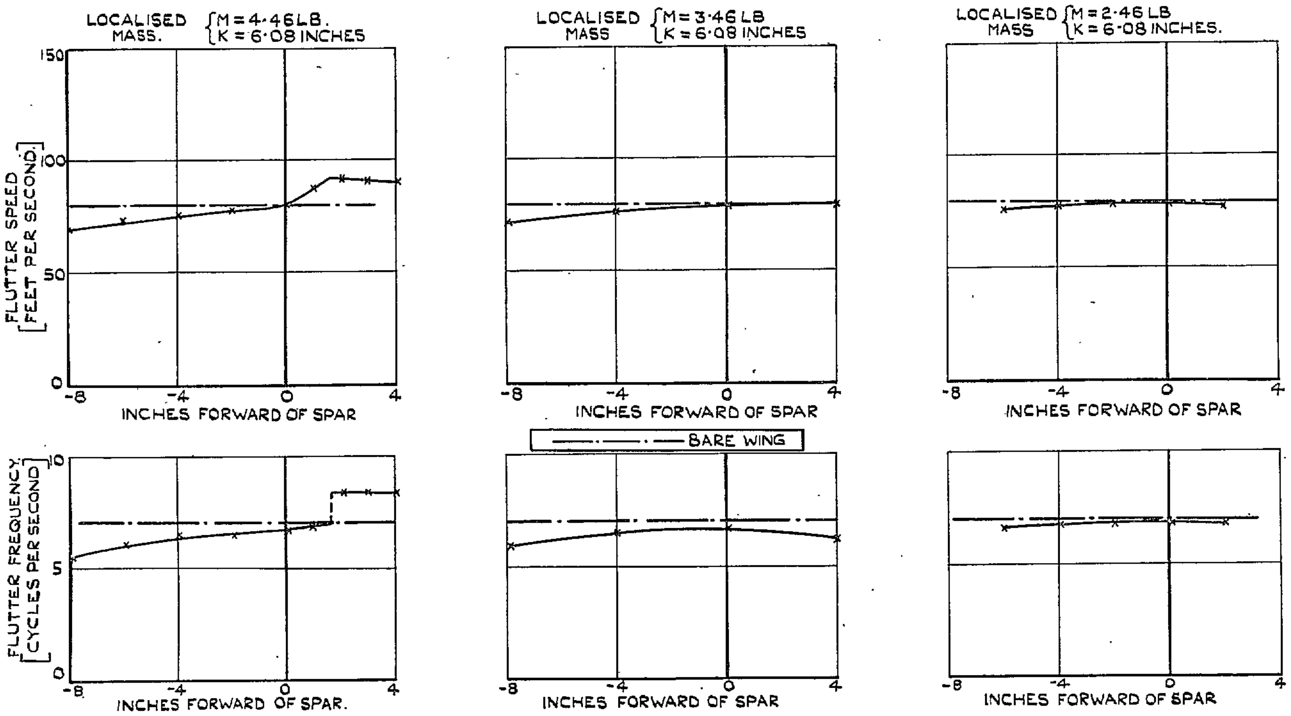


FIG. 17. The effect of chordwise position of a localised mass at 0·25 span (13-deg sweepback).

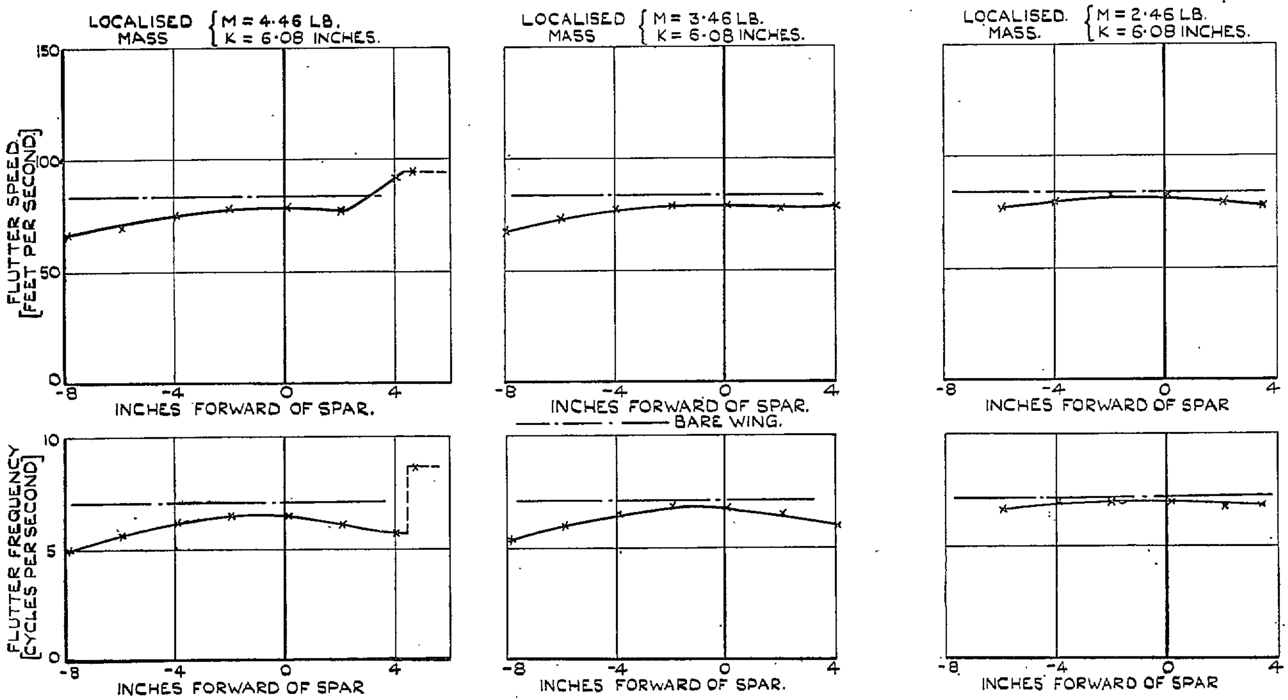


FIG. 18. The effect of chordwise position of a localised mass at 0·25 span (23-deg sweepback).

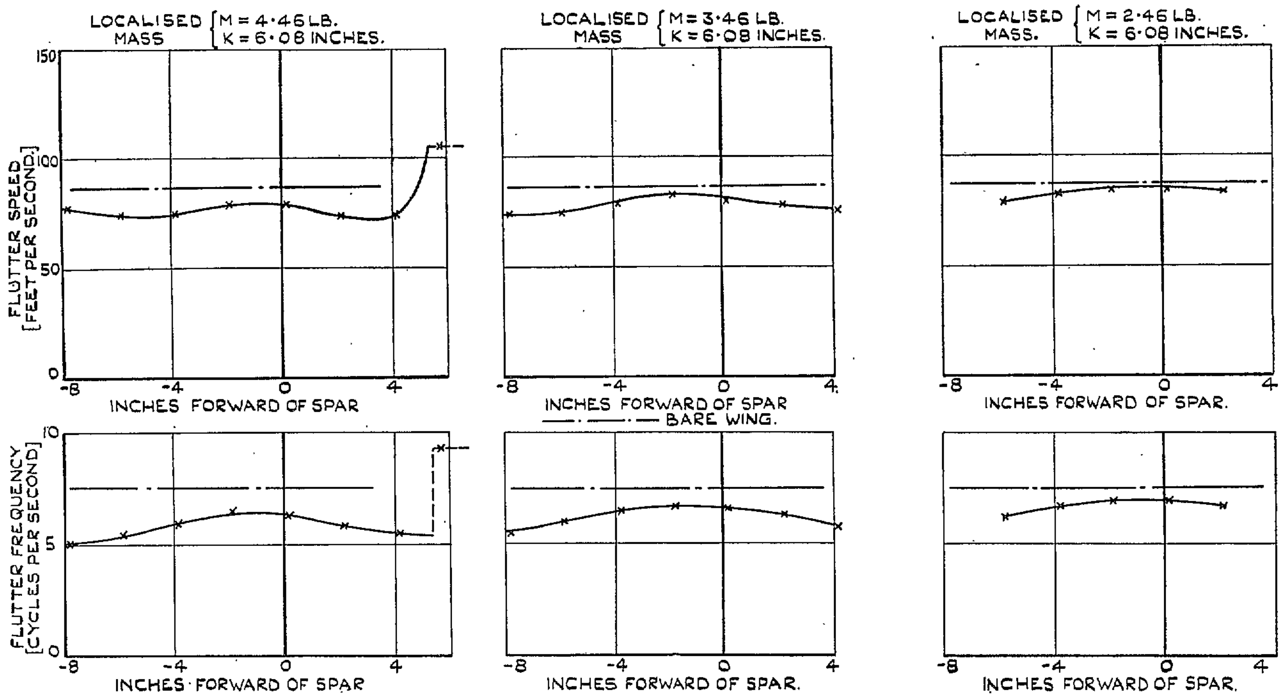


Fig. 19. The effect of chordwise position of a localised mass at 0·25 span (33-deg sweepback).

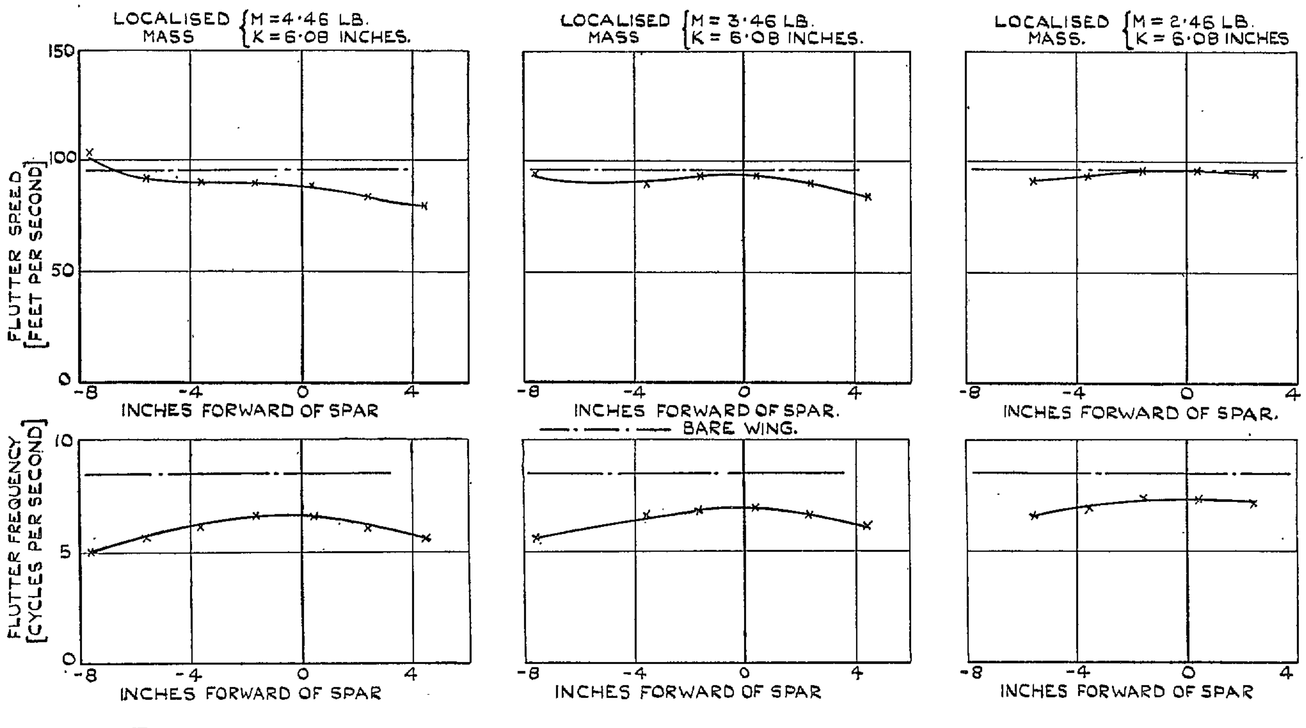


Fig. 20. The effect of chordwise position of a localised mass at 0·25 span (43-deg sweepback).

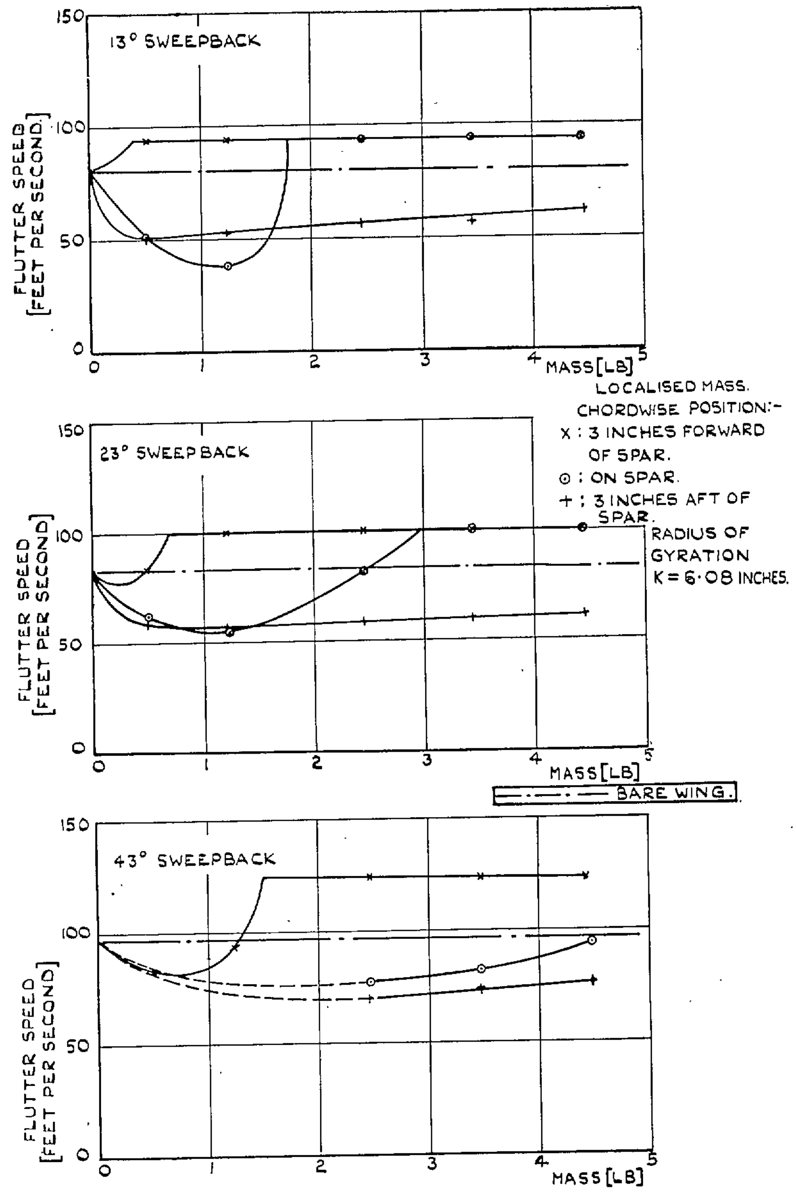


FIG. 21. The variation of flutter speed with mass at the tip (Constant radius of gyration).

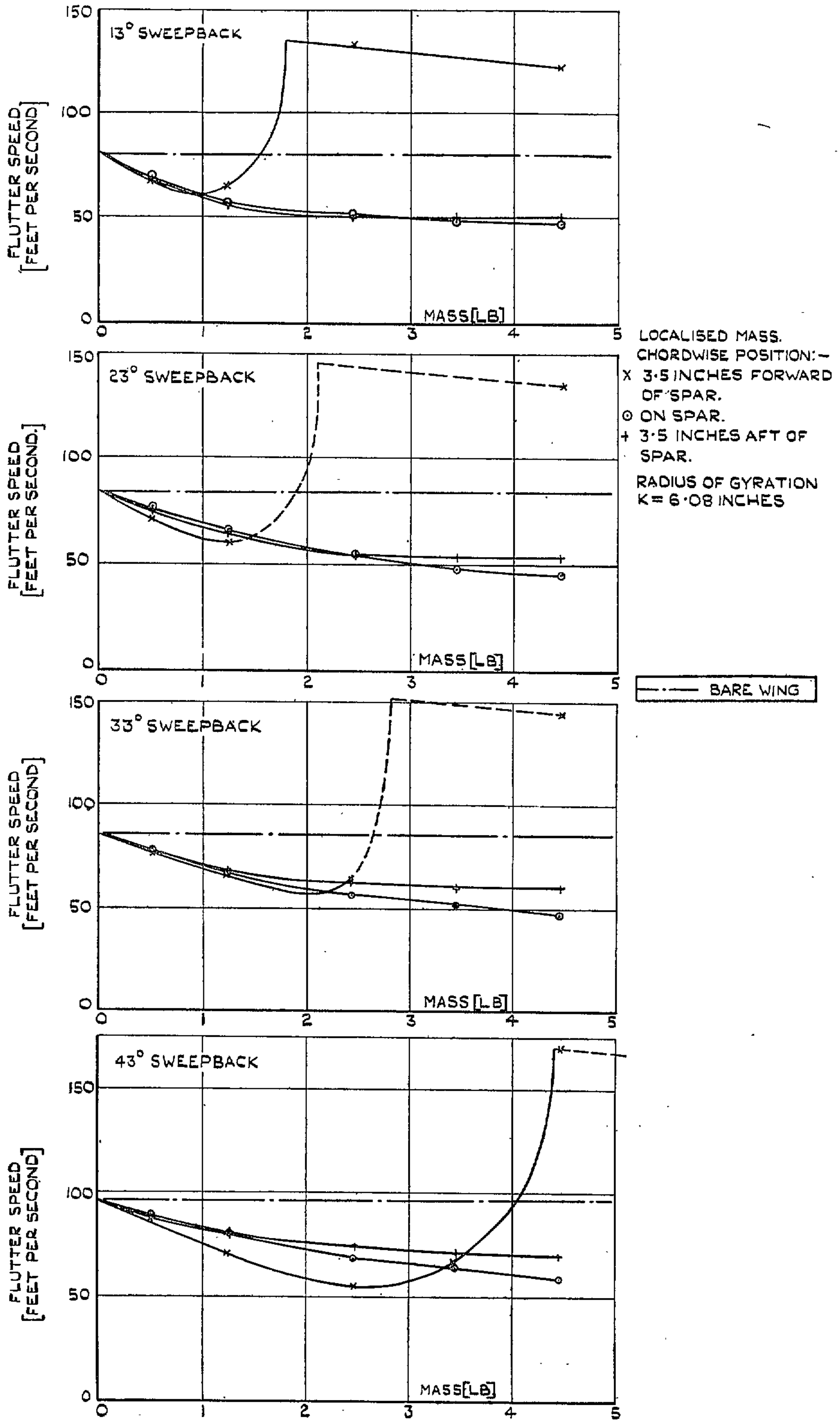


FIG. 22. The variation of flutter speed with mass at 0·5 span (Constant radius of gyration).

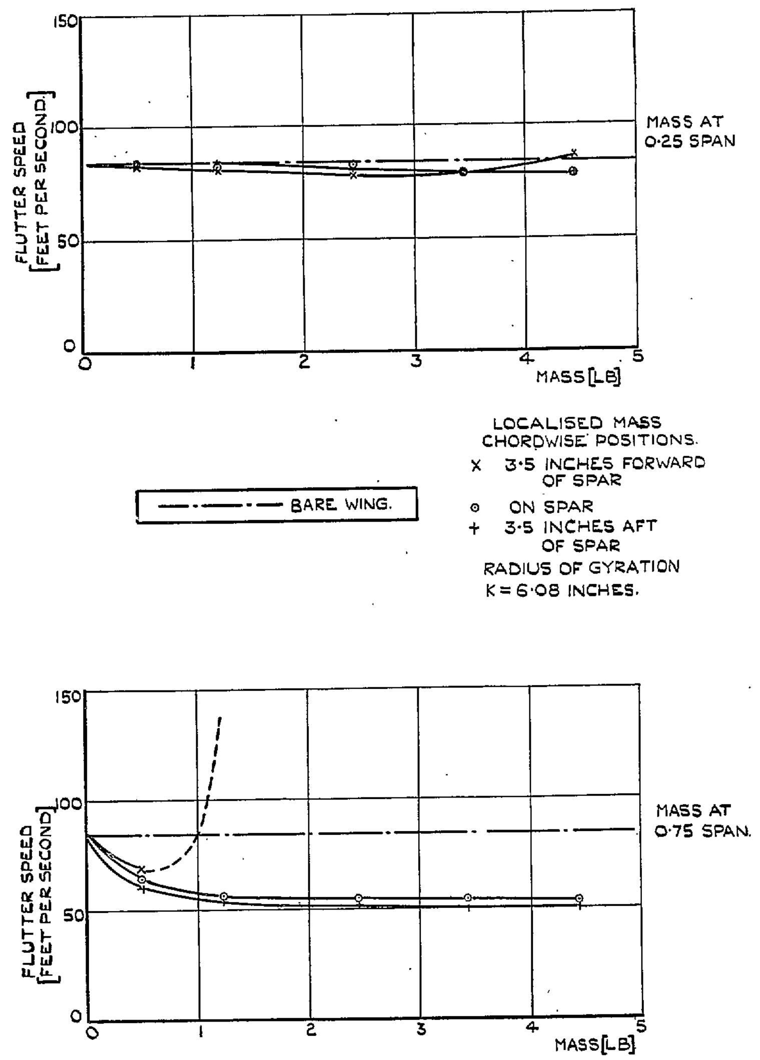


FIG. 23. The variation of flutter speed with mass at 23-deg sweepback (Constant radius of gyration).

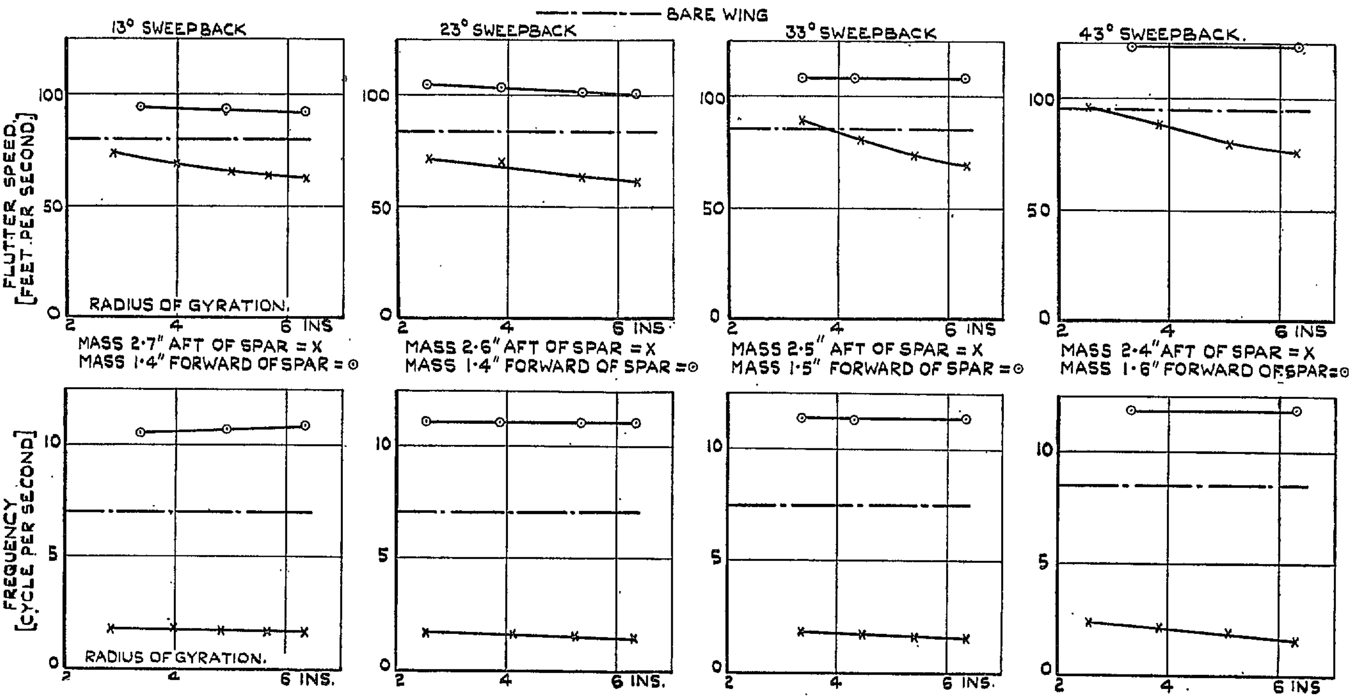


FIG. 24. The effect of radius of gyration of a mass 4·46 lb at the tip.

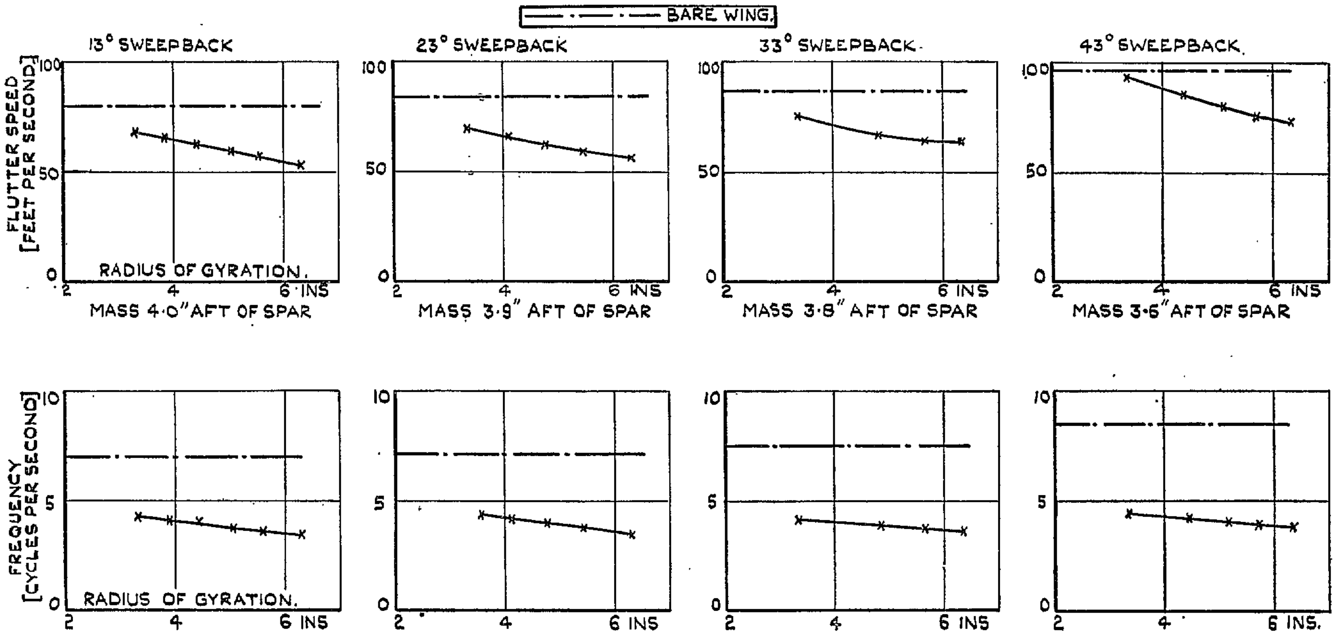


FIG. 25. The effect of radius of gyration of a mass 4·46 lb at 0·5 span.

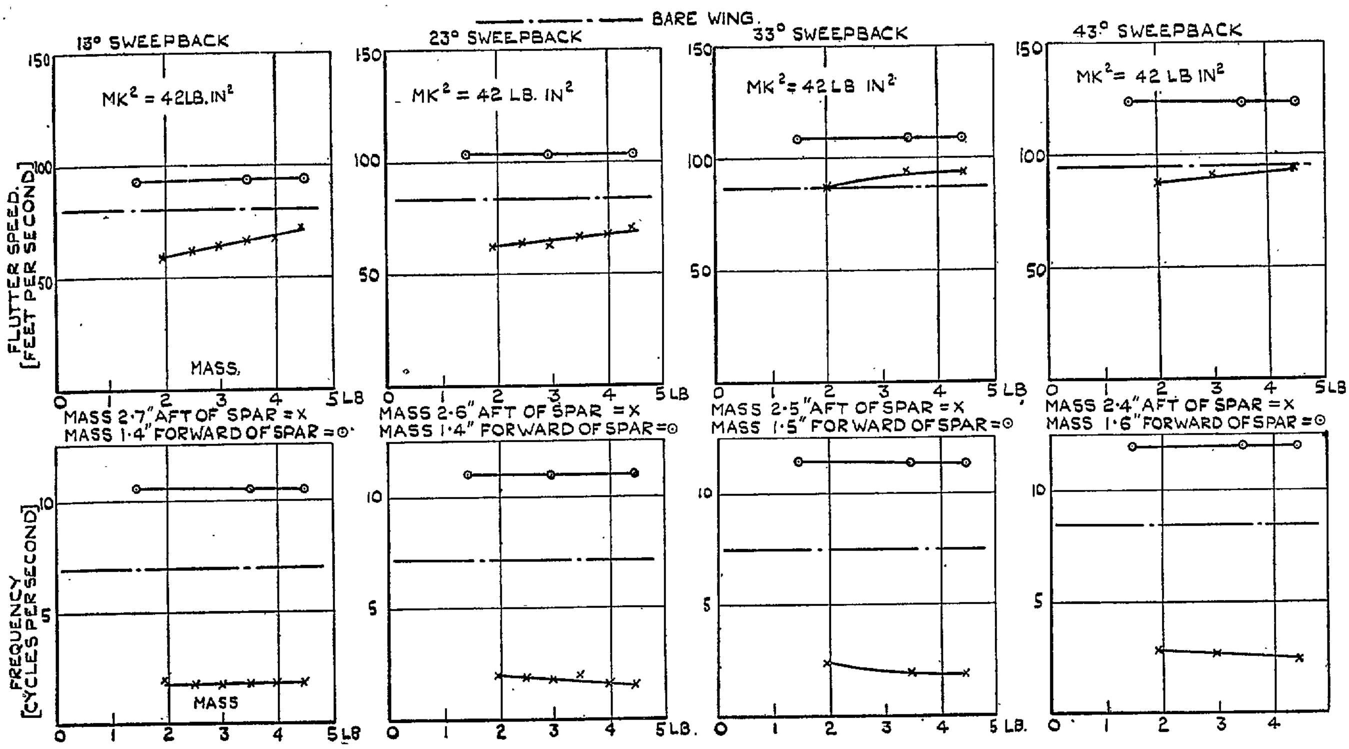


FIG. 26. The effect of mass at the tip with constant moment of inertia.

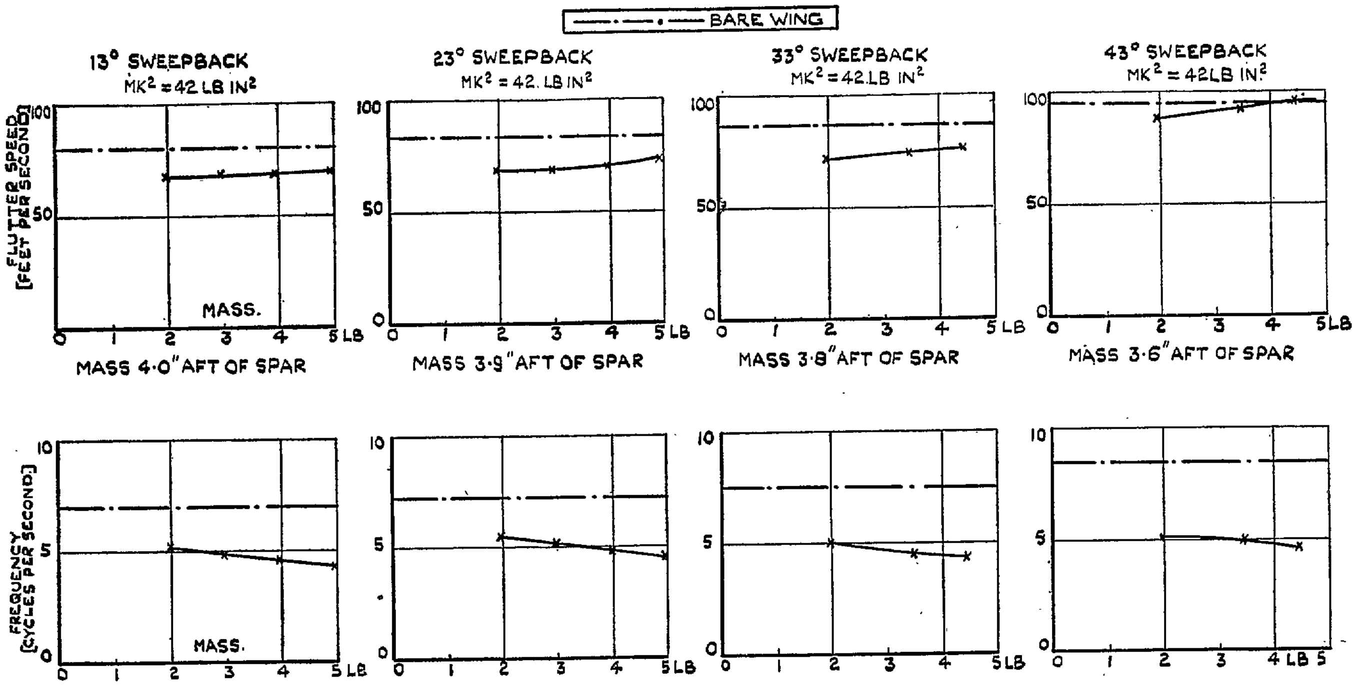


FIG. 27. The effect of mass at 0·5 span with constant moment of inertia.

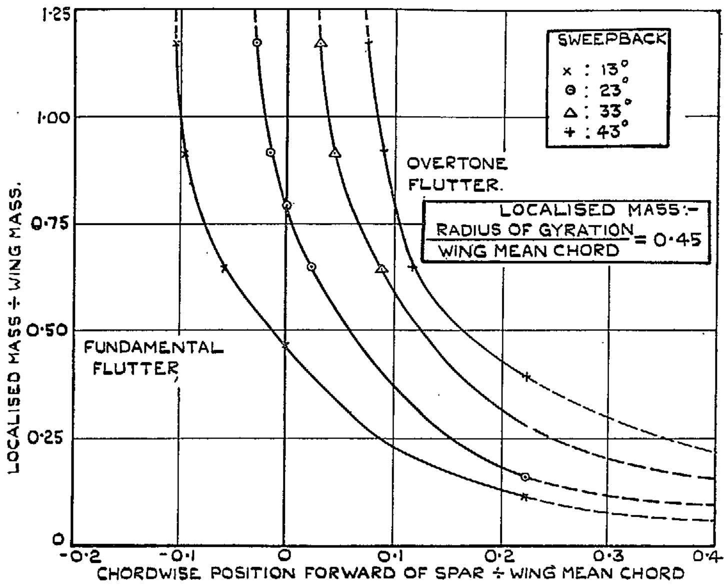


FIG. 28a. The transition curves for a localised mass at the tip.

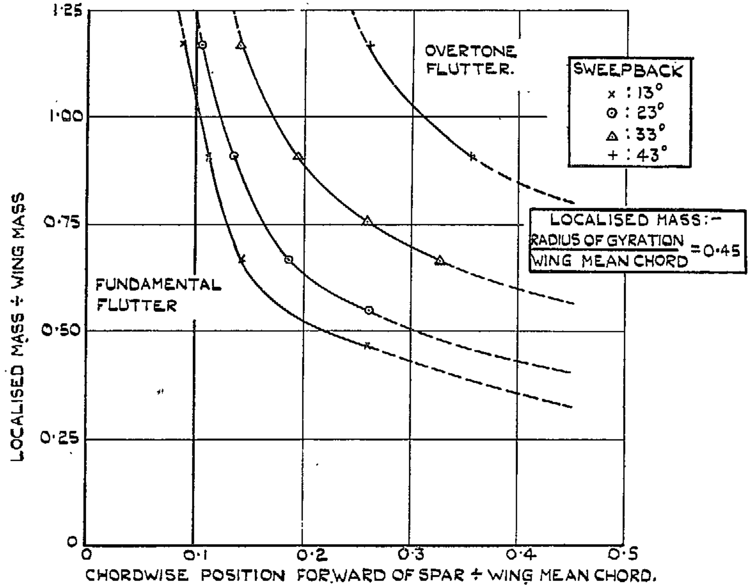


FIG. 29a. The transition curves for a localised mass at 0·5 span.

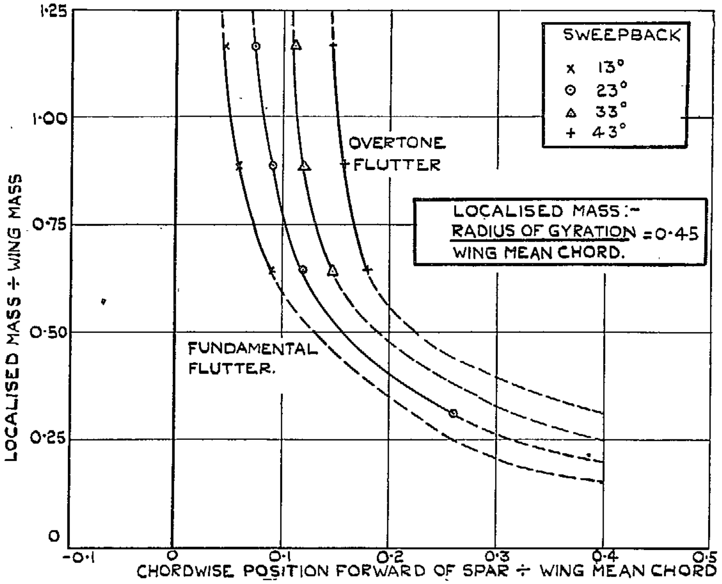


FIG. 28b. The transition curves for a localised mass at 0·75 span.

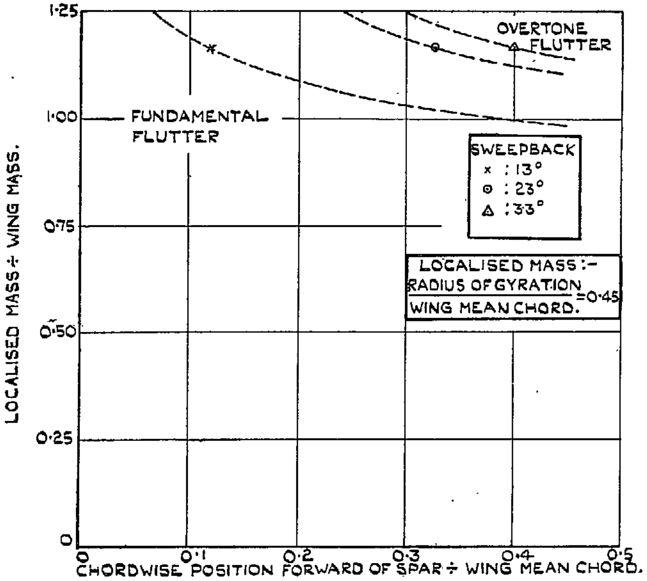


FIG. 29b. The transition curves for a localised mass at 0·25 span.

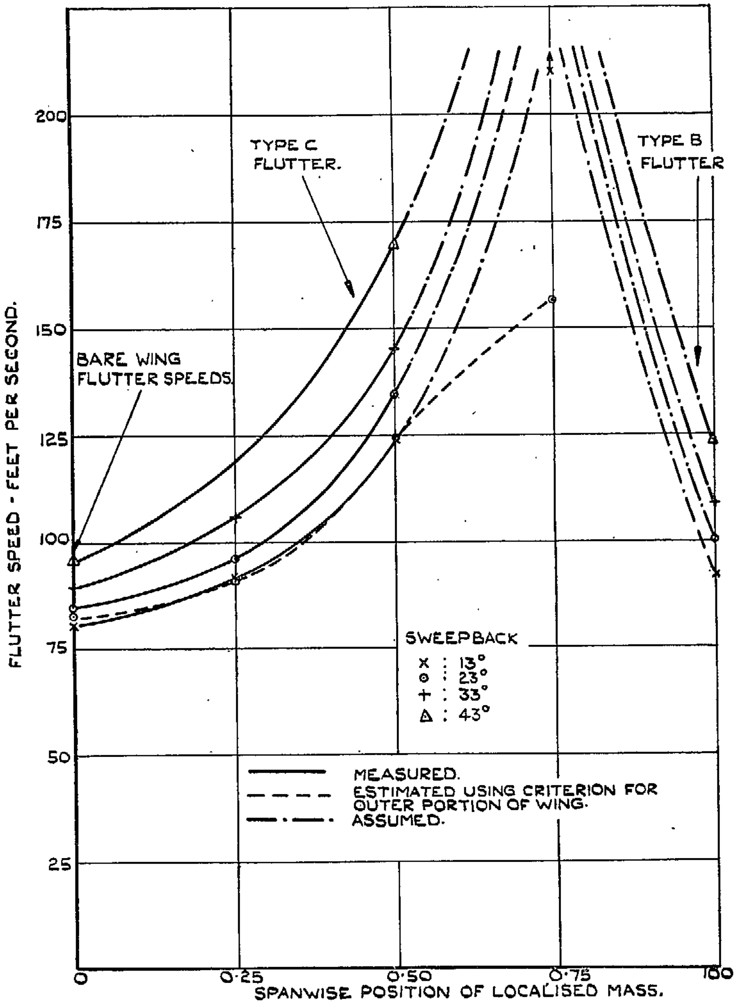


FIG. 30. The overtone flutter speeds.

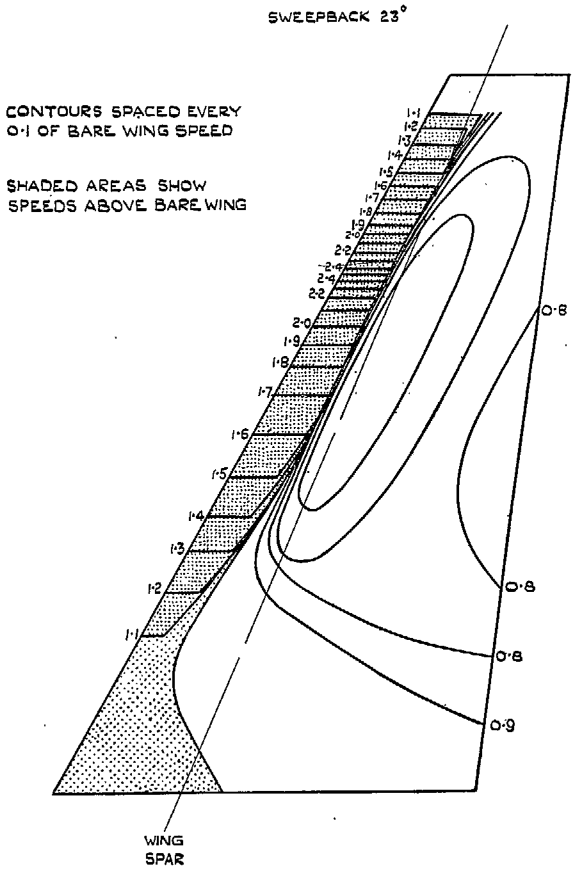


FIG. 31. Flutter speed contours for a localised mass of 117 per cent wing mass and radius of gyration 45 per cent wing mean chord.

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