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D. R. GAUKROGER and E. W. CHAPPLE

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Summary.—Wind-tunnel test results for the flutter of a swept-back wing carrying a localised mass, and having symmetric or antisymmetric freedoms of the root, are given. The tests were made on a model wing of 23 deg sweepback, the chordwise and spanwise positions of a localised mass being varied for two localised mass values. In most of the symmetric flutter tests the inertia conditions of the fuselage were constant, and representative of full scale. For the antisymmetric tests, the fuselage rolling moment of inertia was varied.

The test results indicate that, in general, the symmetric flutter case is more critical than the antisymmetric for masses at outboard positions on the wing, but for heavy inboard masses the antisymmetric case may be the more critical. The results are too complex for any detailed use in predicting the effects of mass loading on the flutter of particular aircraft.

1. *Introduction.*—An experimental investigation of the effect of a localised mass on the flutter of a swept-back wing, fixed at the root, was recently made at the Royal Aircraft Establishment[1]. The investigation covered a wide range of mass value and position, as well as the effect of wing sweepback, but the effects of body-free conditions, representative of flight, were not included in the tests. This report describes an investigation in which a model wing carrying a localised mass had body freedoms in pitch, normal translation and roll. The symmetric and antisymmetric flutter characteristics were separately obtained for a range of localised mass parameters, and variations in fuselage inertia characteristics were also made.

The results of these tests show that the flutter characteristics of a fixed-root wing carrying a localised mass are modified considerably by the introduction of body freedoms. Except for very high fuselage inertia, the fixed-root characteristics are no guide to those for the free-root case. Moreover, the complexity of the test results is such that the present investigation must be regarded more as a broad indication of the possible flutter characteristics of a wing with localised mass than as a detailed guide to the behaviour of other similar systems.

2. *The Scope of the Investigation.*—Although the free-root investigation of flutter of a wing carrying a localised mass followed logically from the fixed-root investigation already made[1], it was clearly necessary to restrict the test programme to the variation of the more important parameters, and these were determined from the experimental results available[1, 2].

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On the localised-mass side the fixed-root tests had shown that parameters of primary importance were localised-mass value and position, and wing sweepback[1]. However, the variation of sweepback was a steady effect in the sense that it introduced no new types of flutter, but modified a pattern of results. For the symmetric body freedoms[2], the sweepback effect, although important, again did not radically alter the general pattern of the flutter characteristics, but variations of fuselage pitching moment of inertia and tailplane volume coefficient were critical in determining whether body freedom or disturbed root flutter occurred.

On this evidence it was decided not to vary wing sweepback in the present tests. However, the programme should have included a range of variation of fuselage pitching moment of inertia and tailplane volume coefficient such that both ' body-freedom ' and ' disturbed-root ' types of flutter could be obtained for the bare wing, but in practice it was found that the fuselage inertia could not be reduced sufficiently (without the use of springs[2]) for body-freedom flutter to occur. Only disturbed-root flutter was obtainable, and earlier tests[2] showed that this type of flutter was insensitive to variations of either fuselage pitching moment of inertia or tailplane volume coefficient. For this reason, only minor variations of fuselage inertia were made in the tests with symmetric body freedoms, and only the conditions of no tailplane and a tailplane representative of current design were investigated. The main variations considered were spanwise and chordwise position of the localised mass, and the localised-mass value.

In the antisymmetric case previous tests showed[2] that wing sweepback did not alter the general pattern of the results, but that the value of fuselage rolling moment of inertia could have a critical effect on the type of flutter that occurred. Accordingly, the present antisymmetric tests were also made at a fixed angle of sweepback, with variations in fuselage rolling inertia, and with the localised-mass variations that applied to the symmetric case.

From the foregoing it might appear that the investigation was restricted to a small part of the whole problem; nevertheless, nearly five hundred tests were made and sufficient data were obtained to indicate the general effects of body freedoms. It is felt that there would be little value in making an investigation of this sort more detailed; the results indicate that the type of flutter, the flutter speed, and frequency, are all dependent upon a number of parameters, and that the flutter characteristics of a particular configuration cannot be reliably assessed from the results of a general investigation. The present tests may be regarded as an indication of the way in which body freedoms and localised masses can affect the flutter properties of a wing, but they should not be looked upon as an accurate guide to the flutter properties of all wing-mass combinations.

3. *Test Equipment.*—3.1. *Model Wing.*—The model used in the tests was built to the same design as that used in the previous localised-mass tests with fixed root[1] (Fig. 1). Having a span (root to tip) of 36 in., root chord 21 in. and tip chord 6 in., the model had a single spruce spar at 30 per cent chord swept-back at an angle of 23 deg. The spar was of square cross-section and tapered uniformly from root to tip, the sectional area at any spanwise position being proportional to the square of the local chord. Spruce ribs were glued to the spar parallel to the airflow at intervals of one inch. The ribs were $\frac{3}{8}$-in. thick and were shaped to aerofoil section RAE 101 with a thickness/chord ratio of 10 per cent. A lead block having a weight proportional to the square of the rib chord was built into each rib to give an overall wing inertia axis at 43 per cent chord. Each rib was fitted with cartridge-paper shrouds over the leading and trailing edges which projected $\frac{3}{16}$ in. in a spanwise direction on each side of the rib. The structure was covered with silk, and doped with a solution of Vaseline in chloroform.

3.2. *Localised-Mass Technique.*—The ' remote loading ' method of localised mass testing has been fully described elsewhere,[1] but a short description is given here. Localised-mass inertia loads under oscillating conditions are applied to the wing at any section by a parallel-motion linkage (Fig. 2); this consists of two rods of equal length and parallel to one another, that are attached to the wing by universal joints at a spanwise section. The other ends of the rods are outside the air stream and are connected to a loading platform by bearings permitting motion only in the plane of the rods. The loading platform is supported by long cords, giving a low-frequency pendulum support, and the rods are at right angles both to the plane of the wing and to the air stream. Under these conditions a weight on the loading platform is equivalent to the same weight at the corresponding chordwise position on the wing section for oscillatory motion in pitch and normal translation.

4. *Presentation of Test Results.*—These are described in two sections, symmetric and antisymmetric tests (Sections 5.3 and 6.3 respectively). The symmetric-test results are much less complex than the antisymmetric, partly because as many as five different types of flutter occurred under antisymmetric conditions, and partly because the antisymmetric tests covered a wide range of fuselage inertia conditions which could not be covered in the symmetric tests. It may be pointed out here, however, that although the antisymmetric tests are presented in rather more detail than the symmetric, the latter are of equal, if not greater, significance in their application to full-scale flutter problems. In order to classify the types of flutter, type letters are used throughout the report; types *A*, *B* and *C* occurred in the fixed-root tests[1], and these three types occur again with both symmetric and antisymmetric body freedoms, though modifications in mode may be apparent. The same lettering has been used for the present tests, and additional types of flutter that occur antisymmetrically are called types *D* and *E*. The three types of flutter that occurred in the fixed root tests were:

Type A.—Flutter involving mainly the fundamental modes of the wing-mass combination, and associated with aft chordwise positions of the localised mass.

Type B.—An overtone type of flutter that occurs with forward chordwise positions of the mass at the wing tip, and involves very little movement of the tip, with flexural and torsional displacements of the wing between root and tip.

Type C.—An overtone type of flutter that occurs with forward chordwise positions of 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.

In the fixed-root tests it was convenient to compare flutter speeds with that of the bare wing (*i.e.*, with no localised mass). In the present tests the bare-wing fixed-root flutter speed is again adopted as a standard, and is shown on all the diagrams. It may be noted that in the symmetric case the bare-wing disturbed-root flutter speed is equal to the ' standard ' speed, and in the antisymmetric case the ' standard ' speed represents the lowest antisymmetric bare-wing flutter speed[2]. Some time elapsed between the two series of tests (the antisymmetric case was investigated first) and the wing deteriorated during this time; for this reason direct comparison between the symmetric and antisymmetric results is unreliable except in relation to the bare-wing fixed-root flutter speeds. Each series of tests, however, was made over a fairly short period of time, during which deterioration had a negligible effect on the bare-wing fixed-root speed.

The first four normal modes with the root fixed were obtained for a localised mass on the spar (i) at the tip, and (ii) at $0 \cdot 25$ span. The nodal lines and frequencies are shown in Figs. 5 and 6.

The normal modes of flexural overtone were also obtained for the bare wing for three conditions of the root: (i) fixed, (ii) with symmetric freedoms and fuselage inertia conditions representative of the wind-tunnel tests and (iii) with antisymmetric freedom in roll and a small value of fuselage rolling moment of inertia (90 lb/in.^2). The frequencies and nodal line positions are shown in Fig. 7; the significance of these results is discussed in Section 7.3.

5. *Symmetric Flutter Tests.*—5.1. *Symmetric Body Freedom Rig.*—The rig used for the tests is shown in Fig. 3. It consisted of a body (or fuselage) supported on three light vertical legs having cross-spring bearings at each end. Two of the legs supported the body just aft of the wing attachment points, and were equally spaced on each side of the body. A rigid cross member joined the tops of the legs to the body. The third leg was attached to the body centre-line at a point well aft of the other two legs. An angled drag bar, pivoted to the body, prevented backward movement and was designed in such a way that for deflections of the model from the mean

position a component of the drag provided a restoring force. A light spring was fitted to hold the drag bar in its runners at low wind speeds. Owing to the destabilising effect of the leg support, the system had very low stiffness in the body freedoms. At a wind speed of approximately 50 ft/sec, the stabilising forces provided by the cross-spring bearings in the legs, and by the drag-bar system, just balanced the gravitational instability of the rig. The need for a rig of this sort, having practically zero natural frequency in the body freedoms, arose from the difficulty experienced during preliminary tests when the more conventional rig, suggested by Jordan and Smith[3], was used. With the conventional rig, the effective mass and moment of inertia of the body is a function of the ratio of the support frequency and the flutter frequency[3]; the exceptionally low flutter frequencies obtained with a large value of localised mass made it almost impossible to achieve a sufficiently low support frequency to give effectively positive inertia conditions of the fuselage under oscillating conditions. The rig used in the present tests had no restraining springs of the type used by Jordan and Smith, and for this reason was difficult to control in the wind tunnel; on the other hand the support stiffness was low enough to offer a negligible contribution to the fuselage inertia properties, which were thus independent of the flutter frequency. Another important point is that whereas the conventional rig enables effective fuselage inertias of zero (or negative values) to be obtained by reason of the spring correction, the present rig imposes minimum inertia conditions represented by the structure of the rig itself.

5.2. *Range of Tests.*—All the tests were made on the wing with 23 deg sweepback of the spar. Two values of localised mass were tested, 4·46 lb and 2·46 lb, equal respectively to 1·17 and 0·64 times the weight of the wing. The radius of gyration of the localised mass in the pitching sense was 6·08 in. in each case, equal to 0·45 of the wing mean chord. The tests were made with four spanwise positions of the localised mass, 0·25, 0·50, 0·75 span, and at 0·95 span (subsequently referred to as the ' tip '). At each spanwise position, chordwise positions of the localised mass were chosen so that the flutter characteristics of the model could be obtained in the regions where changes in the type of flutter took place. The chordwise range of localised-mass position was rather less for the small mass than for the large mass.

For each combination of localised-mass value and position the tests were made with and without tailplane. A tailplane volume coefficient of 0·592, which is representative of current design, was used. The tailplane was untapered and unswept, and was mounted on the fuselage in the plane of the wing with a tailplane arm 1·76 times the wing-root chord. For the tests without tailplane, the latter was replaced by a weight to maintain constant fuselage inertia conditions. To achieve longitudinal stability of the system when a localised mass was attached to the wing, a compensating mass was attached to the fuselage at the forward end. This fuselage mass depended on the position and value of the wing mass, but in order to avoid changing fuselage inertia conditions with each localised-mass loading, two values of the compensating mass were chosen, one for localised masses at 0·75 span and at inboard sections, and the other for localised masses at the tip.

The flutter of the bare wing without localised masses, but with or without compensating weights and tailplane, was of the disturbed-root type. That is to say, the minimum fuselage pitching moment of inertia was too great for the flutter to be of the body-freedom type[2].

With all values and positions of localised mass the fixed-root flutter speeds and frequencies were obtained for comparison with the body-free results. Some additional body-free tests were also made to check the results of the main programme; these are discussed in Section 5.3.

5.3. *Test Results.*—5.3.1. *Localised masses at tip.*—The test results are shown for the 4·46 lb mass in Fig. 8 and for the 2·46 lb mass in Fig. 9. With the furthest aft positions of the masses, the flutter speeds are slightly higher than the corresponding fixed-root speeds, and as the mass is moved forward towards the spar the free-root speeds rise and the fixed-root fall, so that the differences in speed are greatest for localised-mass positions close to the spar. The flutter is of type A, but in the free-root case there is some pitching of the fuselage in addition to the wing motions. When the localised mass is moved forward of the spar, the free-root flutter speed rises until a transition occurs, and for localised-mass positions forward of the transition point, type B flutter is obtained, the flutter speed remaining constant with this type of flutter. The free-root curve is thus similar to the fixed-root curve both in respect of the types of flutter, and of the general shape; the flutter speeds of type B flutter are the same, and since there is no perceptible body motion in type B flutter with the root free, the modes are identical in appearance. The chordwise position of the transition point is changed when the root is freed, and in Fig. 9 it is seen to be forward of the fixed-root position. The effect of tailplane is very small, although the addition of the tailplane moves the transition from type A to type B flutter toward the fixed-root position.

The fuselage inertia conditions for these tests were as follows: the fuselage mass was 1·81 times the wing mass, the overall pitching radius of gyration was 0·92 of the wing mean chord, and the overall centre-of-gravity position was 0·69 of the wing mean chord forward of the aerodynamic centre for the wing alone (' overall ', here, does not include the localised mass).

5.3.2. *Localised masses at* 0·75 *span.*—Figs. 10 and 11 show the test results. The same trend of rising flutter speed with forward position of the localised mass occurs both with fixed root and with free root, though in neither case is an overtone type of flutter obtained. The flutter speeds with the root free are, in general, somewhat higher than with the root fixed for mass positions aft of the spar, but are lower for forward positions. As with a localised mass at the tip, the flutter with free root is of type A, but includes some pitching of the fuselage. There is little effect due to the tailplane.

The fuselage inertia conditions were: fuselage mass 1·30 times wing mass, overall pitching radius of gyration 0·83 of the wing mean chord, and overall centre-of-gravity position 0·49 of the wing mean chord forward of the aerodynamic centre for the wing alone.

5.3.3. *Localised masses at* 0·5 *span.*—The free-root results here show a marked difference from the fixed root (Figs. 12 and 13). With aft positions of the 4·46 lb localised mass, flutter of type A occurs, and the free-root speed is above the fixed-root. Moving the localised mass forward results in a considerable drop in fixed-root speed, but the free-root speed rises steadily and continues to do so for localised-mass positions forward of the spar. In the latter region the fixed-root speed rises rapidly and there is a transition to an overtone form of flutter, type C. No transition occurs in the free-root case, the flutter being of type A throughout the range of chordwise position, and the effect of tailplane is negligible. There is a very marked effect on the flutter characteristics when the localised mass is reduced to 2·46 lb. Fig. 13 shows that the free-root curve now follows closely the shape of the fixed-root, and it may be noted that this effect is only obtained for the localised mass at 0·5 span. This was investigated in some detail, and a localised mass of 3·46 lb was tested over the same range of chordwise position as the 4·46 lb and 2·46 masses; the shape of the flutter-speed curve obtained was intermediate between the flat curve for the 4·46 lb. mass and the U-shaped curve for the 2·46 lb mass. The fuselage conditions for the tests described were the same as for the tests with the localised mass at 0·75 span. Additional tests were made to determine whether the overtone flutter, type C, that occurred with the root fixed could be obtained with the root free. The mass and pitching moment of inertia of the fuselage were increased and it was found that type C flutter could be obtained for forward positions of the localised mass. The transition between flutter of types A and C occurred in chordwise positions further aft as the inertia of the fuselage was increased, until, with a very heavy fuselage the flutter curve approximated to the fixed-root curve.

5.3.4. *Localised masses at* 0·25 *span.*—The results given in Fig. 14 and 15 show that within the range of values tested, tailplane, localised-mass value and chordwise position are unimportant in their effect on flutter speed. Only type A flutter occurs in the free-root case, although type C is obtained for forward positions of the localised mass with fixed root. The fuselage conditions under which the test results of Figs. 14 and 15 occurred were the same as for the 0·5 and 0·75 span localised-mass tests (Section 5.3.2). As with the localised mass at 0·5 span, additional tests were made with increased fuselage inertias and type C flutter was obtained with free root with a very heavy fuselage.

6. *Antisymmetric Flutter Tests.*—6.1. *Antisymmetric Body Freedom Rig.*—The model wing was attached to a rig that permitted body freedom in roll about an axis corresponding to the centre-line of an aircraft. The rig was previously used for antisymmetric flutter tests on a bare wing[2], and consisted of a framework that was free to roll on two ball races (Fig. 4). By means of a linkage system, the rolling moment of inertia of the rig could be varied by attaching weights to a rod outside the working-section of the tunnel. The model wing was attached to the framework so that it stood vertically in the air stream with the tip uppermost. The system was stabilised by springs on the linkage structure, which provided a restoring moment when the model was displaced in roll. Under steady oscillating conditions, the effective rolling moment of inertia of the ' fuselage ' was represented by the moment of inertia of the rig plus the (negative) moment of inertia of the spring restraint. Thus the effective fuselage rolling moment of inertia could be varied either by attaching weights to the rig, or by varying the stiffness of the restraining springs.

6.2. *Range of Tests.*—The same range of localised-mass parameters was tested as for the symmetric flutter tests (Section 5.2). For each localised-mass loading, the rolling moment of inertia of the fuselage was varied. Generally, the minimum value of rolling moment of inertia in each case was negative (about $-$ 100 lb/in.^{2}) and the maximum about $+$ 600 lb/in.^{2}. In one or two cases where the test was made in order to establish a transition between two forms of flutter, only a small variation of rolling moment of inertia was made.

The arrangement of the test rig was such that variations of both fuselage rolling moment of inertia and of localised-mass chordwise position could be made from outside the air stream while the wind tunnel was operating. The effective value of fuselage rolling moment of inertia depended upon the frequency of the flutter oscillation, since the negative mass effect of the springs contributed a negative rolling moment of inertia that was inversely proportional to the square of the frequency. Hence it was practically impossible to vary chordwise position of the localised mass without the rolling moment of inertia of the fuselage varying at the same time. The method adopted, therefore, was to vary the fuselage rolling moment of inertia while keeping the chordwise localised-mass position fixed. From the flutter-speed and frequency curves so obtained, the variation of speed and frequency with chordwise localised-mass position at fixed values of fuselage rolling moment of inertia was subsequently found by interpolation.

6.3. *Test Results.*—6.3.1. *Localised masses at the tip.*—The variation of flutter speed and frequency with fuselage rolling moment of inertia for a localised mass of 4·46 lb is given in Figs. 16, 17 and 18 for seven chordwise positions of the localised mass. With the furthest aft position of localised mass (6·6 in. aft of the spar) (Fig. 16), the flutter speed and frequency remain constant with variation of fuselage rolling moment of inertia. The flutter is type A and involves wing flexure and torsion in the fundamental modes with some amplitude of the wing in roll. As the localised mass is moved forward the flutter speed rises, but remains approximately constant with change of fuselage rolling moment of inertia. With the localised mass 0·35 in. aft of the spar, the variation of fuselage rolling moment of inertia produces a change in the type of flutter (Fig. 16). The transition occurs for a rolling moment of inertia value of aproximately 400 lb/in.^{2} and for values greater than this an overtone form of flutter, type B, is obtained. The mode of this flutter consists of displacements in the overtone modes of both flexure and torsion of the wing, with very small amplitudes in the rolling freedom. The value of the rolling moment of inertia at the transition from type A to type B flutter decreases as the localised mass is moved forward, and with the mass 0·1 in. aft of the spar (Fig. 17) this value lies between zero and 200 lb/in.^{2}, although it cannot be precisely determined from the test results. With the localised mass 1·4 in. forward of the spar, a third form of flutter occurs which will be called type E; the mode combines overtone flexure and fundamental torsion of the wing and there is some roll of the fuselage. The flutter frequency is higher than that of the type A flutter, but well below type B. Type E flutter occurs for small values of the fuselage rolling moment of inertia when the localised mass is 1·4 in. forward of the spar, and replaces type A flutter which is obtained neither with this chordwise position of the mass nor with any further forward chordwise position. As the rolling moment of inertia is increased the flutter changes to type B, and for values of rolling moment of inertia greater than that at the transition, type B flutter occurs, with the speed falling as the rolling moment of inertia is further increased. The value of fuselage rolling moment of inertia at transition from type *E* to type *B* could not be accurately determined for the localised mass 1·4 in. forward of the spar, but a comparison of the results with those obtained when the mass is 5·4 in. forward of the spar (Fig. 17) shows that the transition point moves in a direction of increasing fuselage rolling moment of inertia as the chordwise position moves forward. The most forward position of the localised mass was 7·4 in. forward of the spar (Fig. 18), and in this condition types *B* and *E* flutter occur and the transition is at a comparatively large value of fuselage rolling moment of inertia.

The test results for the localised mass of 2·46 lb at the tip are shown in Figs. 19 and 20. The types of flutter conform to the general pattern of the results for the larger mass. Type *A* flutter occurs with aft positions of the localised mass throughout the rolling moment of inertia range. With the localised mass 0·9 in. forward of the spar a transition occurs (Fig. 19) and type *B* flutter is obtained for values of rolling moment of inertia greater than that at transition. When the localised mass is 1·4 in. forward (Fig. 20), a further type of flutter is obtained. The mode is predominantly flexural overtone, with relatively large rolling of the fuselage, and torsion of the wing over the mid-span sections only. This type of flutter (type *D*) differs from type *B* in having a lower frequency (approximately 8 c.p.s. compared with 14 c.p.s. for type *B*) and in the large rolling amplitude that does not occur with type *B* flutter. It is associated with lower values of fuselage rolling moment of inertia than type *B*, and a transition to type *B* takes place if the rolling moment of inertia is increased. In the region of type *B* flutter, the flutter speed falls with increase of rolling moment of inertia beyond that at the transition. Three forms of flutter were obtained with the localised mass 1·9 in. forward of the spar: Types *E*, *D* and *B* in order of increasing rolling moment of inertia (Fig. 20). It is of interest to note that in the tests the three forms of flutter occurred simultaneously at the same wind-tunnel speed. Owing to the correction that is applied to the rolling moment of inertia, due to the spring effect, the test conditions represented three rolling-moment-of-inertia conditions, since each frequency required a separate spring correction. Although the control of the model was difficult in this condition it was possible to arrest the motion in any mode, so that each type of flutter continued quite independently of the others and enabled the flutter frequencies to be separated. By increasing the rolling moment of inertia from this condition, the flutter continued as type *B* and the flutter speed fell rapidly. The localised mass of 2·46 lb was finally tested 3·4 in. forward of the spar (Fig. 20) and in this position two forms of flutter, types *E* and *B* are obtained. Type *E* is associated with the lower values of fuselage rolling moment of inertia and type *B* with the higher, transition from one to the other occurring at a larger value of rolling moment of inertia than with the localised mass position further aft.

6.3.2. *Localised masses at* 0·75 *span*.—The tests with localised masses of 4·46 and 2·46 lb at 0·75 span are shown in Figs. 21 and 22. These results are the most straight-forward of the anti-symmetric test programme, in that only one type of flutter was obtained. This is type *A* flutter—flexure and torsion of the wing in its fundamental modes. The flutter speeds change little with fuselage rolling moment of inertia, but increase gradually as the localised mass is moved forward. Finally a rapid increase of flutter speed with chordwise position occurs, and for both the masses no flutter was obtained with a chordwise position of the localised mass forward of a point 2·05 in. aft of the spar; maximum tunnel speeds of 170 ft/sec were reached with the forward chordwise mass positions but no flutter nor any characteristic indications of an approach to the flutter condition (such as decreasing damping in a possible flutter mode) occurred.

6.3.3. *Localised masses at* 0·5 *span*.—Figs. 23, 24 and 25 show the test results for the localised masses at 0·5 span. With both masses two types of flutter are obtained, type *A* associated with aft positions of the localised mass, and a type *C* associated with forward positions. The type *C* flutter may be described as flexure-torsion flutter of the section of the wing that is outboard of the localised mass. The localised mass itself is almost stationary, and there is negligible amplitude of the model in roll.

With the localised mass well aft of the spar, type *A* flutter occurs (Figs. 23 and 25), and the flutter speed varies only slightly with change of fuselage rolling moment of inertia. As the localised mass is moved forward, the flutter speed increases throughout the moment of inertia range, and for both mass values tested type *C* flutter occurs for forward positions of the mass, the flutter speeds remaining practically constant with variation of fuselage rolling moment of inertia.

6.3.4. *Localised masses at* $0 \cdot 25$ *span.*—The test results are shown in Figs. 26 to 30. For a localised mass of $4 \cdot 46$ lb (Figs. 26, 27 and 28), the flutter is of type *A* for chordwise mass positions well aft of the spar and for low values of fuselage rolling moment of inertia. A transition occurs, even with the most aft position of localised mass, when the rolling moment of inertia reaches a large value (550 lb/in.^{2} with the localised mass $7 \cdot 9$ in. aft of the spar). The flutter changes from type *A* to type *C*, i.e., to flexure-torsion flutter of the portion of the wing outboard of the localised-mass section. As with type *C* flutter for a localised mass at $0 \cdot 5$ span, there is practically no displacement of the wing inboard of the localised-mass section, and no displacement in roll. The transition from type *A* to type *C* flutter occurs at lower values of rolling moment of inertia as the localised mass is moved forward. A second transition appears with the localised mass $3 \cdot 9$ in. aft of the spar (Fig. 27). This occurs at values of the rolling moment of inertia greater than those at which transition from type *A* to type *C* takes place. The new form of flutter combines flexural overtone of the wing with fundamental torsion, and relatively large amplitudes in fuselage roll are present in the oscillation. In appearance, this type of flutter resembles type *E*, which occurs with a localised mass at the tip (Section 6.3.1). For both types the maximum torsional displacement appears to be at the localised-mass section and there is a region of minimum amplitude at about $0 \cdot 75$ span. For the localised mass at $0 \cdot 25$ span, therefore, the flutter may be called type *E*. For values of fuselage rolling moment of inertia greater than that at the transition from type *C* to type *E* flutter, the flutter speed falls, rapidly at first and then less rapidly as the rolling moment of inertia is further increased. As the localised-mass position is moved forward, the transition from type *C* to type *E* flutter takes place at lower values of fuselage rolling moment of inertia. With the localised mass $1 \cdot 9$ in. aft of the spar (Fig. 28) only type *A* and type *E* flutter were recorded, but it is possible that type *C* flutter was missed owing to the difficulty of obtaining moment of inertia values within a small range.

The test results for the localised mass of $2 \cdot 46$ lb are given in Figs. 29 and 30. The general pattern differs from that of the larger mass owing to the absence of type *C* flutter. In all cases where a transition takes place with change of rolling moment of inertia, it is from type *A* to type *E*. This transition is obtained with the localised mass $5 \cdot 9$ in. aft of the spar, and it occurs at lower values of the fuselage rolling moment of inertia as the mass is moved forward.

7. *Discussion.*—7.1. *Symmetric Tests.*—Most of the tests described in Section 5 were made with a fuselage having constant inertia properties. The only variations in fuselage inertia parameters were made in the additional tests, where the mass and pitching moment of inertia were increased. For localised masses at any spanwise section, the flutter characteristics approximate to the fixed-root characteristics provided the fuselage inertia is large enough. As the fuselage inertias are reduced from this large value the flutter speeds tend to fall for localised-mass positions well forward on the wing, and to rise for positions aft. Where a transition from one type of flutter to another occurs (type *A* to type *B* for a localised mass at the tip, and type *A* to type *C* for a mass at $0 \cdot 5$ and $0 \cdot 25$ span) the chordwise position of the localised mass moves forward as the inertias of the fuselage are reduced. It may be concluded that, compared with fixed root, the effect of the symmetric body freedoms with a representative fuselage is to increase the range of position of the localised mass on the wing for which type *A* flutter will occur, and to reduce the flutter speeds for forward positions of the localised mass which, under fixed-root conditions, give an overtone type of flutter. It should be noted however, that the values of fuselage mass and pitching radius of gyration used in the tests (Section 5.3) are small by present-day standards. For a single-engined fighter aircraft the fuselage mass might be twice the wing mass, and the pitching radius of gyration of the fuselage more than twice the wing mean chord. It is evident, therefore, that the wing flutter characteristics of such an aircraft will lie somewhere between the fixed-root and the free-root results of this report. The effect of tailplane in all the tests was small, but the flutter of the bare wing without the tailplane was of the disturbed-root type throughout, in which conditions (on the basis of fixed-root tests) the tailplane would have no

effect on the flutter speed or type of flutter[2]. There must be some doubt as to the flutter properties of a configuration where the fuselage inertia conditions are such that body-freedom flutter occurs with no localised mass. This, however, is unlikely to occur in practice as the requirements for this type of flutter (no tailplane, small angle of sweepback and low fuselage pitching moment of inertia[2]) are unlikely to be satisfied with present design trends.

The two localised-mass values investigated in the tests are sufficient to show that the effect of mass value is similar root free to its effect root fixed. Since the flutter obtained with the symmetric body freedoms is predominantly type A and the flutter speeds for the two mass values tested do not, in general, differ appreciably (a characteristic of the same two mass values in type A flutter with the root fixed), it may be concluded that for localised-mass values between zero and the lowest value tested the flutter speeds will, in all probability, vary in much the same way with the root free as with the root fixed. The optimum position for a localised mass was found in the fixed-root tests to be at $0 \cdot 75$ span for mass values greater than $0 \cdot 3$ of the wing mass[1]. A forward chordwise position of a localised mass could give a very high flutter speed. The same is true of the symmetric body-free case, although the present tests do not determine the minimum value of localised mass required, and indicate that a more forward chordwise position may be required than with fixed root.

The symmetric test results may be summarised as follows: The effect of the body freedoms is to lower the critical speeds for localised-mass positions that, under fixed-root conditions, are the most favourable from the flutter aspect. This speed reduction is not due to the occurrence of any new type of flutter, but to the modification of the fixed-root pattern of results in such a way that the more favourable forms of flutter (the overtone types B and C) occur for fuselage inertia values that are outside the representative range for aircraft.

7.2. *Antisymmetric Tests.*—The antisymmetric test results, described in Section 6, are more complex than the symmetric by reason of the number of types of flutter that occurred. The existence of many types of flutter, each of which may be dependent on more than one parameter, suggests that to assess the flutter characteristics of an actual aircraft wing there is probably no alternative to a detailed investigation, although tests of a general research nature, such as those described in this report, may be useful in helping to determine the degrees of freedom to be considered in a calculation.

Of the five types of flutter encountered in the present antisymmetric tests, the three types A, B and C occur with the root fixed[1], and also with the root free in roll. Types D and E occur only with the antisymmetric freedom and are both associated with large rolling amplitudes relative to the wing displacements. With the localised-mass values tested, a wide range of frequency is covered by the five types of flutter, from $1 \cdot 3$ c.p.s. for type A flutter to $14 \cdot 0$ c.p.s. for type B. One of the effects of the rolling freedom on flutter of types B and C is to cause a variation in flutter speed with variation of rolling moment of inertia. With the root fixed, the speeds at which these types of flutter occurred were constant with variation both in localised-mass value and in chordwise position of the mass[1]. It is evident that the freedom in roll results in variation of flutter speed which, although primarily dependent upon the value of fuselage rolling moment of inertia, is not constant with variation of localised-mass value and chordwise position of the mass. In other words the flutter of types B and C occurs at constant speed for variation of localised-mass value and chordwise position only when the fuselage rolling moment of inertia is sufficiently large to approximate to the fixed-root condition.

In the case of a wing fixed at the root, the boundaries between the types of flutter occurring with a localised mass attached to the wing could be fairly simply interpreted[1]. The transition curves representing the changes from a fundamental-type flutter to an overtone type approximated to curves showing localised-mass conditions that would give flutter speeds above or below the bare-wing values. No such simple interpretation is possible with the results of the present tests, partly because of the speed variations occurring with each type of flutter, and partly because of the number of types of flutter that were obtained. Moreover, in the present tests the emphasis is placed on the effects of variation of rolling moment of inertia, and the transition curves have been drawn to show mainly the effect of variation of this parameter.

Fig. 41 shows the boundaries between flutter of types A, B and E for the mass of 4·46 lb at the tip section. Fuselage rolling moment of inertia is plotted against chordwise position of the mass, and it may be seen that the boundary represented by the transition from type A flutter to one of the other types is almost independent of the value of the fuselage rolling moment of inertia. On the other hand the boundary between type B and type E flutter is dependent on both chordwise position of the mass and fuselage rolling moment of inertia. The corresponding curve for the mass of 2·46 lb at the tip is shown in Fig. 42. The boundary for type A flutter is again relatively insensitive to fuselage rolling moment of inertia, but is forward of the boundary for the larger mass. The boundary between types B and E flutter is similar to that obtained with the larger mass, but a small region of type D flutter occurs for values of fuselage rolling moment of inertia near zero, and for positions of the localised mass near the wing leading edge. The fixed-root condition in Figs. 41 and 42 is represented by an infinite positive value of fuselage rolling moment of inertia, and it may be seen that in this condition only flutter of types A and B would occur.

The tests with localised masses at 0·75 and 0·5 span were not sufficiently detailed for boundary curves to be drawn. In any case, the flutter characteristics closely resembled the corresponding fixed root tests[1], and in particular, the introduction of the rolling freedom did not result in any new types of flutter. The tests with the localised mass at 0·25 span, however, were made in sufficient detail for the transition curves to be drawn (Figs. 43 and 44). Types A, C and E flutter occurred with the mass of 4·46 lb, but only types A and C with the mass of 2·46 lb. Fig. 43 indicates that the range of chordwise position of the localised mass and values of the fuselage rolling moment of inertia for which type C flutter occurs is relatively small, and in Fig. 44 this region does not occur. With the root fixed the transition from type A to type C flutter occurs when the mass is well forward of the spar; if the fixed-root case approximates to large values of the fuselage rolling moment of inertia, then it is not obvious from Figs. 43 and 44 how the test results can be consistent, and it is suggested that the transition curves shown do not fully indicate the flutter regions, particularly for large values of fuselage rolling moment of inertia.

A clearer view can be obtained of the way in which the various types of antisymmetric flutter form a co-ordinated picture by drawing perspective graphs of flutter speed against fuselage rolling moment of inertia and localised mass chordwise position. This has been done for two of the more interesting results (Figs. 45 and 46). It may be noted that the boundary curves of Figs. 41 to 44 are the boundaries of the flutter regions shown in the perspective diagrams projected on to a plane of constant flutter speed.

To enable a direct comparison to be made of the flutter characteristics of the model under fixed-root and free-root conditions, Figs. 31 to 40 have been drawn by interpolating the test results at constant values of fuselage rolling moment of inertia. The corresponding fixed-root flutter speeds and frequencies are also shown in the figures. The antisymmetric body freedom has a beneficial effect on flutter speed for localised masses at 0·5 span and at sections outboard, and this applies not only for the overtone forms of flutter but also for the fundamental form, type A. Figs. 37 to 40 for the localised mass at 0·25 span show clearly that the rolling freedom radically alters the flutter characteristics, in particular causing a reduction of flutter speed for forward chordwise positions of the localised mass.

The optimum localised-mass position that occurred in fixed-root tests[1] and in the symmetric body-freedom case (Section 7.1) appears to be in the same region in the antisymmetric case, *i.e.*, at 0·75 span, though the present tests do not determine the minimum value of localised mass necessary to ensure a high flutter speed.

7.3. *Comparison of Symmetric, Antisymmetric and Fixed-Root Tests.*—Although symmetric and antisymmetric flutter have been separately considered in this report, it will normally be necessary to consider both forms when a flutter analysis of a specific wing with a localised mass is undertaken. Certain important points emerge from a comparison of the symmetric and antisymmetric test results. Firstly, it seems fairly certain that, for conventional aircraft, the symmetric case will be more critical than the antisymmetric for localised masses such as fuel tanks that are normally carried on outboard sections of the wing. Secondly, a wing carrying heavy inboard localised masses, such as wing engines that are normally mounted well forward, may be susceptible to antisymmetric flutter at a lower critical speed than symmetric flutter. Thirdly, the existence of an optimum position for the localised mass both in the symmetric and antisymmetric conditions (as well as in the fixed-root case[1]) may lead to a useful guide in the problem of correct positioning of a localised mass for the avoidance of flutter. For the wing tested, the optimum position (root free or fixed) is in the region of three-quarter span and well forward on the wing. Resonance tests on the wing with no localised mass show that the nodal line in the overtone flexure mode lies in this region, slight differences being obtained according to the root restraint (Fig. 7). It may be that the optimum section is associated with the position of the nodal line in the overtone flexure mode, subject of course to the overriding conditions that the magnitude of the localised mass and its chordwise position shall be such as to avoid flutter in the fundamental modes of flexure and torsion.

It is often the case that a fixed-root test is used as a guide to the behaviour of a wing-mass system under root-free conditions. The present tests clearly show how unreliable this procedure can be; the body freedoms, both symmetric and antisymmetric, have been shown to be relatively unimportant for a conventional aircraft[2] from the flutter aspect. But the addition of a large localised mass to a wing may make the body-freedom parameters important in such a way that a flutter speed obtained from a fixed-root test is unconservative.

The main conclusion that can be drawn from the tests is that the flutter properties of a wing carrying a localised mass, and having body freedoms, are dependent on a large number of parameters; variation of any one of these parameters may alter both the flutter speed and the flutter mode, and it is obviously out of the question to attempt to use a general investigation to obtain a flutter speed estimate in a particular case.

8. *Conclusions.*—(*a*) Symmetric and antisymmetric body freedoms are both found to have important effects on the flutter characteristics of a wing carrying a localised mass. In general, the symmetric forms of flutter yield lower flutter speeds than the antisymmetric for localised masses at outboard sections of the wing, but the antisymmetric case may be the more critical for heavy inboard localised masses.

(*b*) Fixed-root tests of localised mass loadings do not provide a reliable guide to the free-root characteristics.

(*c*) The complexity of the test results is an indication that detailed use cannot be made of a general research investigation for predicting the flutter properties of a particular case of localised mass loading.

(*d*) The three types of flutter that occurred with the root fixed were also obtained, in slightly modified form, with the symmetric body freedoms. In the antisymmetric case the three types again occurred in modified form, together with two further types. If the three fixed-root types of flutter are counted separately when modified by the inclusion of root displacement, a total of eleven different forms of flutter was obtained.

(*e*) Previous results had shown the optimum position for a localised mass to be in the region of 0·75 span for a wing fixed at the root. With the root free this optimum position applies equally to the present model provided the mass value and position are such that the fundamental type of flutter, involving flexure and torsion of the wing in its fundamental modes, is avoided.

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No.	*Author*	*Title, etc.*
1	D. R. Gaukroger	Wind-tunnel tests on the effect of a localised mass on the flutter of a sweptback wing with fixed root. R.A.E. Report Struct. 159. A.R.C. 16,811. December, 1953.
2	D. R. Gaukroger	Wind-tunnel tests on symmetric flutter of sweptback wings including the tailplane effect. R. & M. 2911. April, 1952.
3	P. Jordan and F. Smith . .	Wind-tunnel technique for flutter investigations on swept wings with body freedoms. R. & M. 2893. September, 1950.

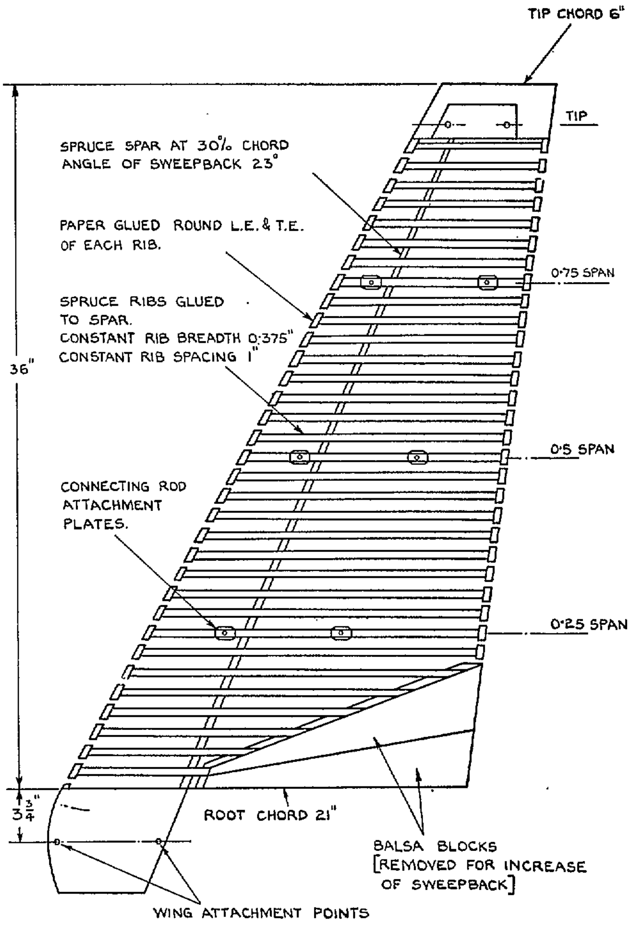

FIG. 1. Details of model wing.

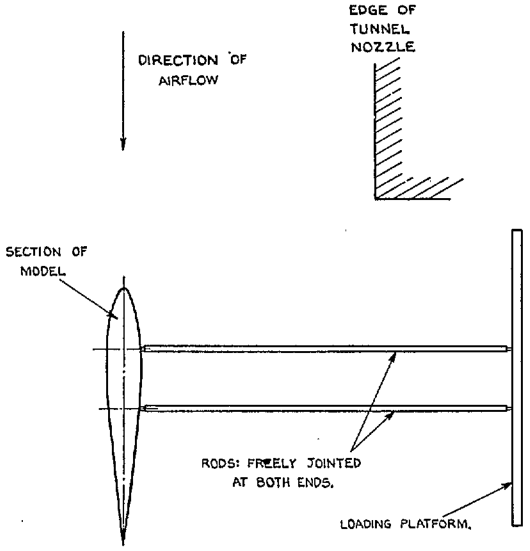

FIG. 2. Method of applying inertia loads.

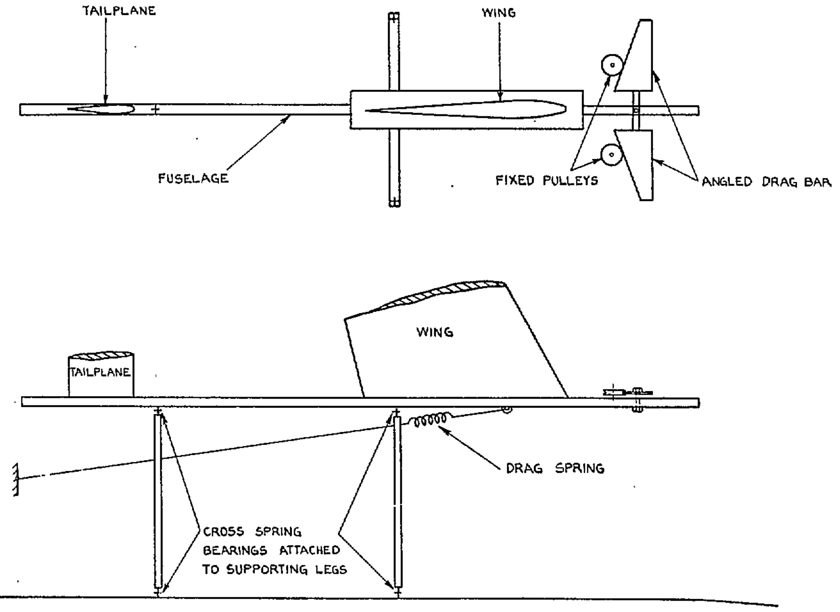

FIG. 3. Arrangement of symmetric rig.

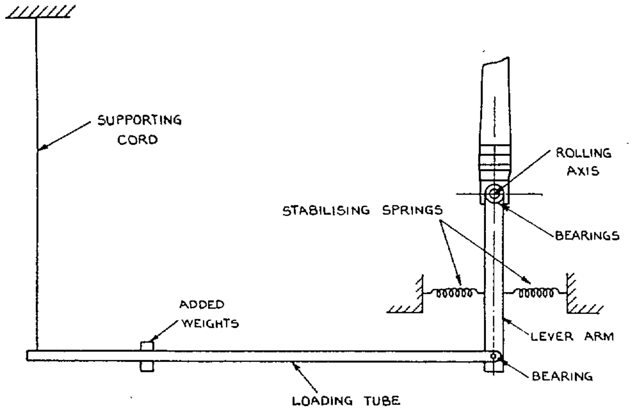

FIG. 4. Arrangement of antisymmetric rig.

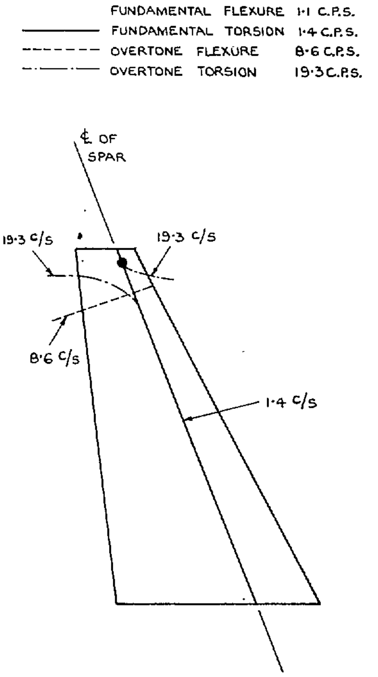

FIG. 5. Normal mode frequencies and nodal lines for a localised mass of 4·46 lb on the spar at the tip—Fixed root.

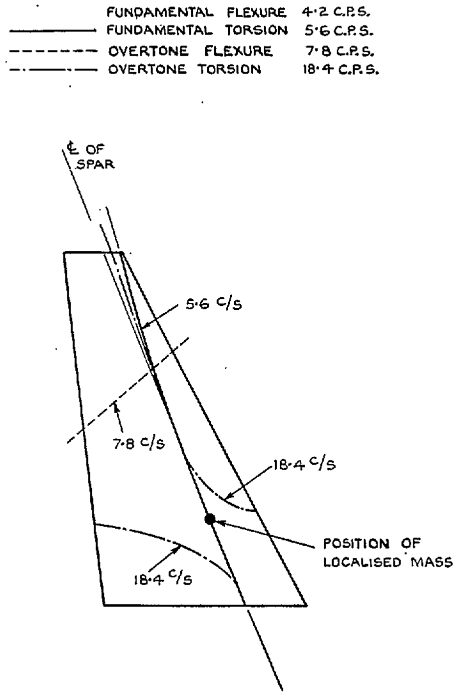

FIG. 6. Normal mode frequencies and nodal lines for a localised mass of 4·46 lb on the spar at 0·25 span—Fixed root.

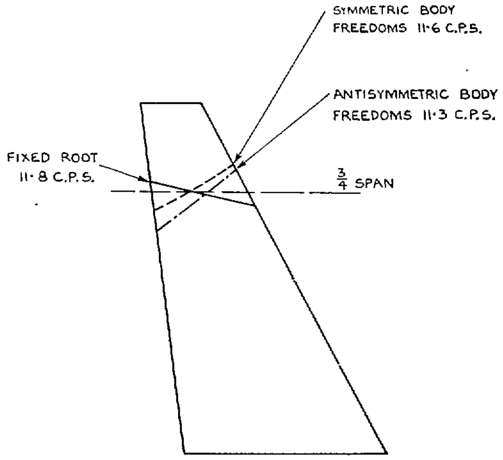

FIG. 7. Nodal line positions and frequencies for the flexural overtone modes of the bare wing.

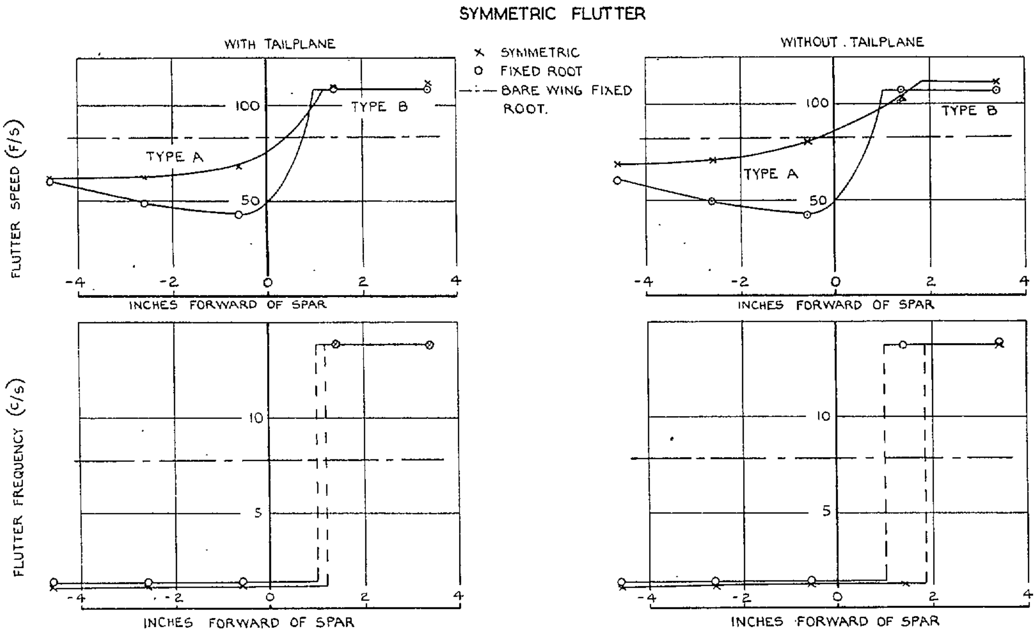

FIG. 8. The effect of chordwise position on flutter speed and frequency for a localised mass of 4·46 lb at the tip.

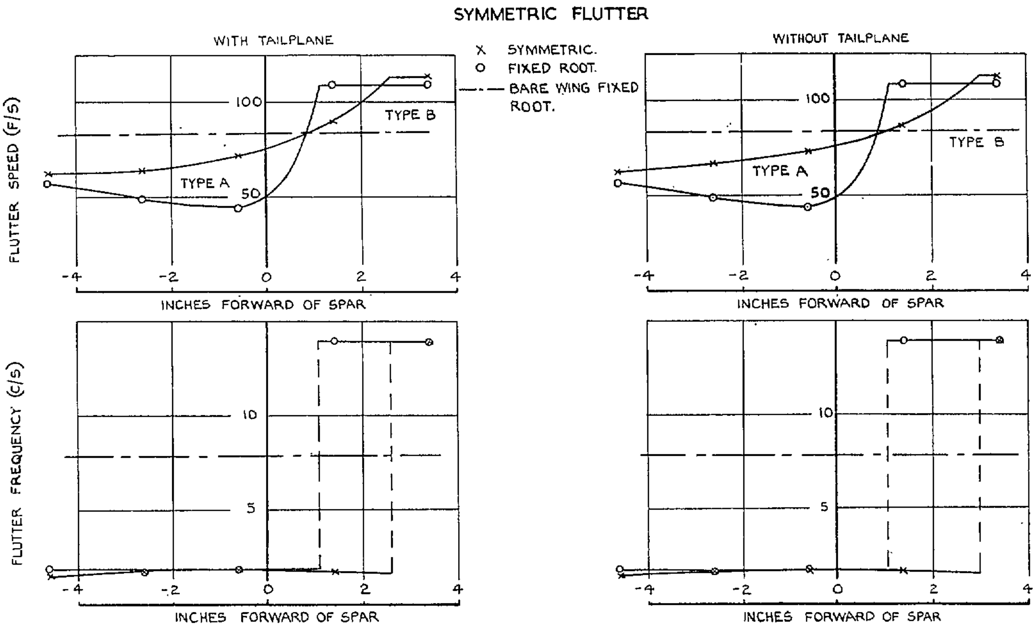

FIG. 9. The effect of chordwise position on flutter speed and frequency for a localised mass of 2·46 lb at the tip.

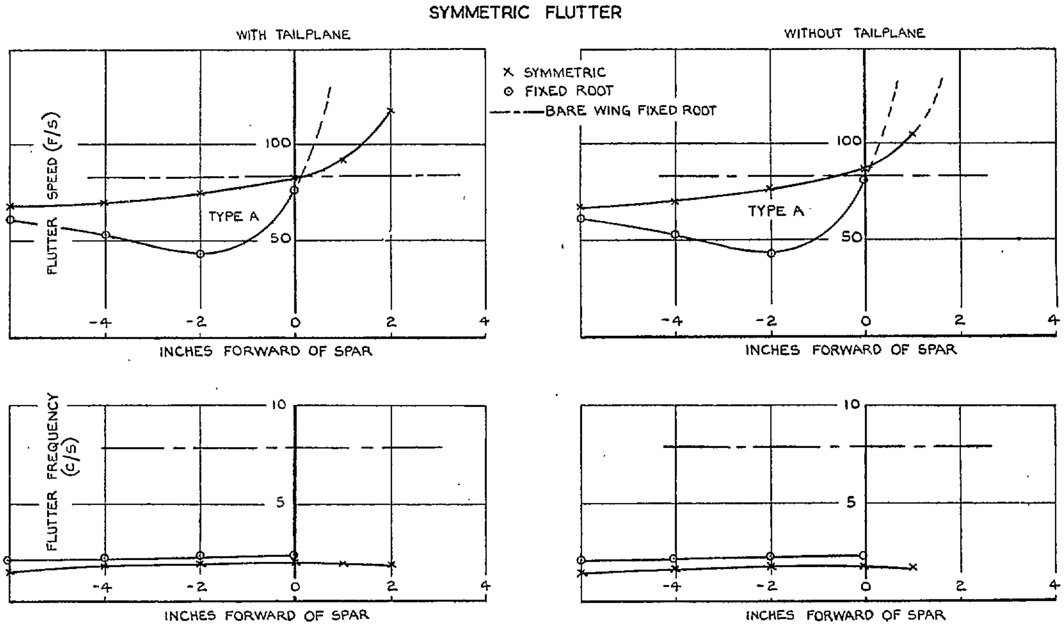

FIG. 10. The effect of chordwise position on flutter speed and frequency for a localised mass of 4·46 lb at 0·75 span.

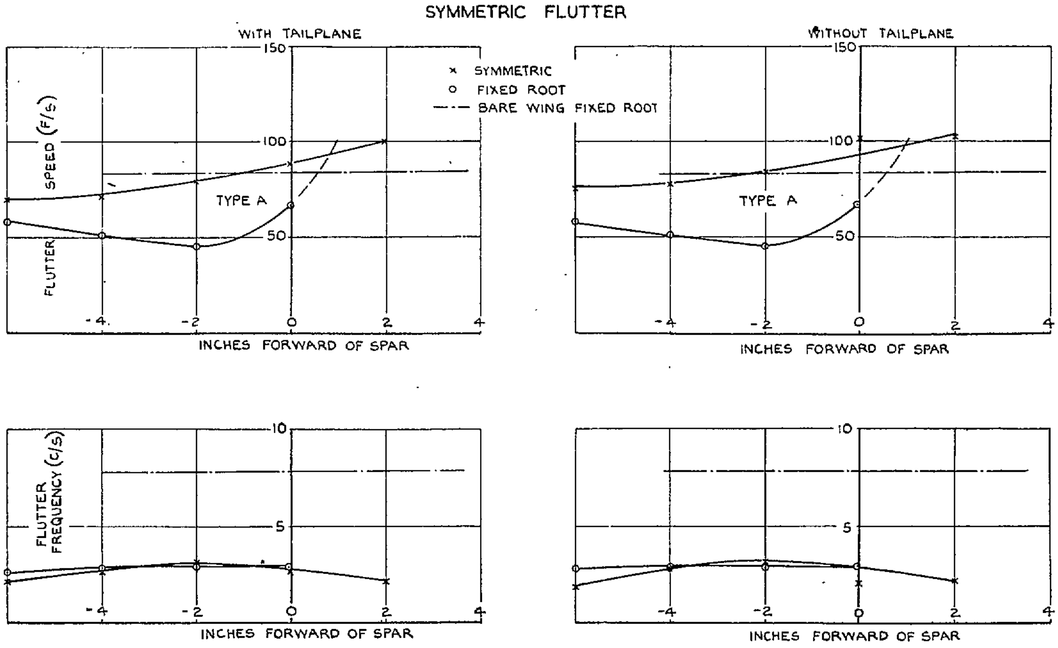

FIG. 11. The effect of chordwise position on flutter speed and frequency for a localised mass of 2·46 lb at 0·75 span.

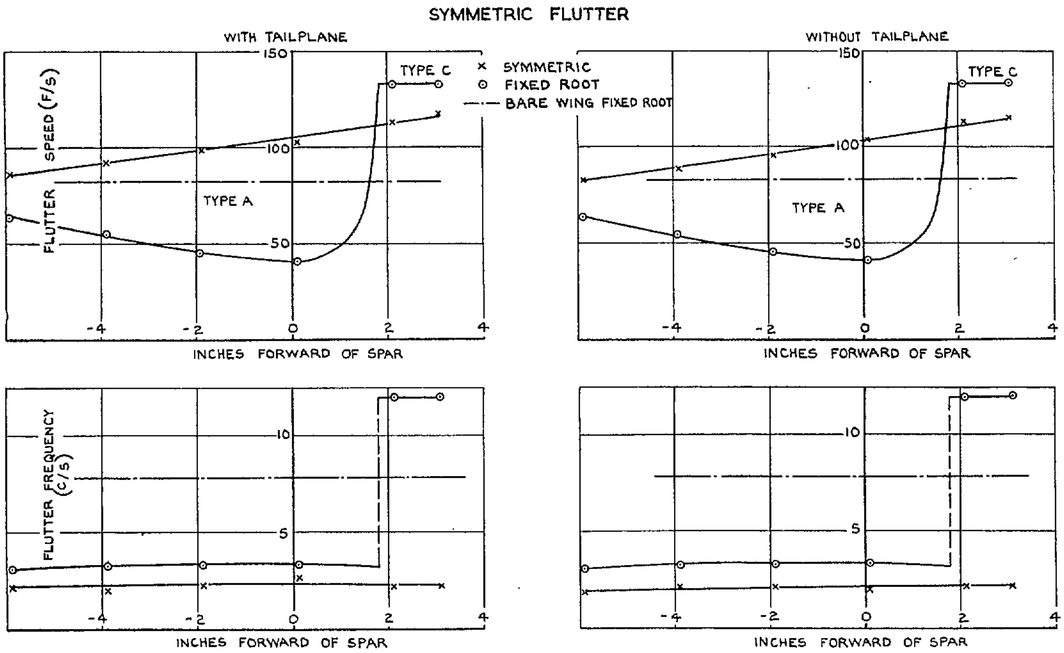

FIG. 12. The effect of chordwise position on flutter speed and frequency for a localised mass of 4·46 lb at 0·5 span.

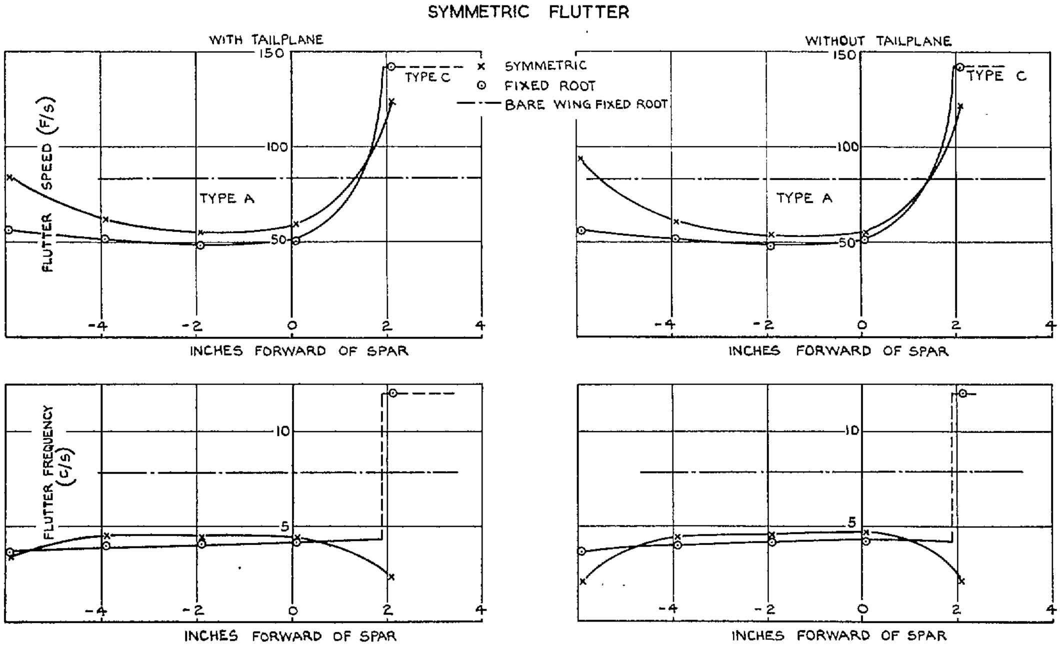

FIG. 13. The effect of chordwise position on flutter speed and frequency for a localised mass of 2·46 lb at 0·5 span.

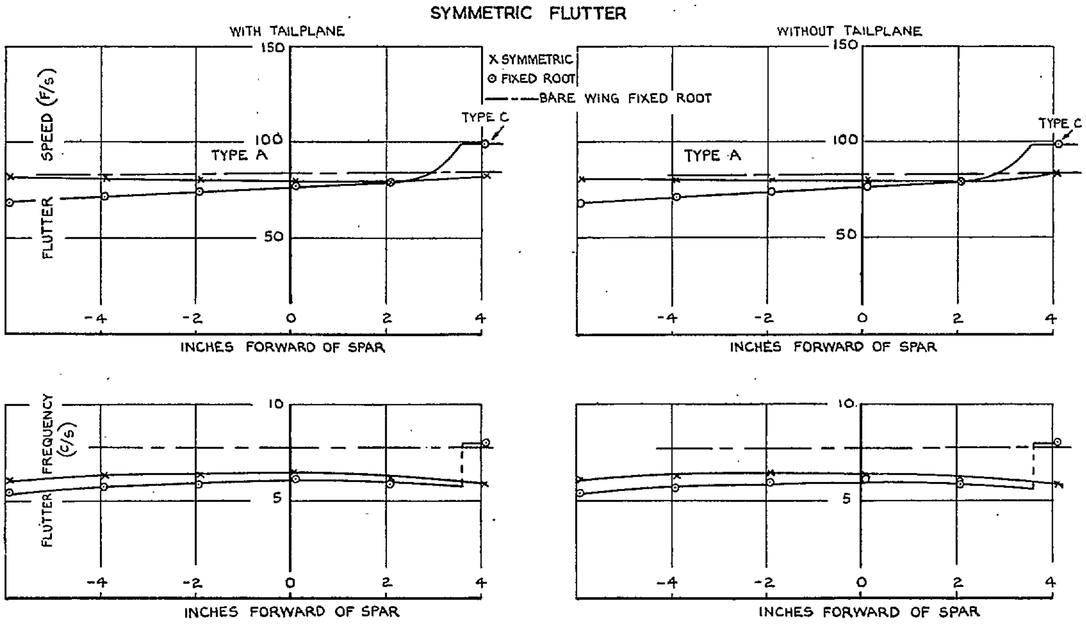

Fig. 14. The effect of chordwise position on flutter speed and frequency for a localised mass of 4·46 lb at 0·25 span.

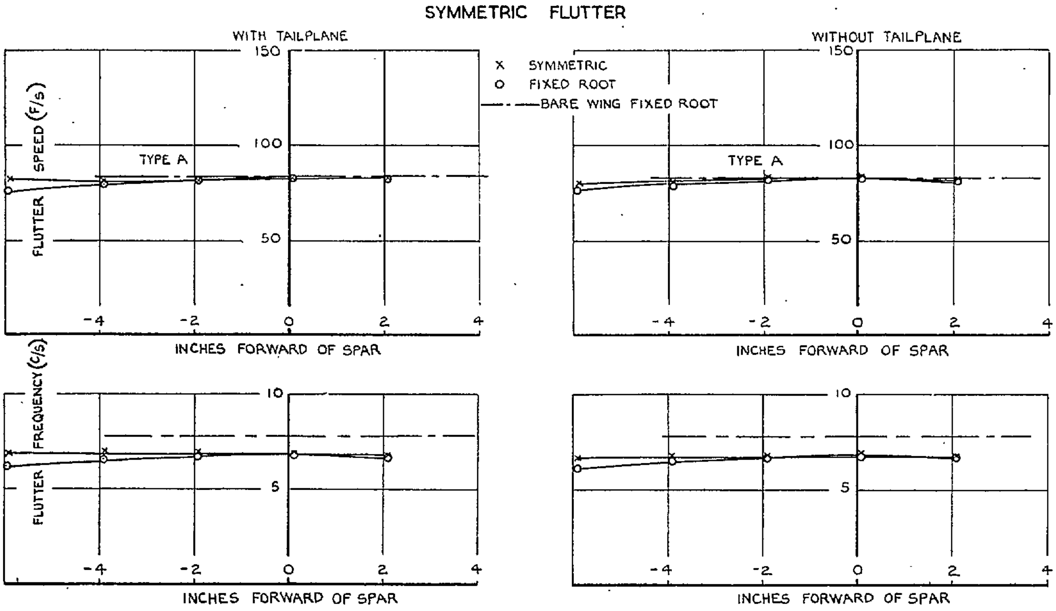

Fig. 15. The effect of chordwise position on flutter speed and frequency for a localised mass of 2·46 lb at 0·25 span.

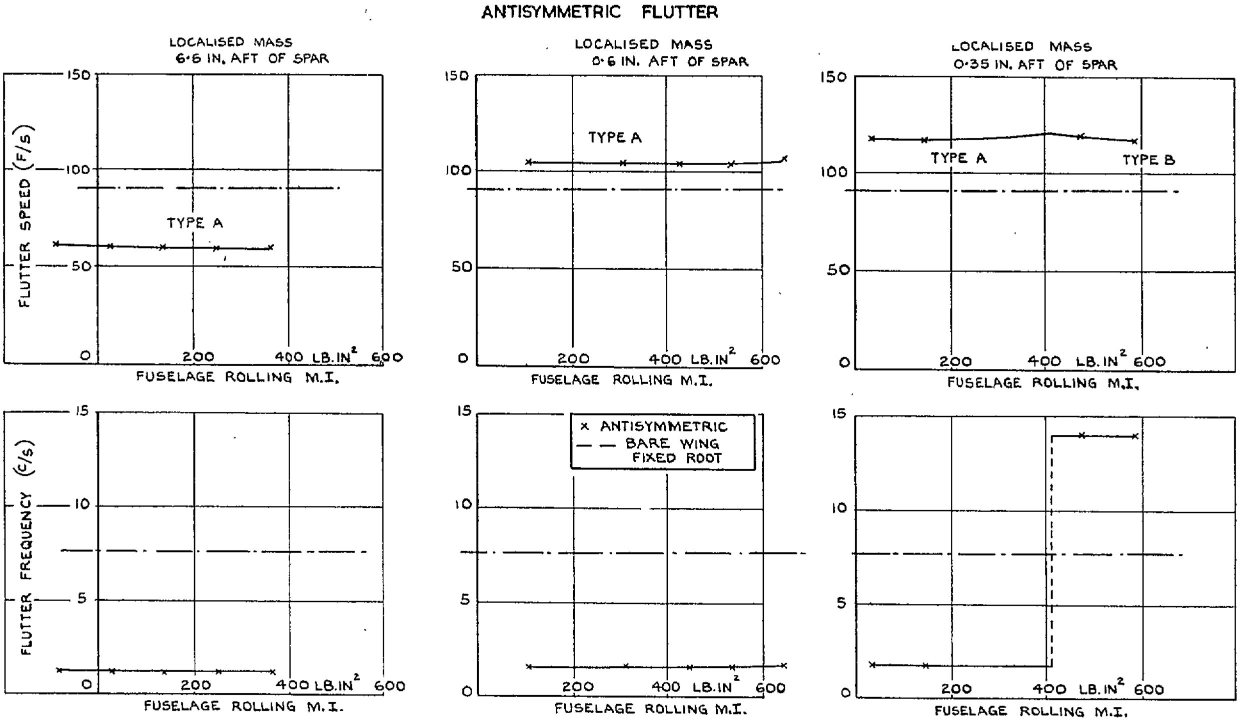

FIG. 16. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 4·46 lb at the tip.

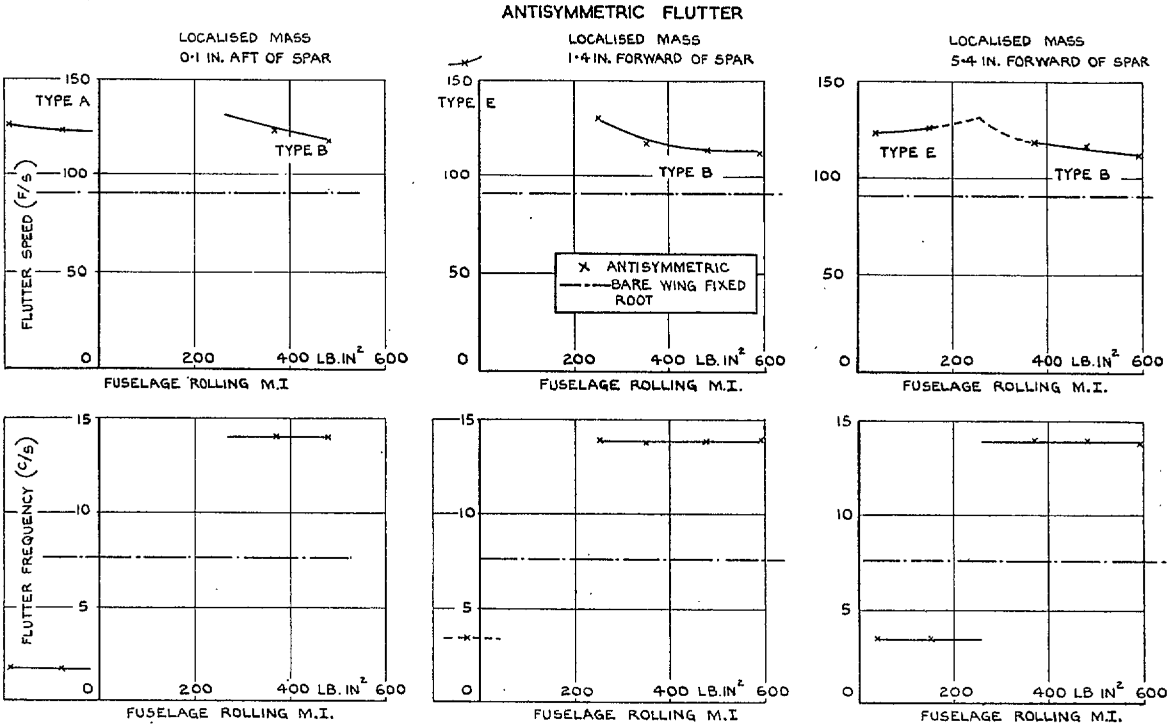

FIG. 17. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 4·46 lb at the tip.

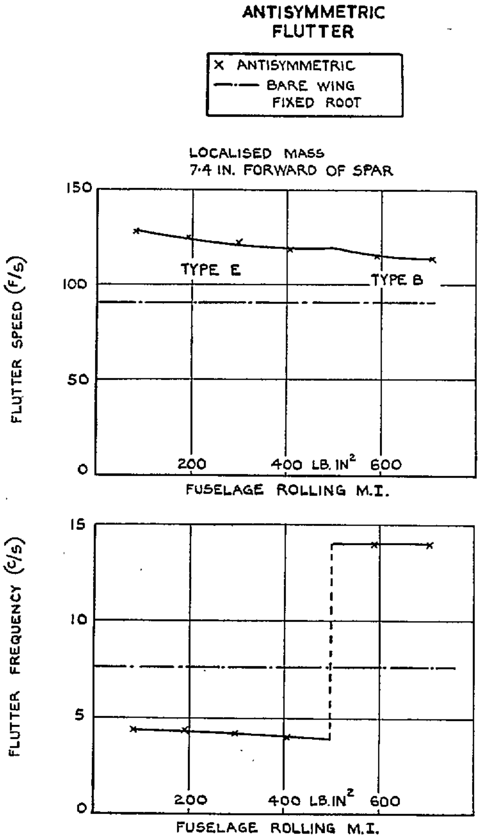

FIG. 18. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 4·46 lb at the tip.

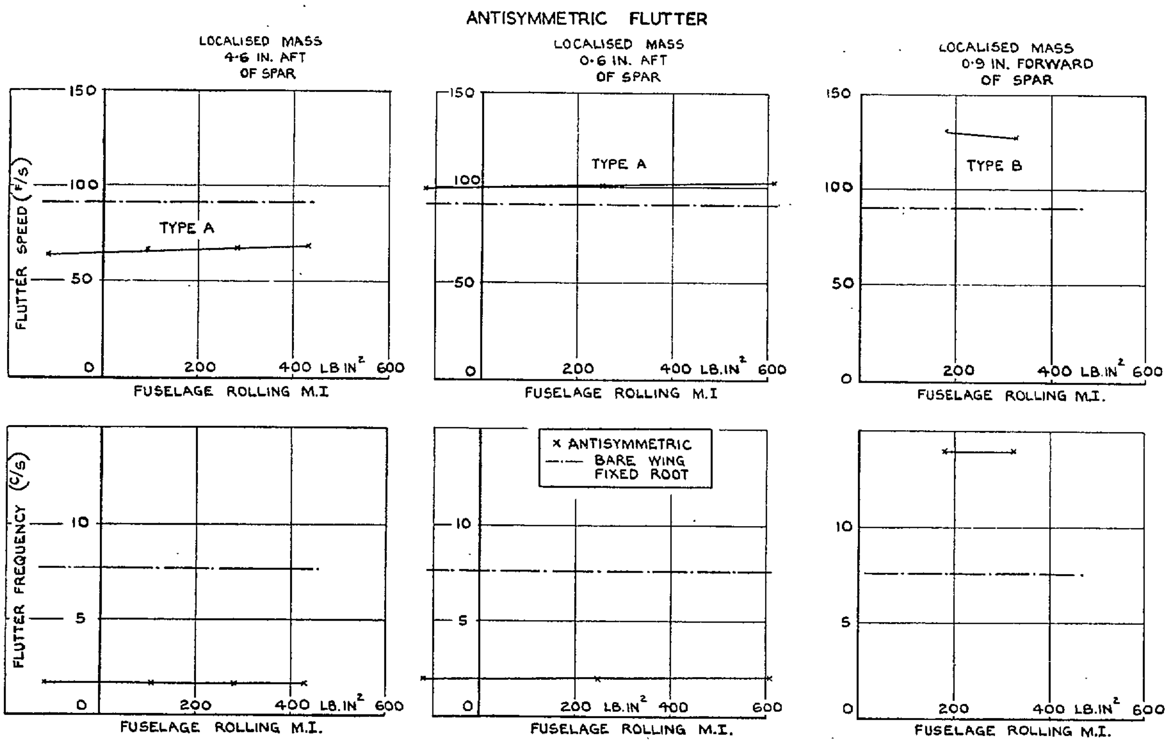

FIG. 19. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 2·46 lb at the tip.

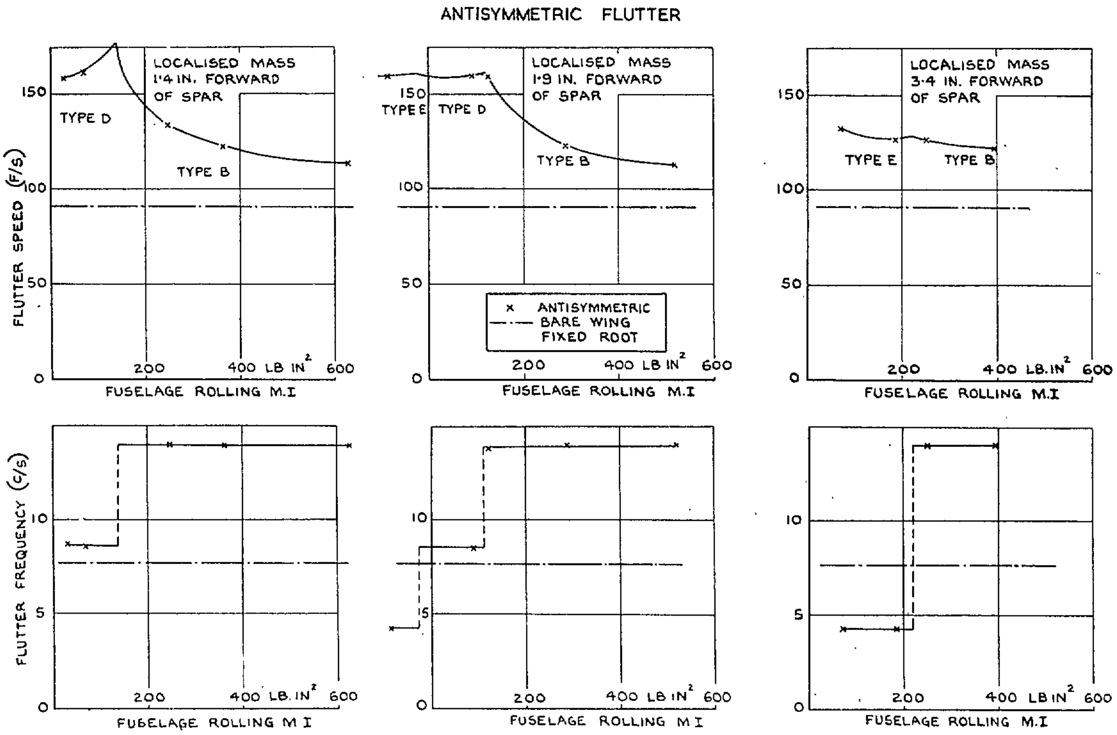

FIG. 20. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 2·46 lb at the tip.

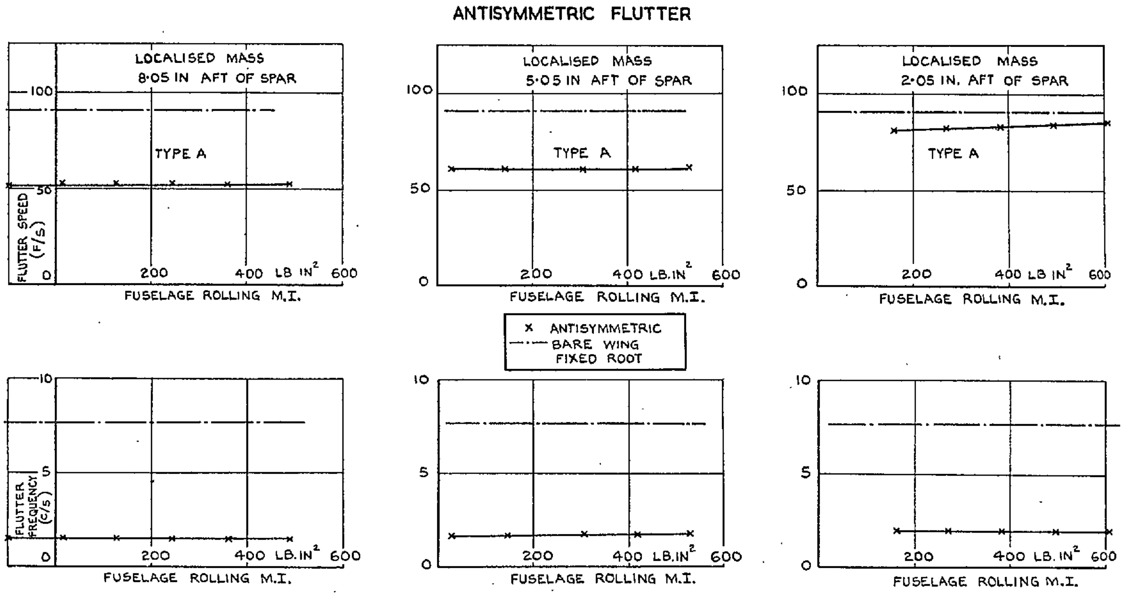

FIG. 21. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 4·46 lb at 0·75 span.

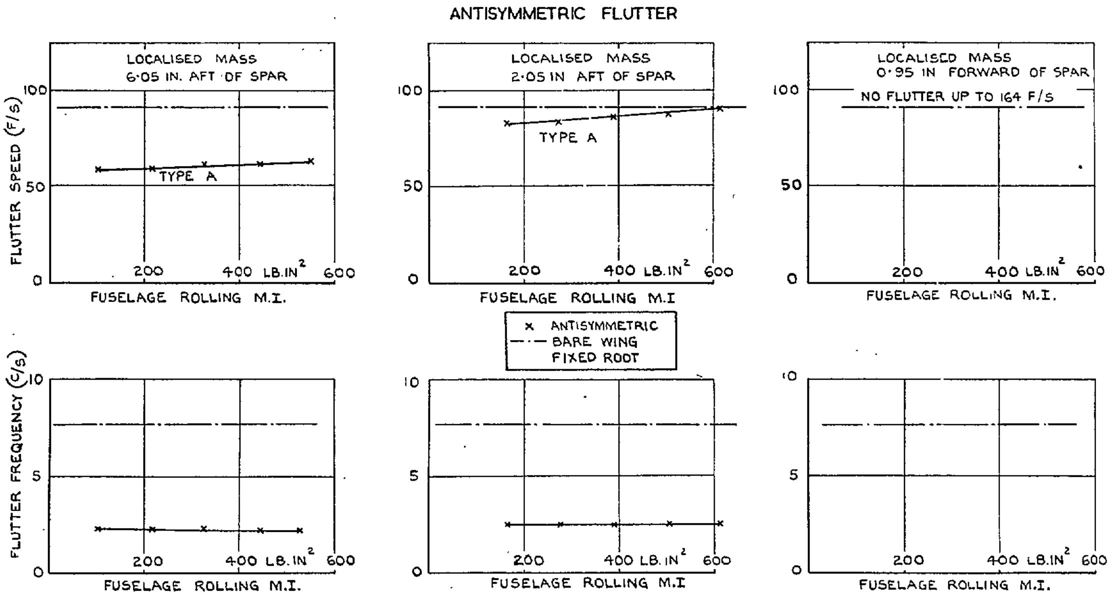

Fig. 22. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 2·46 lb at 0·75 span.

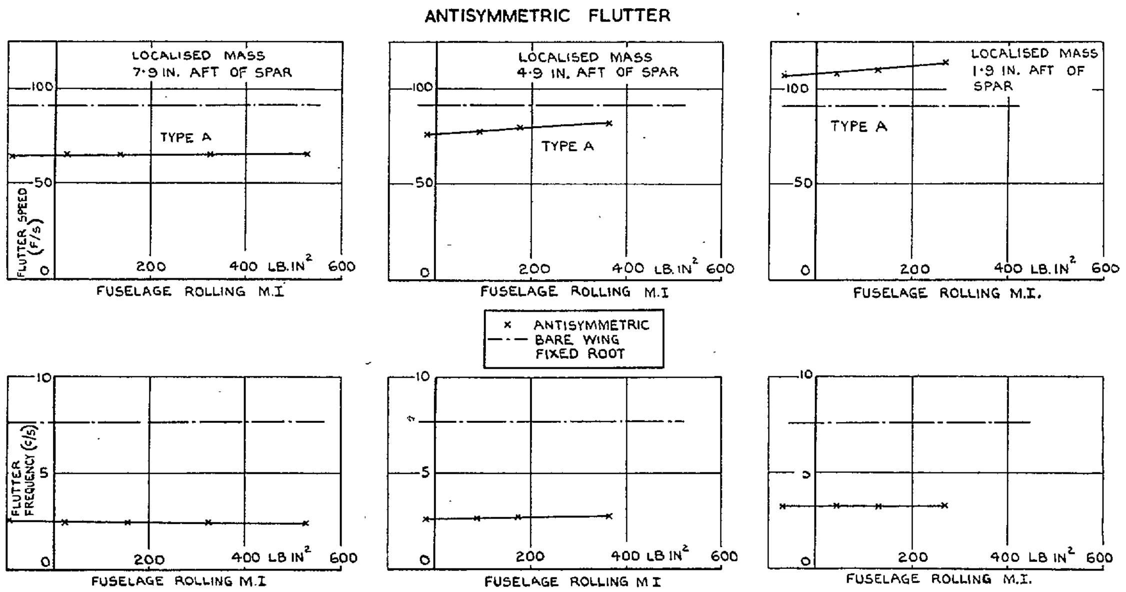

Fig. 23. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 4·46 lb at 0·5 span.

ANTISYMMETRIC FLUTTER

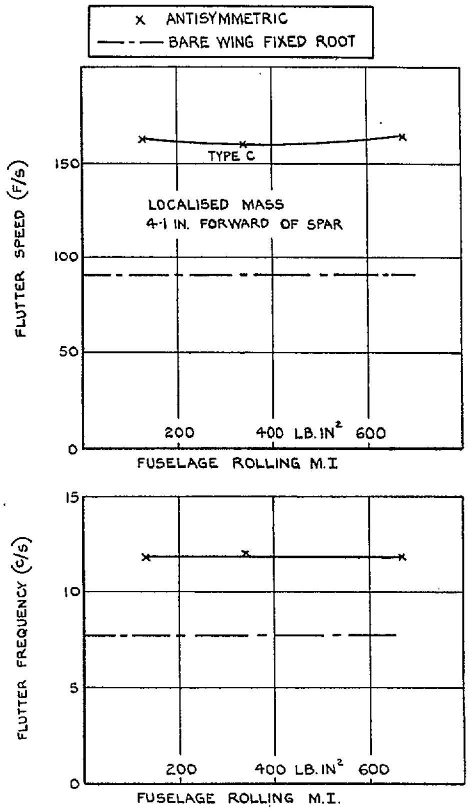

FIG. 24. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 4·46 lb at half span.

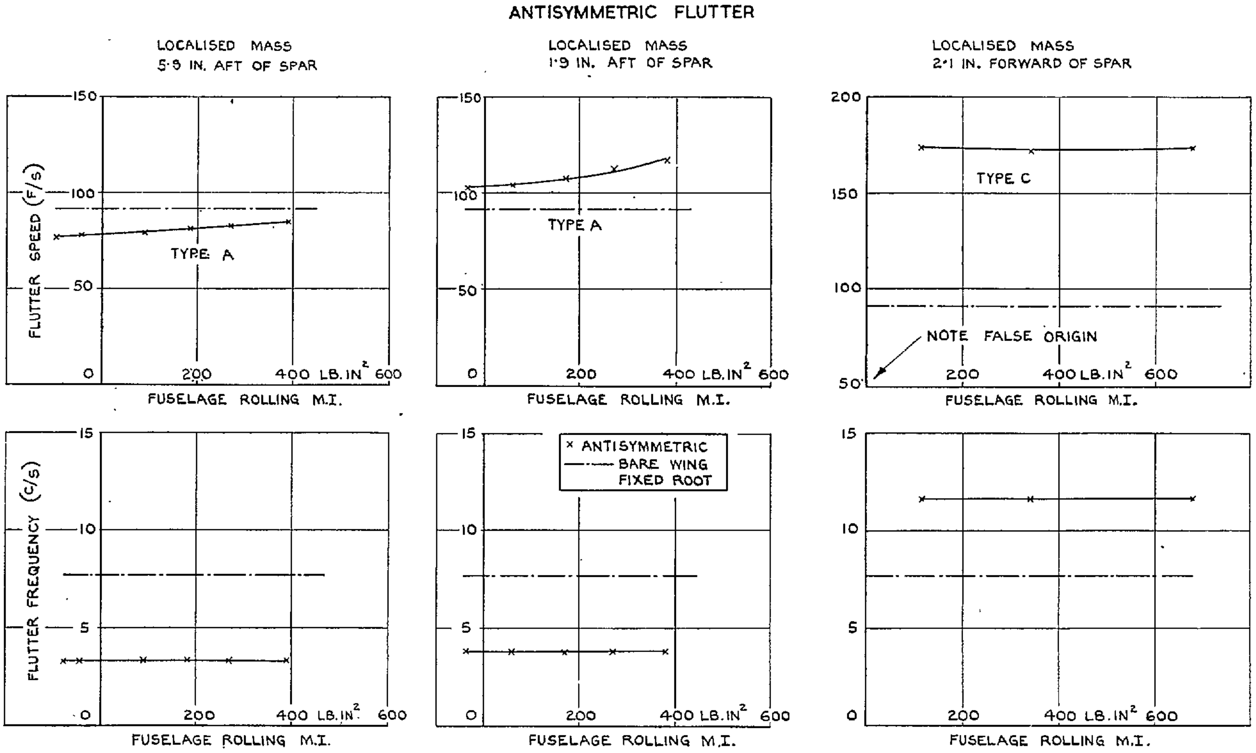

FIG. 25. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 2·46 lb at 0·5 span.

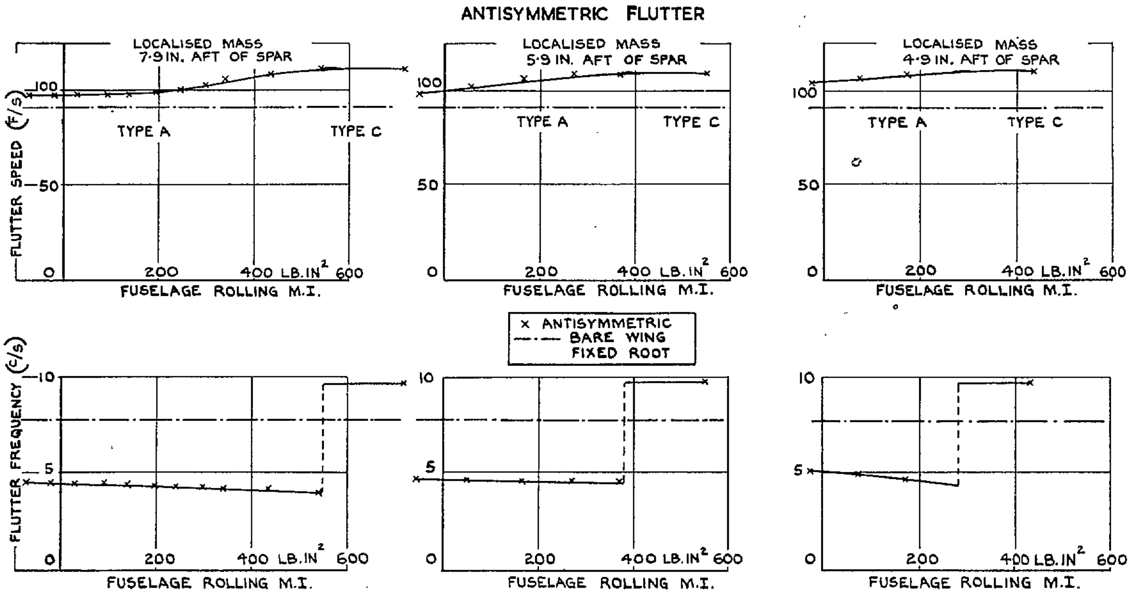

FIG. 26. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 4·46 lb at 0·25 span.

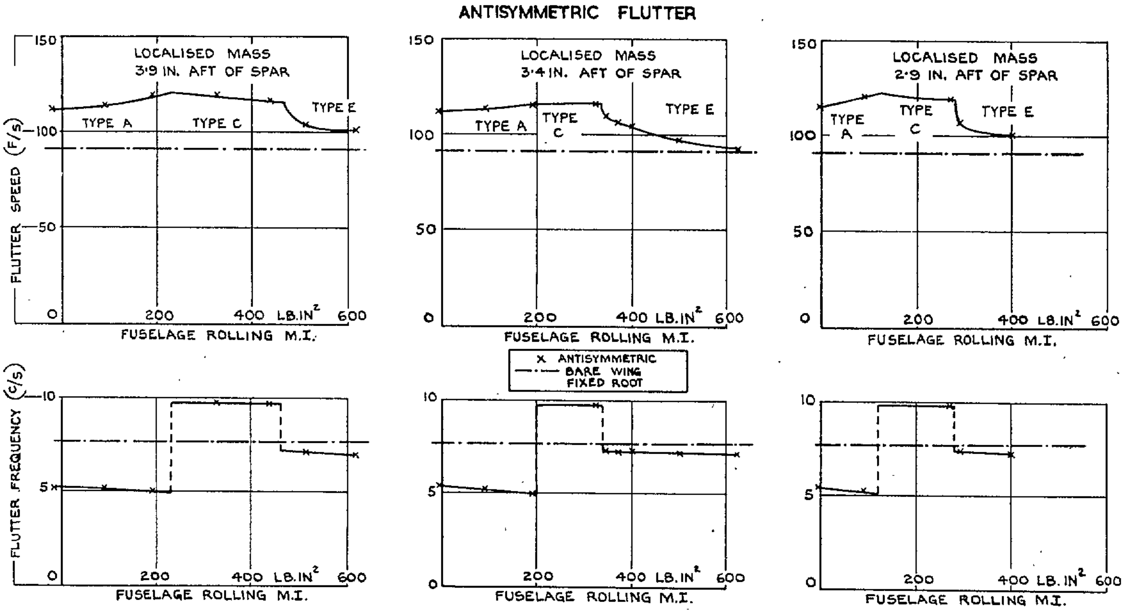

FIG. 27. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 4·46 lb at 0·25 span.

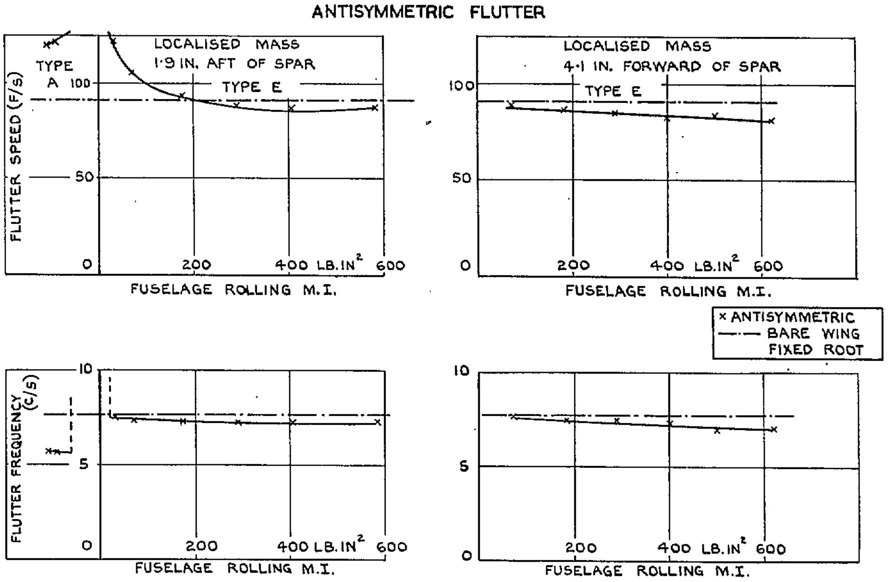

FIG. 28. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 4·46 lb at 0·25 span.

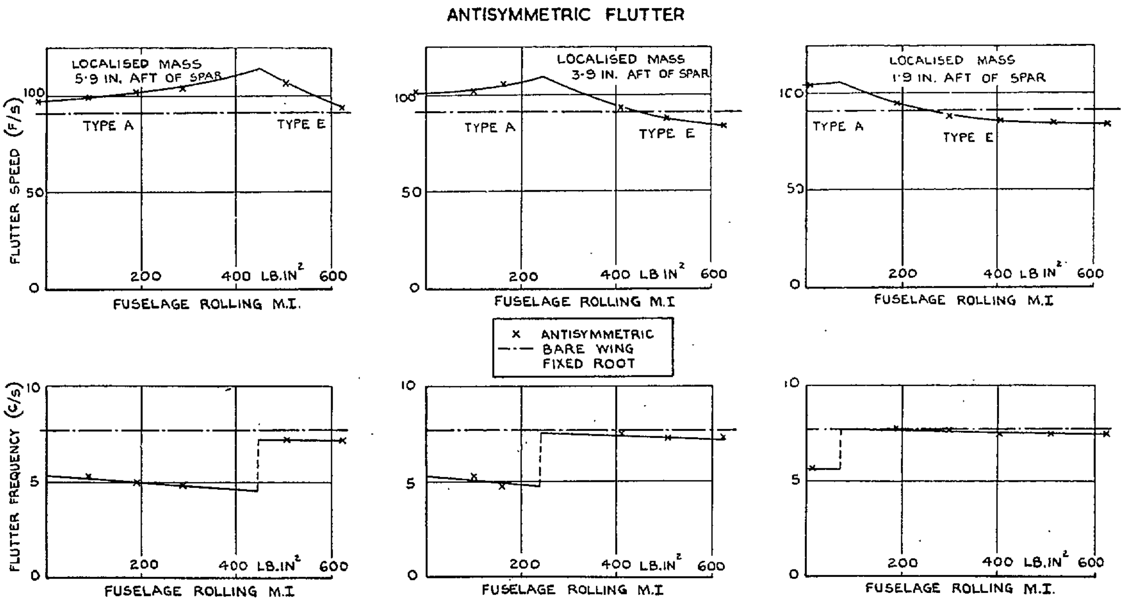

FIG. 29. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 2·46 lb at 0·25 span.

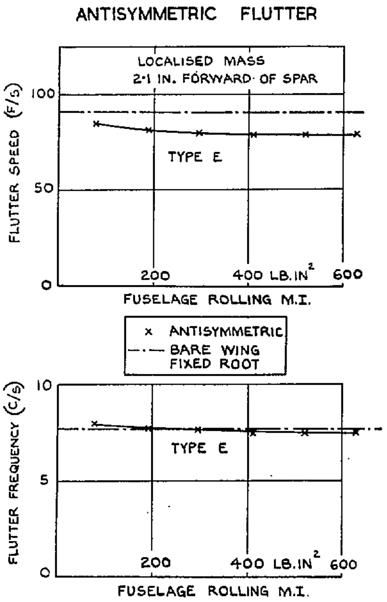

FIG. 30. The effect of fuselage rolling moment of inertia on flutter speed and frequency with a localised mass of 2·46 lb at 0·25 span.

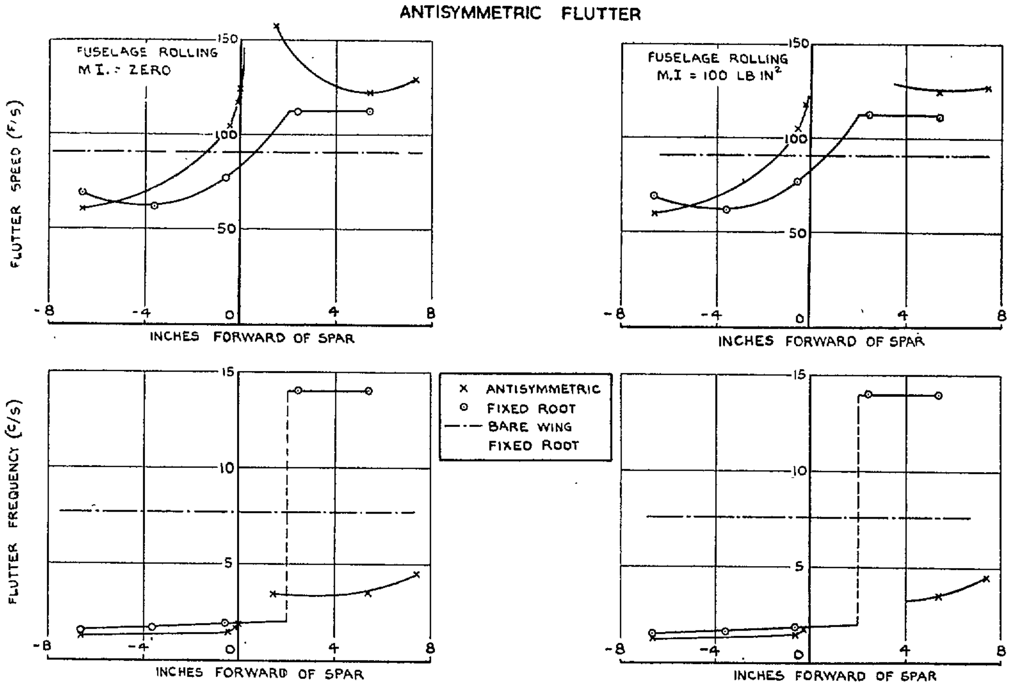

Fig. 31. The effect of chordwise position on flutter speed and frequency for a localised mass of 4·46 lb at the tip.

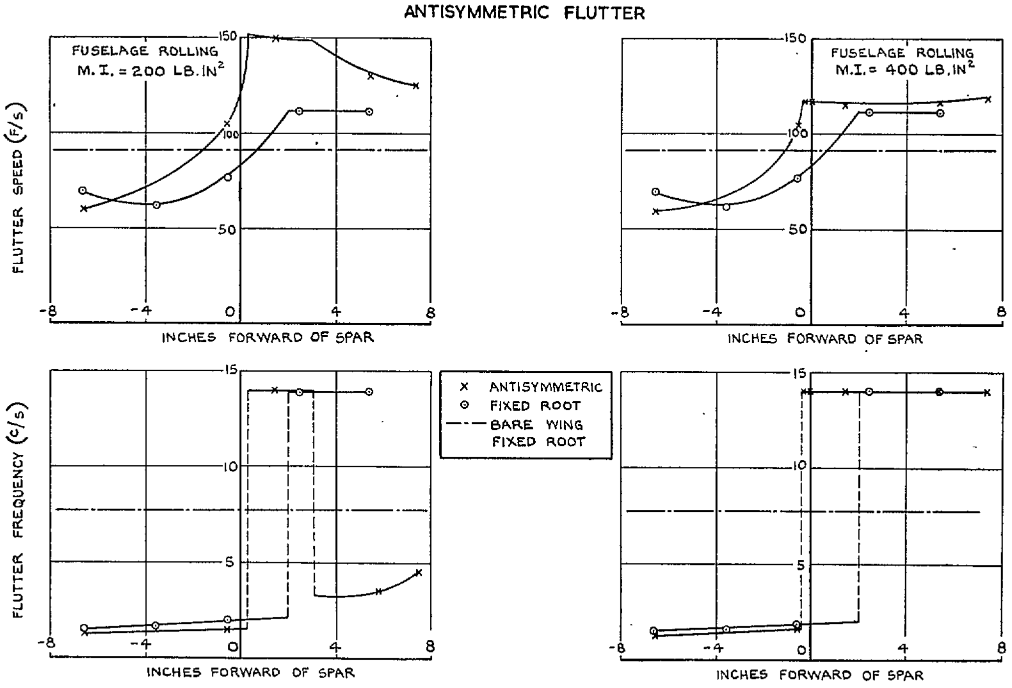

Fig. 32. The effect of chordwise position on flutter speed and frequency for a localised mass of 4·46 lb at the tip.

ANTISYMMETRIC FLUTTER

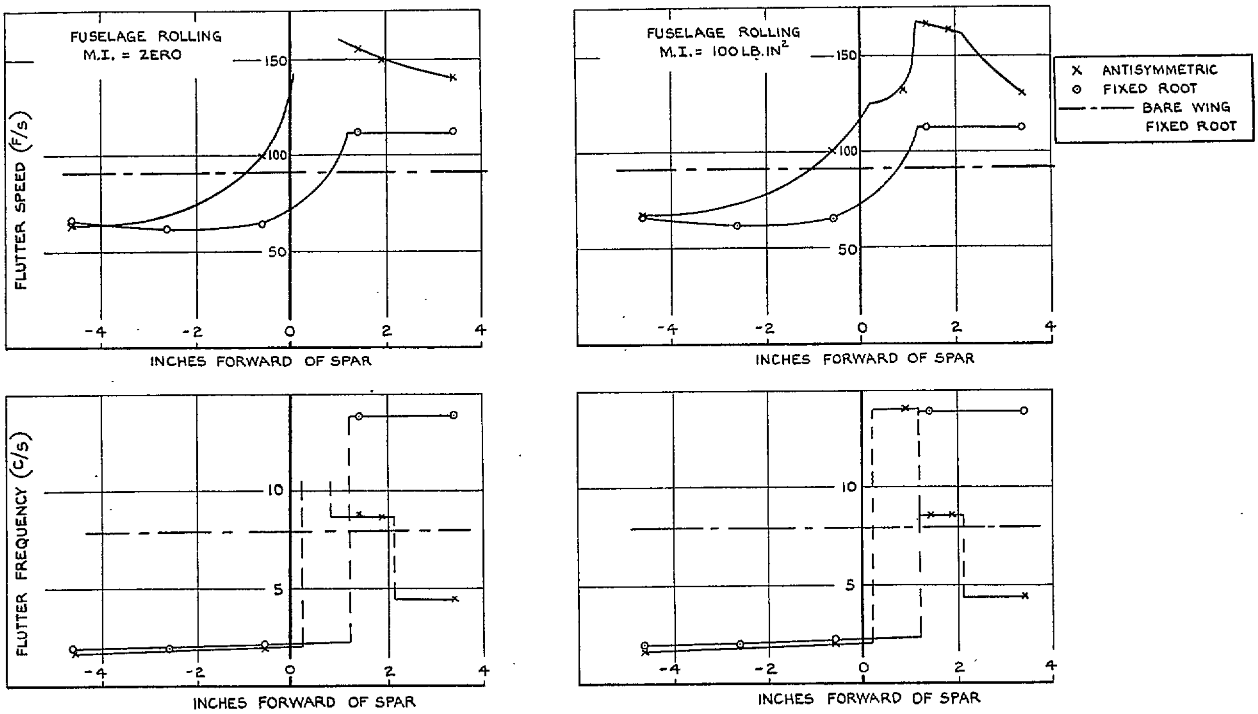

Fig. 33. The effect of chordwise position on flutter speed and frequency for a localised mass of 2·46 lb at the tip.

ANTISYMMETRIC FLUTTER

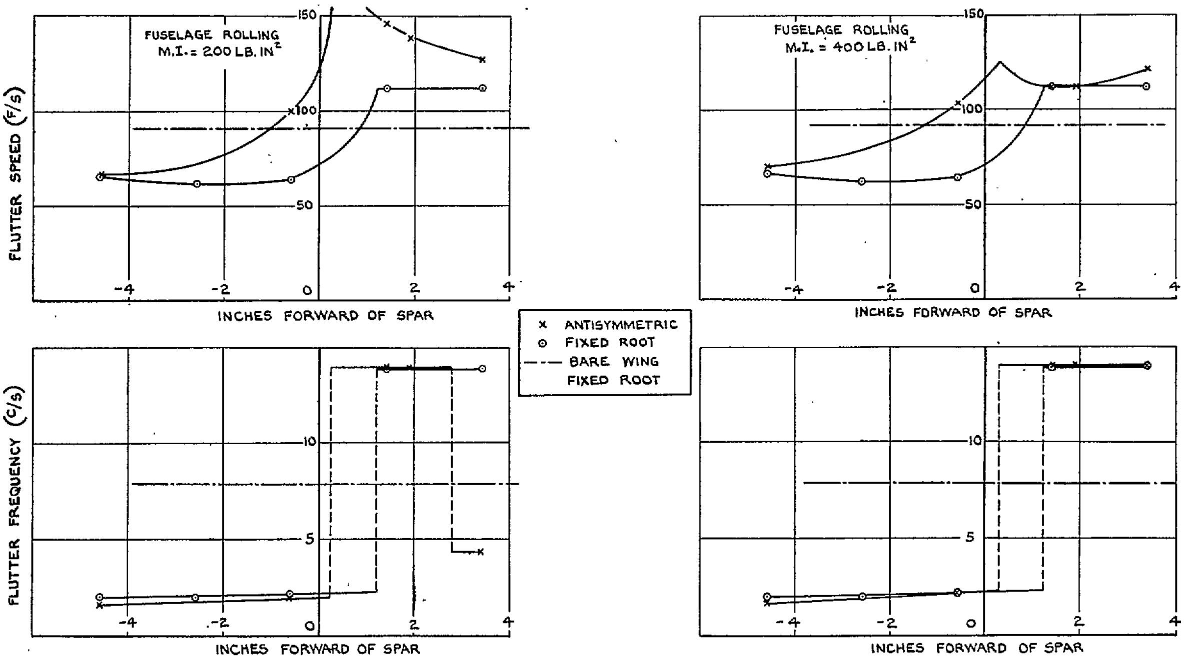

Fig. 34. The effect of chordwise position on flutter speed and frequency for a localised mass of 2·46 lb at the tip.

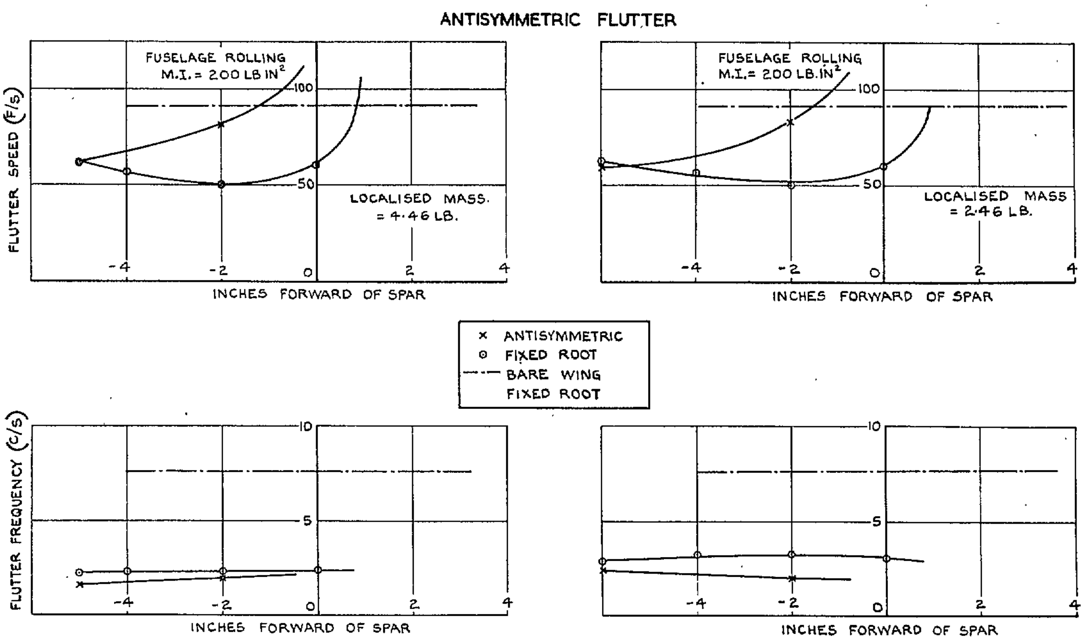

FIG. 35. The effect of chordwise position on flutter speed and frequency for a localised mass at 0·75 span.

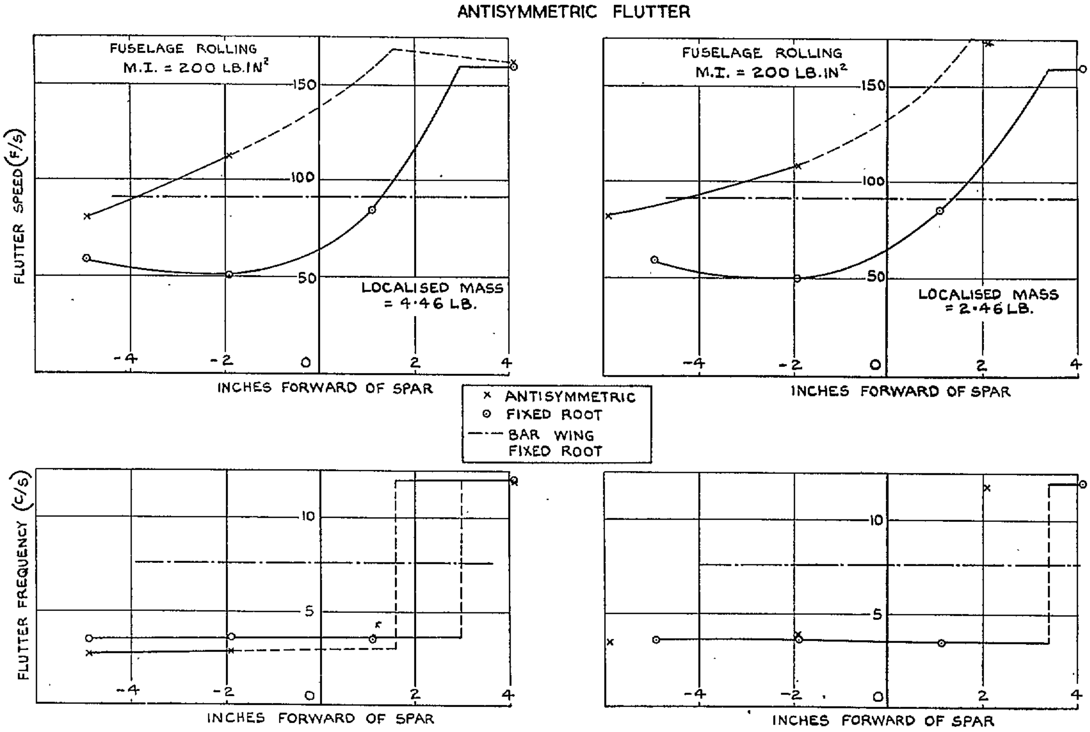

FIG. 36. The effect of chordwise position on flutter speed and frequency for a localised mass at 0·5 span.

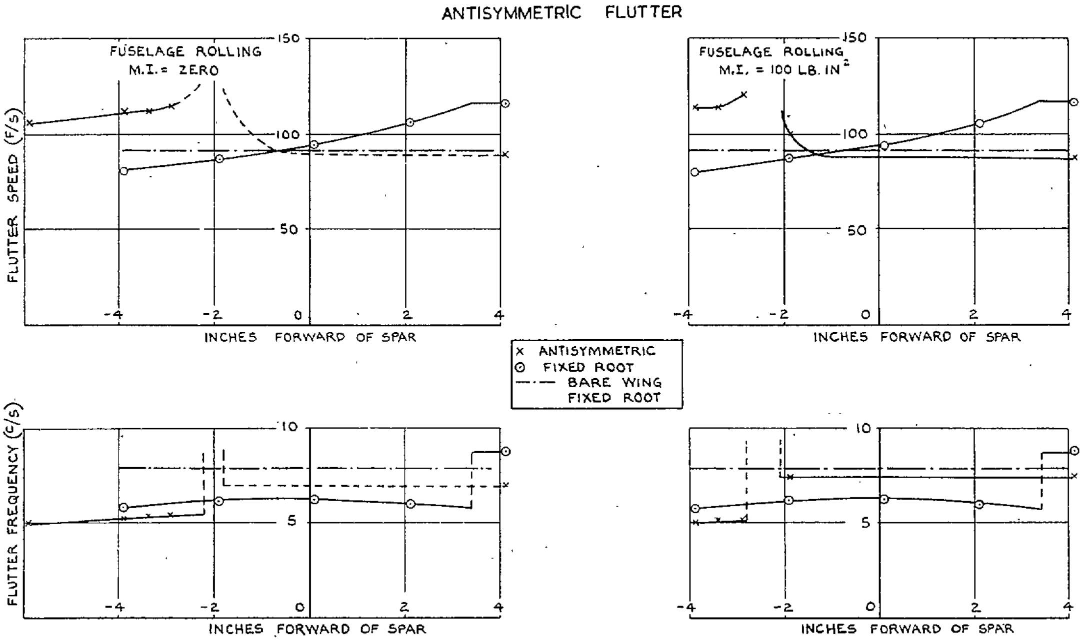

FIG. 37. The effect of chordwise position on flutter speed and frequency for a localised mass of 4·46 lb at 0·25 span.

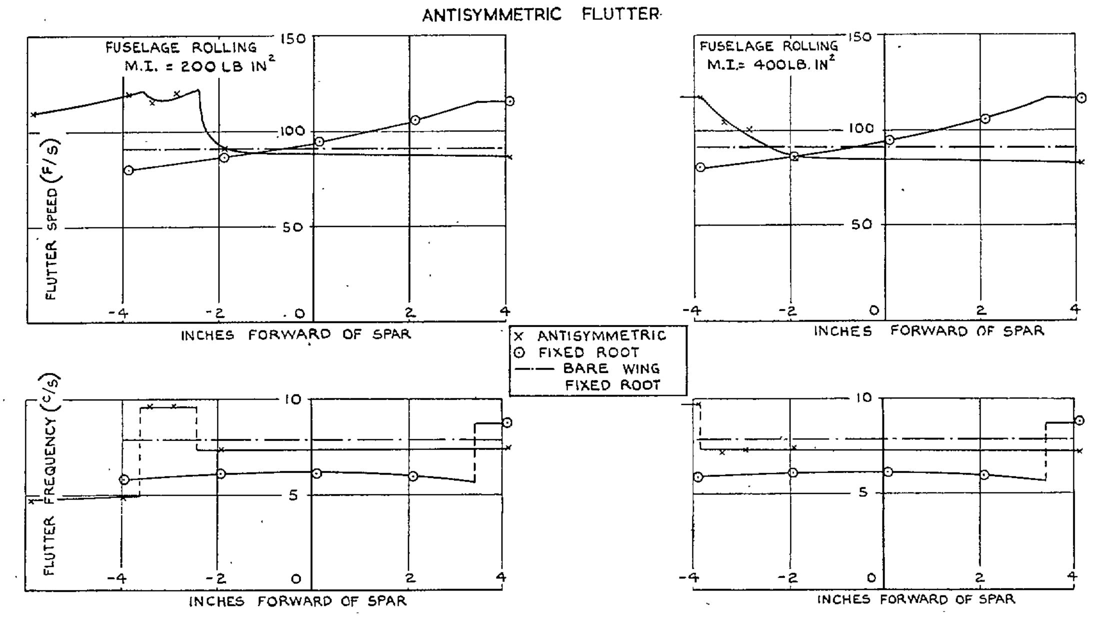

FIG. 38. The effect of chordwise position on flutter speed and frequency for a localised mass of 4·46 lb at 0·25 span.

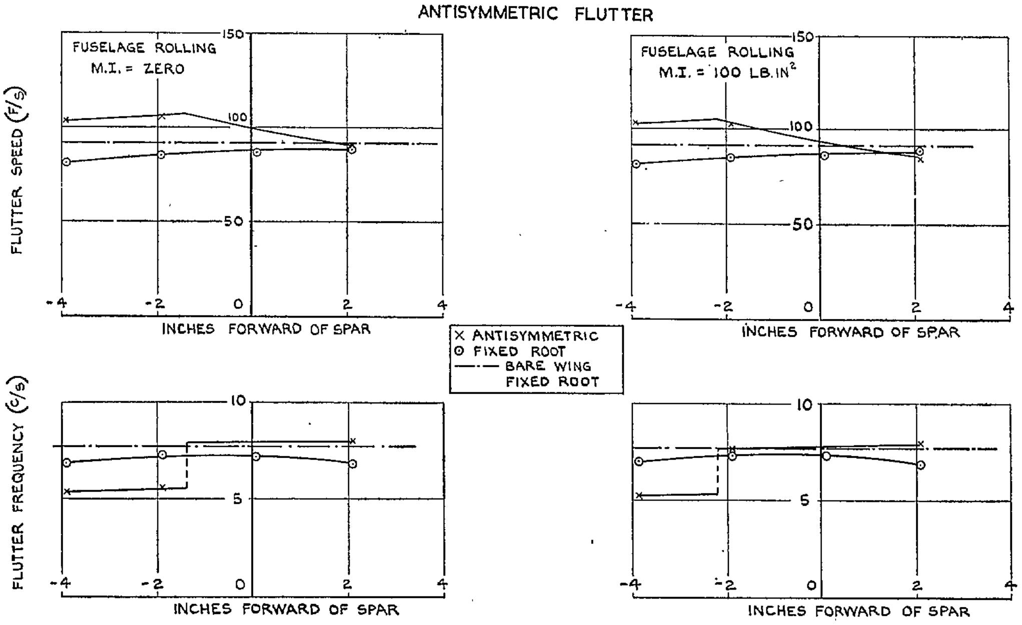

FIG. 39. The effect of chordwise position on flutter speed and frequency for a localised mass of 2·46 lb at 0·25 span.

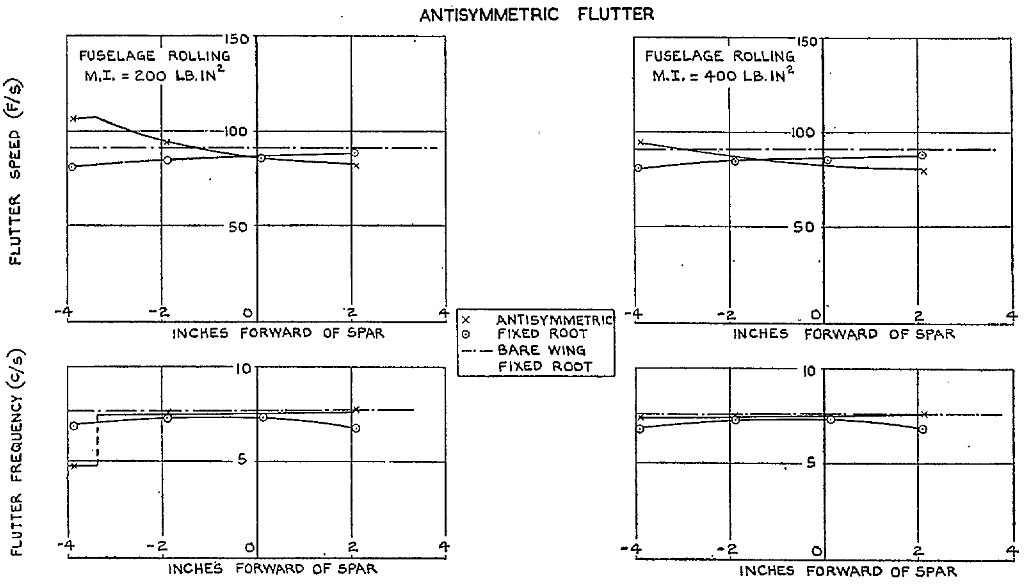

FIG. 40. The effect of chordwise position on flutter speed and frequency for a localised mass of 2·46 lb at 0·25 span.

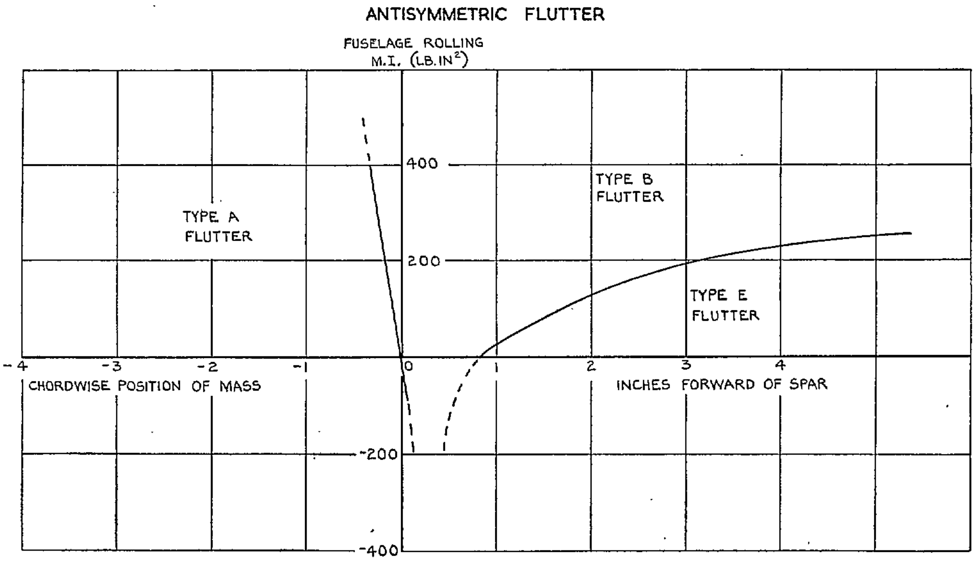

Fig. 41. The transition curves for a localised mass of 4·46 lb at the tip.

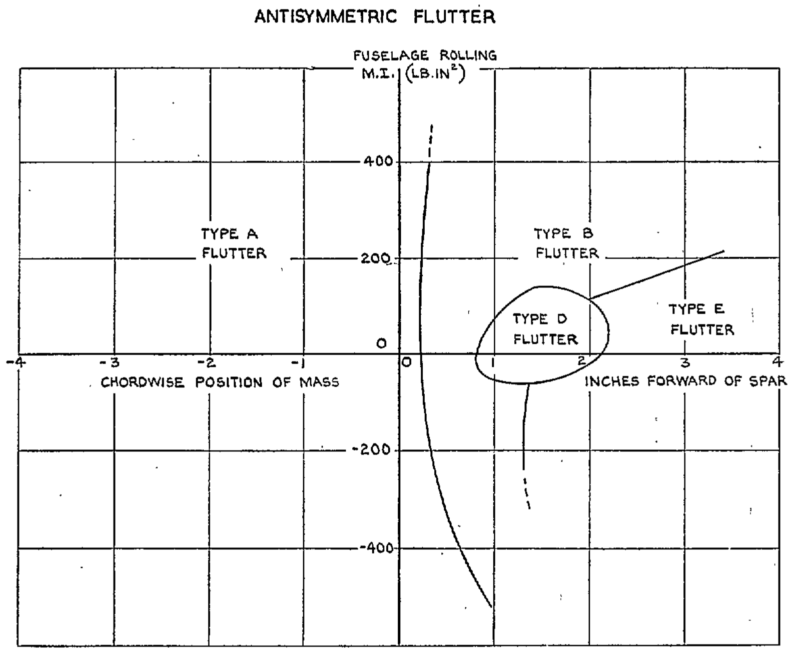

Fig. 42. The transition curves for a localised mass of 2·46 lb at the tip.

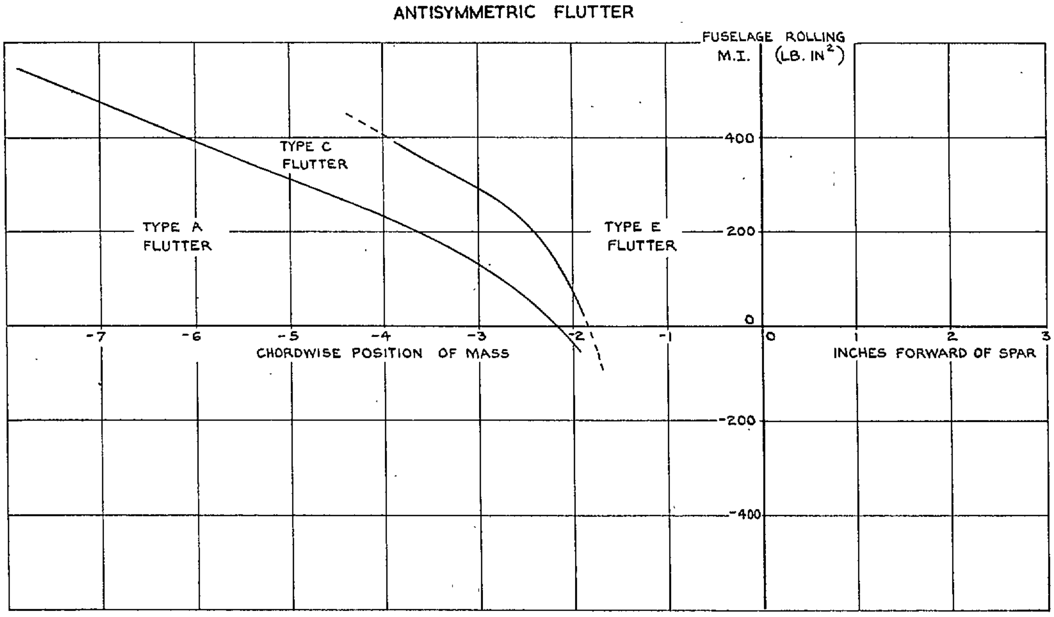

FIG. 43. The transition curves for a mass of 4·46 lb at 0·25 span.

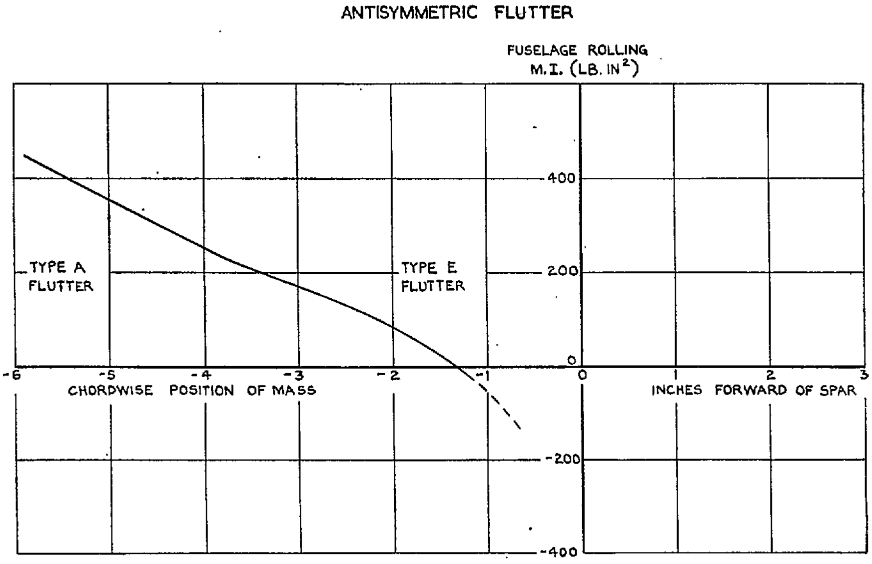

FIG. 44. The transition curves for a localised mass of 2·46 lb at 0·25 span.

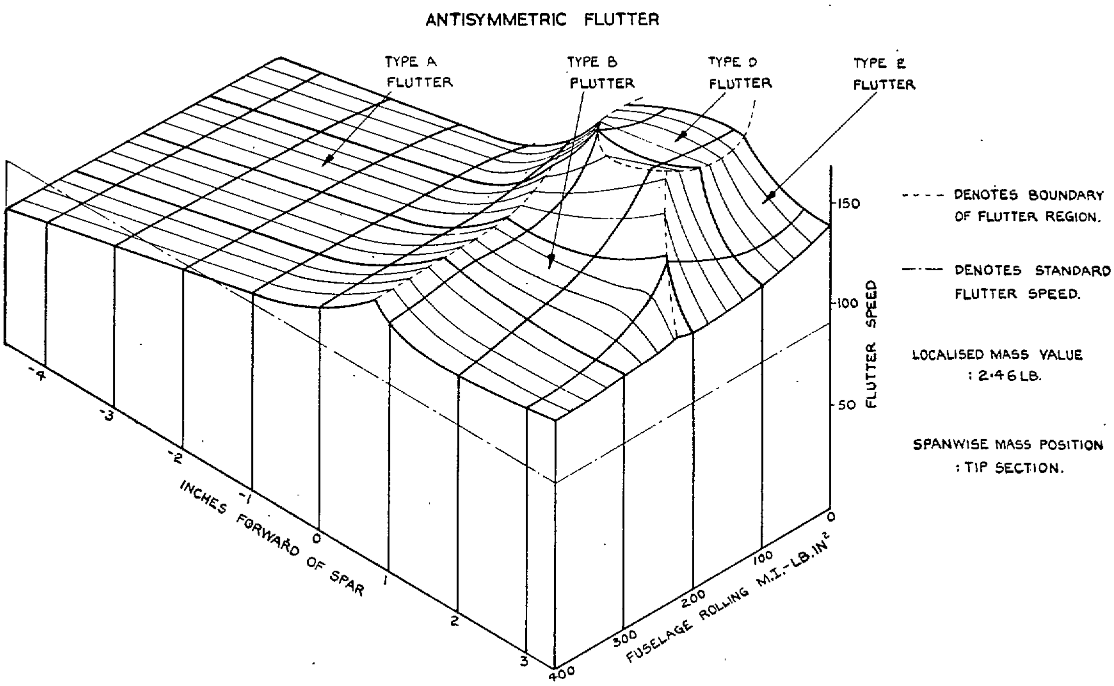
ANTISYMMETRIC FLUTTER

FIG. 45. The effect of fuselage rolling moment of inertia and chordwise position of a localised mass on flutter speed.

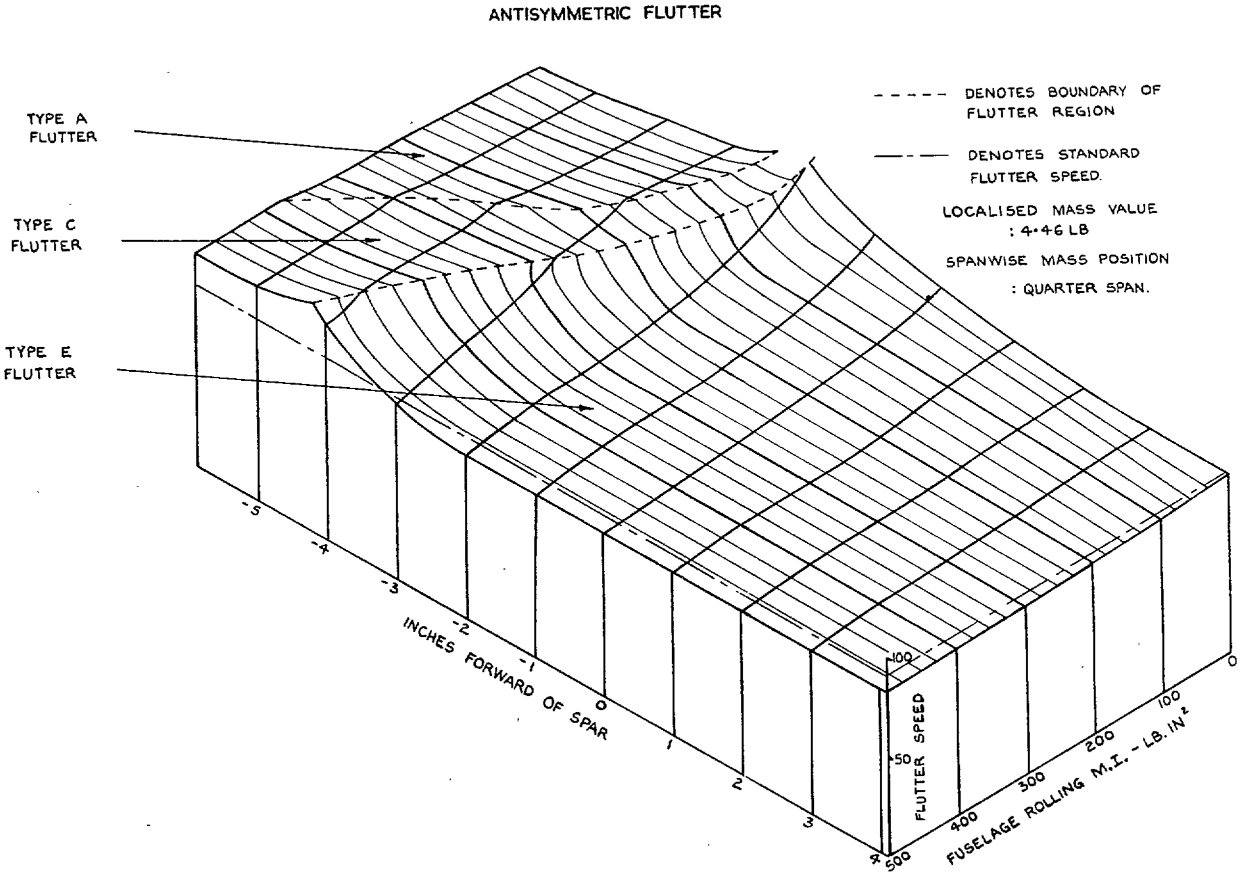
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FIG. 46. The effect of fuselage rolling moment of inertia and chordwise position of a localised mass on flutter speed.

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