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Wind-Tunnel Flutter Tests on a Delta Wing with an All-Moving Tip Control Surface

By

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Summary.—Wind-tunnel tests on a half-span model delta wing, fitted with an all-moving tip control surface, are described. The model, which is flexible, has a leading-edge sweepback of 45 deg ; and the control surface, which is rigid, has an area 9·3 per cent of the gross wing area. The control surface is hinged at 47·4 per cent of its root chord. Provision is made for varying the circuit stiffness and the position of the centre of gravity of the control surface and its pitching moment of inertia.

The tests show that certain combinations of control-surface inertia and circuit stiffness produce very low flutter speeds. The effect of reducing the control-surface area by cropping the tip is examined, and in general is found to be beneficial. It is shown that the most favourable conditions for avoiding low flutter speeds exist when the control-surface centre of gravity is well forward of the hinge-line and the control-surface natural frequency is well removed from the natural frequency of the wing in its fundamental flexural mode.

1. *Introduction.*—The increasing interest that is being taken in control by all-moving wing tips resulted in consideration being given to the flutter characteristics of such controls. In particular, it was thought that the delta wing with an all-moving tip control might present special flutter problems. The experimental work that is described in this report was undertaken in order to obtain a general picture of the flutter characteristics of a delta wing with an all-moving tip control ; particular attention was paid to the parameters that are of major importance in the flutter of conventional flap-type control surfaces. In addition, the effects of changes in control plan-form, obtained by cropping the tip of the control, were investigated.

The test results show that the requirements for the avoidance of unfavourable flutter characteristics of the conventional control surface apply also to the all-moving tip control. Adequate mass-balance and high circuit stiffness are the most effective means for the avoidance of low flutter speeds associated with essentially binary control-surface flutter. Coincidence of the natural frequencies of the control and the wing fundamental flexure mode is shown by the tests to result in very low flutter speeds if the mass-balance condition is unfavourable, and the importance of avoiding proximity of these frequencies is stressed.

2. *Model Details.*—2.1. *Wing.*—The half-span model delta wing used for the tests (Fig. 1) was of wood and silk construction, with 45-deg sweepback of the leading edge, and a root chord of 48 in. The span of the wing, from the root to the inboard edge of the control surface, was $33\frac{1}{4}$ in. The main structural member of the model was a spruce spar of square cross-section at 35 per cent chord, which tapered uniformly, both in width and depth, in proportion to the wing taper. Composite spruce and balsa wood ribs of $\frac{5}{16}$-in. thickness were glued to the spar

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parallel to the airflow at 1-in. spacing. The ribs, which were of symmetrical section (RAE 101), had a thickness/chord ratio of 10 per cent, and were weighted with built-in blocks to give an inertia axis position for the wing at 40 per cent chord. The wing mass per unit length was proportional to the square of the local wing chord. The leading and trailing edges of the model were covered with stiff paper glued to the ribs, and the structure was covered with silk, and doped with a solution of Vaseline in chloroform. Inertia properties of the wing are given in Table 1.

2.2. *Control Surface.*—The all-moving tip control surface was of delta plan-form with 45-deg sweepback of the leading edge (Fig. 1). The dimensions of the uncropped control surface were such that the plan-form of the half wing and the control was a complete 45 deg triangle, and the clearance between the wing and the control was $\frac{1}{8}$ in. Thus the span and root chord of the control were $14\frac{5}{8}$ in., and the ratio of control-surface area to gross wing area was 0·093. The control surface was constructed of balsa wood glued to a central plywood sheet $\frac{1}{16}$-in. thick; it was strengthened at its inboard end by a spruce rib, 1-in. thick. To accommodate the control mass-balance weights, a housing was provided at the inboard end of the control which projected externally from the control surface and extended $3\frac{1}{2}$ in. forward of the leading edge and $1\frac{1}{8}$ in. aft of the trailing edge. The arrangement may be seen in detail in the diagram of Fig. 1. The mass-balance housing contained two lead weights which could be adjusted to any required position within the housing. The hinge-line was at 47·4 per cent of the root chord of the control surface, and the control surface was connected to the hinge mechanism by a Dural rod, which fitted into a bush in the control surface and was locked to the bush by two grub screws. The net weight of the control surface was 0·860 lb and each mass-balance weight was 0·245 lb. The ratio of the weight of the control surface to the weight of a geometrically similar control having a structure similar to the wing structure was 3·07.

Two modifications to the control were made by cropping the tip in the line of flight, the control surface area being reduced by 10 per cent of its initial value with each modification. The reductions in mass for successive modifications were 0·03 and 0·06 of the original total mass of the control. These mass variations as fractions of the total wing and control mass were 0·0024 and 0·0048; the modifications did not result in any measurable change in the natural frequencies of the first three wing normal modes with the control locked. The normal mode frequencies and inertia properties of the control surface are given in Table 1.

2.3. *Hinge Mechanism.*—The control circuit and hinge mechanism are shown diagrammatically in Fig. 2. The Dural rod to which the control surface was attached, was square sectioned inboard of the control surface and passed through two of the wing ribs. It was held in position by two leaf springs one inch apart, the ends of which were screwed to the rod. The other ends of the springs were bolted to angle brackets, which in turn were bolted to two adjacent wing ribs. It will be seen from Fig. 2 that rotation of the control takes place about the axis BB; this axis lay on the centre-line of the wing section, and at right-angles to the planes of the ribs. The circuit stiffness depended on the stiffness of the leaf springs, and beryllium copper springs varying in thickness from 0·006 to 0·024 of an inch were used in the tests, either singly or in pairs in each spring position. A make and break contact was fitted to the hinge mechanism, and the leads from the contact were taken to the wing root inside the silk covering; the contact operated when the control surface was rotated relative to the wing, and was used in conjunction with an automatic counting mechanism to measure the flutter frequency. The outboard three ribs of the wing were fixed relative to one another by Dural plates, in order to provide a rigid fixing for the hinge mechanism; Perspex inspection covers were fitted over the hinge mechanism on both surfaces of the wing.

2.4. *Wind Tunnel Rig.*—The tests were made in the Royal Aircraft Establishment 5-ft Open Jet Wind Tunnel. The wing was mounted vertically in the tunnel with the tip uppermost; the root was rigidly held, the root rib being aligned with the edge of the tunnel nozzle.

In the preliminary experiments difficulty was experienced because of the occurrence of fore-and-aft motion of the model in one of the flutter modes. A tethering cord was therefore attached to the wing close to the control surface and fixed at its other end to the tunnel honeycomb, some eight feet upstream of the model, thus preventing fore-and-aft oscillation.

Three thin cords were attached to the model, two to the forward and aft ends of the mass-balance housing, and the third to the wing, near the trailing edge, at about half-span. The cords were held by the operator standing outside the working-section and were used both to initiate and to restrain the flutter oscillation.

3. *Test Programme.*—3.1. *Control-Surface Plan-Form.*—Three plan-forms of the control surface were tested, the second and third being obtained by cropping the tip (section 2.2).

The plan-forms are referred to throughout the report as A, B and C corresponding to the original control, the first modification and the second modification respectively.

3.2. *Control-Surface Inertia Conditions.*—The range of control-surface centre of gravity positions that could be obtained depended on the values of the control-surface pitching moment of inertia about the hinge-line. Since it was desirable to vary each parameter individually, a value of the moment of inertia was chosen that would allow the centre of gravity position to be varied independently over a wide range. With a moment of inertia value of 30 lb in.^{2}, the centre of gravity position could be varied from 0·4 to 0·6 of the control-surface root chord. This value of the moment of inertia about the hinge-line (30 lb in.^{2}) was taken as the ' standard ' value for all three control-surface plan-forms, and was kept constant for all variations of centre of gravity position. The available range of variation of the centre of gravity position was reduced when the control-surface area was reduced, and with plan-form C it was not possible to obtain centre of gravity positions aft of 0·54 of the control-surface root chord. The forward limit was unaffected.

The pitching moment of inertia of the control surface about the hinge-line was varied for certain fixed positions of the control-surface centre of gravity, the range of variation in each case depending on the centre of gravity position. When the circuit stiffness was such that the natural frequency of the control surface about its hinge was close to the natural frequency of the wing fundamental flexure mode (control locked) with the ' standard ' moment of inertia, the moment of inertia was varied at a number of centre of gravity positions through out the range. At the other values of circuit stiffness the moment of inertia was varied with the centre of gravity at 0·52 of the control-surface root chord. This position of the centre of gravity was chosen to enable a wide range of moment of inertia variation to be obtained.

3.3. *Circuit Stiffness Conditions.*—A range of control circuit stiffness from zero to 90 lb in. per radian was investigated. The upper limit of this range was chosen so that a natural frequency of the control surface about its hinge greater than twice the frequency of the wing fundamental flexure mode (control locked) could be obtained with the standard control-surface moment of inertia (section 3.2). Tests were made with six values of circuit stiffness within this range. In some cases the same spring could not be made to give exactly the same circuit stiffnesses with cropped and uncropped control surfaces, due to the difficulty of obtaining an identical hinge assembly without the aid of an assembly jig. Zero circuit stiffness was obtained by allowing the control to rotate freely on its supporting rod, in which condition the hinge-line was at 0·486 of the root chord and was slightly offset from the centre-line of the section.

4. *Test Results.*—4.1. *Plan-Form A.*—4.1.1. *Centre of gravity position and circuit stiffness variation.*—The effect of varying the centre of gravity of the control surface is shown in Figs. **3**, 4 and **5** for a number of circuit stiffness values. Each curve was obtained for a constant control-surface pitching moment of inertia and, hence, constant control-surface natural frequency. The ratio of the natural frequency of the control surface about the hinge-line to that of the wing fundamental flexure mode (control locked), referred to in the figures, and subsequently in the text, as the ' frequency ratio,' is given on each diagram. The flutter speeds and frequencies of the wing with the control locked to the wing are also indicated.

Similar flutter speed curves are obtained for all the circuit stiffnesses tested ; the main characteristics can be seen best when the frequency ratio is 1·0 (Fig. 4). With the control-surface centre of gravity well aft of the hinge-line the flutter speeds are very low (about 0·25 of the control locked flutter speed) and the flutter frequencies slightly higher than the control natural frequency. The flutter speed falls slightly as the centre of gravity moves forward, reaching a minimum when the centre of gravity is near the hinge-line. As the centre of gravity moves further forward the flutter speed rises rapidly and the curve becomes S-shaped ; there is a small range of centre of gravity position in which three critical flutter speeds occur for each position of the centre of gravity, corresponding to the three intersections of a vertical line drawn through the curve. The lowest flutter speed is the lower boundary of a speed range in which flutter occurs ; the second critical speed is the upper boundary of this range, and the third speed is the lower boundary of a second speed range in which flutter occurs. A detailed investigation of flutter speed was made in this region of the flutter curve to ascertain whether or not there was any abrupt change in the flutter mode. As the flutter speed increased the frequency also increased slightly, but there were no indications of a sudden change of mode. Observation of the phase angle between the control surface and the wing at the trailing edge showed that whereas at the low speed end of the curve the angle was about 180 deg, it decreased as the flutter speed increased, and at the top of the S bend was almost zero. The flutter throughout was essentially a binary type, compounded of wing fundamental flexure and control-surface rotation, but the control-surface amplitude decreased relatively as the centre of gravity was moved forward.

Returning to Fig. 4, as the centre of gravity moves forward of the region in which the rapid rise of flutter speed occurs, the critical speed continues to rise, but less rapidly than before, and with the most forward positions of the centre of gravity the curve begins to flatten out. The flutter speed for the furthest forward position of the centre of gravity is slightly higher than the corresponding wing flutter speed with control locked.

The flutter-speed curves for other circuit stiffnesses have the same general shape, but two important differences may be noted. Firstly, the general level of flutter speed increases as the frequency ratio is increased, or decreased, from unity, and with this general rise the flutter speed curve becomes flatter, and the S bend disappears. This is particularly noticeable for frequency ratios greater than 1·0, and Figs. 4 and 5 for frequency ratios of 1·31, 1·54 and 2·04 show the gradual change in the shape of the curve. Secondly, a form of overtone flutter occurs with forward positions of the control-surface centre of gravity, the range of centre of gravity positions over which it occurs becoming less as the frequency ratio approaches unity. For instance, with the centre of gravity at 0·40, overtone flutter occurs when the frequency ratio is zero, or above 1·31, but not when it is 0·65 or 1·0. The mode of the overtone flutter appeared to be a combination of wing overtone flexure, wing torsion, and control-surface rotation. The overtone flutter frequency is considerably higher than that of the wing with control locked, and this confirms that the overtone flexural mode is involved. The overtone flutter speed does not vary appreciably with either control-surface centre of gravity position or with circuit stiffness, and its value is close to the control locked flutter speed over the range tested. It is interesting to note that with a frequency ratio of 1·0 (when overtone flutter did not occur) the flutter speeds with the most forward centre of gravity position (Fig. 4) are higher than the overtone flutter speeds obtained at other frequency ratios. This indicates that the overtone flutter speed probably rises when the frequency ratio approaches unity.

The frequency in the binary form of flutter, although increasing slightly with forward movement of the control-surface centre of gravity, is in general higher than the control-surface natural frequency for values of frequency ratio up to 1·31. With the frequency ratio 1·54 the two frequencies are nearly equal, and with the highest frequency ratio (2·04) the flutter frequency is lower than the control-surface natural frequency.

4.1.2. *Moment of inertia variation.*—The flutter speed and frequency curves for variations of control-surface pitching moment of inertia with constant circuit stiffness and centre of gravity position are shown in Figs. 6 to 9. For the circuit stiffness of 21 lb in. per radian, chosen so as to give a frequency ratio of 1·0 when the control moment of inertia was 30 lb in.^{2} (*see* section 3.2), the moment of inertia was varied at eight centre of gravity positions, 0·60, 0·56, 0·52, 0·48,

$0 \cdot 46$, $0 \cdot 45$, $0 \cdot 44$ and $0 \cdot 40$ of the control-surface root chord. It may be seen from the figures that with centre of gravity positions aft of the hinge-line the variation of moment of inertia has little effect on flutter speed, but that when the centre of gravity is forward of the hinge-line a decreasing moment of inertia (which increases the control-surface natural frequency) produces a rapid rise in flutter speed. The shape of the flutter speed curve in these conditions must be similar to the S-shaped curves already mentioned in connection with variation of the control centre of gravity position. For the remaining circuit stiffnesses the control moment of inertia was varied only at a centre of gravity position of $0 \cdot 52$ of the control-surface root chord. When the frequency ratio is less than unity the flutter speed increases slightly with increasing moment of inertia, but when the frequency ratio is above unity the flutter speed decreases considerably (though not sharply) with increasing moment of inertia.

4.2. *Plan-Forms B and C.*—The tests on the control surfaces with reduced area were less comprehensive than those made on the original control. The main reason for this was that when the tip was cropped, divergence could occur before flutter, thus restricting the flutter tests at low values of circuit stiffness. With plan-form B, circuit stiffnesses below 21 lb in. per radian could not be tested, and with the maximum circuit stiffness the flutter speeds were all higher than the divergence speed. With plan-form C, no tests were possible with circuit stiffnesses below 32 lb in. per radian. But with both B and C plan-forms, even when some flutter speeds could be obtained the divergence speeds were well below the control locked flutter speeds, and detailed investigations were not possible.

The test results for plan-form B are shown in Figs. 11 to 14. The curves of flutter speed with variation of centre of gravity position (Figs. 11 and 12) are similar to those obtained for plan-form A with comparable circuit stiffness : rather higher flutter speeds are obtained with plan-form B, however, and the region of centre of gravity position in which the flutter speed rises sharply is farther forward with the B than with the A plan-form. The variations of flutter speed with moment of inertia for plan-form B (Figs. 13 and 14) are similar to those obtained with the original control, but the speeds are slightly higher.

Figs. 15 to 17 show the test results using plan-form C. Although only a limited number of tests were made, a comparison with the results for plan-forms A and B indicates that the general level of flutter speeds rises slightly as the control-surface area is reduced. Apart from this, the characteristics of plan-form C are not very different from those of plan-form B.

5. *Discussion.*—5.1. *General.*—The test results indicate that with an all-moving tip control surface on a wing of delta plan-form, low flutter speeds associated with an essentially binary type of control-surface flutter may be prevented by adequate mass-balancing, and to some extent by high circuit stiffness. The requirements for satisfactory flutter characteristics, therefore, follow closely the requirements for the avoidance of flutter with conventional control surfaces. The tests also show that the same general requirements apply when the control-surface plan-form is modified by cropping the tip. Flutter speeds greater than that of the wing with control locked were only obtained in a limited number of cases, and in these cases the speeds were not much greater than the control locked flutter speed. It would appear that the flutter characteristics of the wing cannot be improved appreciably even in the most favourable conditions of control-surface inertia and circuit stiffness. This feature, however, also appertains to wings having conventional control surfaces.

In section 3.3 it was mentioned that the zero stiffness condition was obtained by allowing the control to rotate on its rod support ; owing to the geometry of the hinge mechanism (Fig. 2) this resulted in a small displacement of the hinge-line. The test results do not indicate that this caused any appreciable effect, but it should be noted that the hinge-line is moved aft by just over 1 per cent of the control-surface root chord in the zero stiffness case.

5.2. *Mass Balance and Circuit Stiffness Effects.*—Circuit stiffness and control-surface centre of gravity position are the two parameters that have the greatest effect on the control-surface flutter characteristics. It will be noted however that flutter speed close to the control-locked flutter speed can be obtained for all circuit stiffness values within the range tested if the centre of gravity position is favourable ; but if the centre of gravity position is unfavourable the resulting low flutter speeds cannot be raised appreciably by increasing the circuit stiffness, except of course, by increasing it to such a high value that the control becomes effectively locked. It may be concluded, therefore, that centre of gravity position is a more important parameter than circuit stiffness.

In practice, adjustment of the centre of gravity position by the addition of mass-balance weight also changes the moment of inertia of the control surface, and the total effect of the mass-balancing is then given by the combined effects of both changes. In the present tests, independent moment of inertia variations were found to have a relatively minor effect, except under certain conditions when large reductions in flutter speed could occur with increasing moment of inertia (*see* section 4.1.2). For adequate mass-balancing, such reductions would have to be avoided.

The effect of varying circuit stiffness independently of any other parameter may be seen for plan-form A by cross-plotting the flutter speed curves of Figs. 3 to 5. Fig. 10 shows the variation of flutter speed with frequency ratio for a number of centre of gravity positions. Frequency ratio has been used rather than circuit stiffness, since it shows at a glance the effects of frequency coincidence. In general, with backward centre of gravity positions, minimum flutter speeds occur when the frequency ratio is unity, and the more backward the centre of gravity the smaller the change in flutter speed as the frequency ratio is varied. As the centre of gravity is moved forward the minimum flutter speeds occur at decreasing frequency ratios. For the most forward centre of gravity in the present tests (at 0·40 of the control-surface root chord) the flutter speed curve consists of three branches. The overtone type of flutter is obtained for low values of frequency ratio (zero to 0·55). The binary form of flutter occurs for frequency ratios from 0·55 to 1·05, and overtone flutter occurs for frequency ratios greater than 1·05. The binary flutter branch of the curve has a minimum at a frequency ratio slightly below 0·8. Fig. 10 suggests that with sufficient mass balance only the overtone form of flutter will occur for any value of circuit stiffness, but with the model tested it was not possible to achieve this mass-balance condition.

5.3. *Moment of Inertia Effect.*—The variation of the control-surface moment of inertia about the hinge-line (with a constant circuit stiffness and constant control-surface centre of gravity position) produces a variation in the frequency ratio. The test results indicate that with the centre of gravity at 0·52 of the control root chord an increase in the moment of inertia produces a slight rise in flutter speed when the frequency ratio is less than unity, and a drop in flutter speed when the frequency ratio is greater than unity. The effect is similar to that obtained varying frequency ratio by altering a circuit stiffness (Fig. 10). This indicates that the variation of frequency ratio, whether accomplished by variations of circuit stiffness or of moment of inertia, results in similar variations of flutter speed. In full-scale practice—as in the present tests—it would not be possible to cover a wide range of frequency ratio by merely varying the moment of inertia, but for the small variations that can be obtained it may be assumed that the flutter characteristics will directly depend on the frequency ratio.

5.4. *Control-Surface Plan-Form Effect.*—It has been noted in section 4.2 that cropping the tip of the control surface resulted in divergence of the control at speeds that were well within the range of model flutter speeds. In practice, control surfaces in which the aerodynamic centre is forward of the hinge-line, would be used in conjunction with irreversible control units in order to avoid divergence. The circuit stiffness and frequency ratio would therefore be very high, and the present tests with the cropped control surface do not represent conditions that should occur in practice. The aim in cropping the control surface was, in fact, to ascertain what changes in flutter characteristics occurred with the modifications described.

The reduction of surface area raises the flutter speeds for the same inertia and stiffness conditions of the control surface, but it also results in an important change in the value of centre of gravity position at which the flutter-speed curve rises sharply. With the 10 per cent reduction in control-surface area it seems that a much more forward centre of gravity would be required to obtain flutter speeds of the order of the wing flutter speed than with the original control surface; with the 20 per cent reduction of surface area a still further forward centre of gravity appears to be required, though the occurrence of control divergence with both modifications prevented any very detailed investigation of this effect. The fact that no sudden changes in flutter characteristics occurred when the control was modified suggests that flutter speeds of the order of the wing flutter speed could have been obtained had divergence not occurred. It may be concluded that if the circuit stiffness is sufficiently large to prevent divergence of a control surface which is aerodynamically unstable, then favourable flutter characteristics can be obtained by adequate mass balance of the control.

6. *Conclusions.*—6.1. Two forms of flutter were obtained with the model tested. One form, having a frequency that was generally of the order of the control natural frequency, appeared to consist primarily of control-surface rotation and wing flexure. The second form, which had a frequency considerably higher than the wing flutter frequency with the control locked, appeared to be compounded of control-surface rotation, wing overtone flexure, and wing torsion.

6.2. The overtone form of flutter was obtained at speeds close to that of the wing flutter speeds with the control locked. The mass-balance condition of the control and the ratio of the control-surface natural frequency to the frequency of the wing fundamental flexure mode were the main factors in determining the type of flutter obtained.

6.3. Very low flutter speeds were obtained when the natural frequency of the control surface coincided with the frequency of the wing fundamental flexure mode, and when the centre of gravity of the control surface was aft of the hinge-line. Under these conditions the flutter speeds were only 25 per cent of the wing flutter speed with the control locked.

6.4. There was a critical position of the control-surface centre of gravity forward of which the flutter speed rose rapidly. The critical position was dependent on the natural frequency of the control surface and was furthest forward for values of this frequency between zero and the frequency of the wing fundamental flexure mode (control locked).

6.5. When the control-surface centre of gravity was well forward of the hinge-line the overtone form of flutter occurred, provided the natural frequency of the control surface was not close to the frequency of the wing fundamental flexure mode. When the frequencies were close, the binary form of flutter occurred. The flutter speeds for both forms of flutter under these conditions were almost equal to the flutter speed of the wing with the control locked, for all the values of circuit stiffness tested.

6.6. For small changes in control-surface natural frequency, the variation either of the control-surface moment of inertia or control circuit stiffness had a similar effect on the flutter characteristics.

6.7. The effect of cropping the control-surface tip was to increase flutter speeds, but it also extended the range of control-surface centre of gravity position in which relatively low flutter speeds could be obtained. Control divergence limited the tests that could be made with the control surface cropped.

6.8. The requirements for the avoidance of unfavourable flutter characteristics of the all-moving tip control surface on a delta wing are similar to the requirements for conventional controls. Adequate mass balance and high circuit stiffness represent the most effective means for the avoidance of low flutter speeds.

Acknowledgments.—The author acknowledges the invaluable assistance given throughout the tests by Mr. K. G. Fonteneau and Mr. N. Stocker of R.A.E.

TABLE 1

Model Details

Weight of wing (without control)	15·18 lb
Weights of control surface without mass balance :	
Plan-form A	0·86 lb
Plan-form B	0·82 lb
Plan-form C	0·78 lb
Weight of mass balance	0·49 lb
Weight ratio*	$\frac{\text{Control surface + mass balance}}{\text{Equivalent weight of wing structure}}$
Plan-form A	3·07
Plan-form B	3·07
Plan-form C	3·14
Natural frequencies of first three normal modes of the wing with the control locked :	
Fundamental flexure	2·6 cycles/second
Overtone flexure	7·4 ,, ,,
Fundamental torsion	9·5 ,, ,,

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* *See* section 2.2.

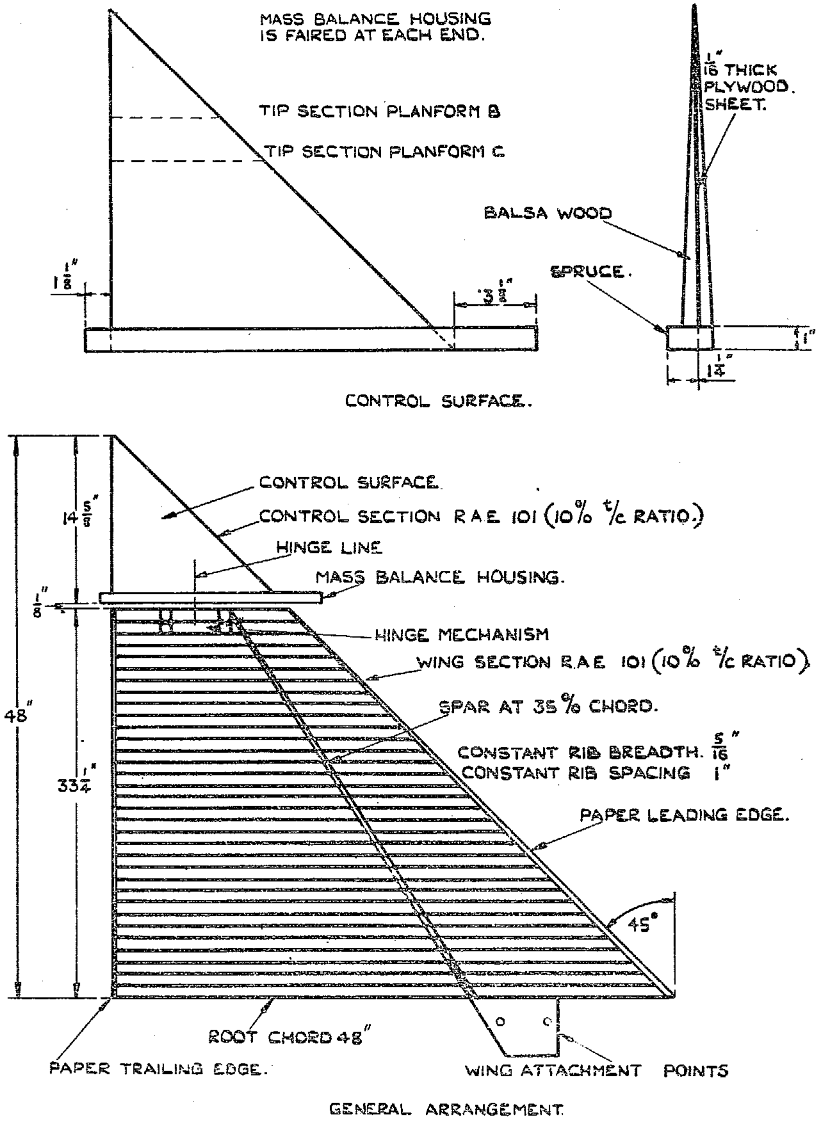

FIG. 1. Model details.

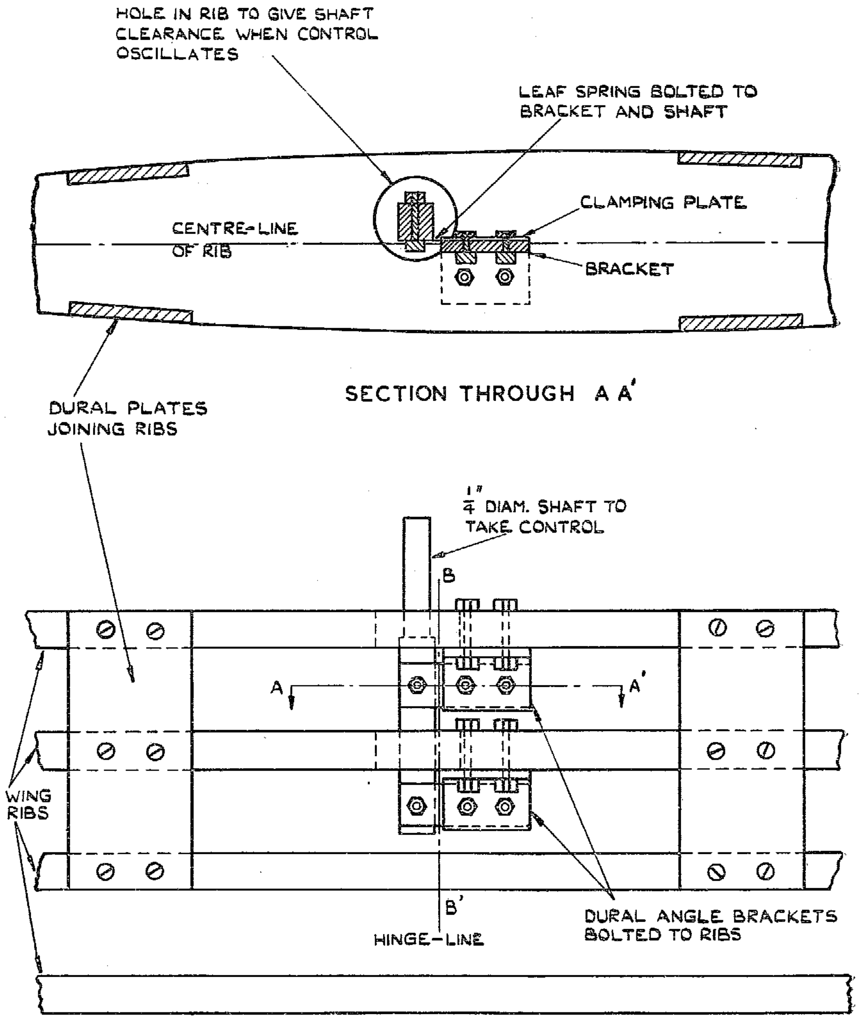

FIG. 2. Hinge mechanism

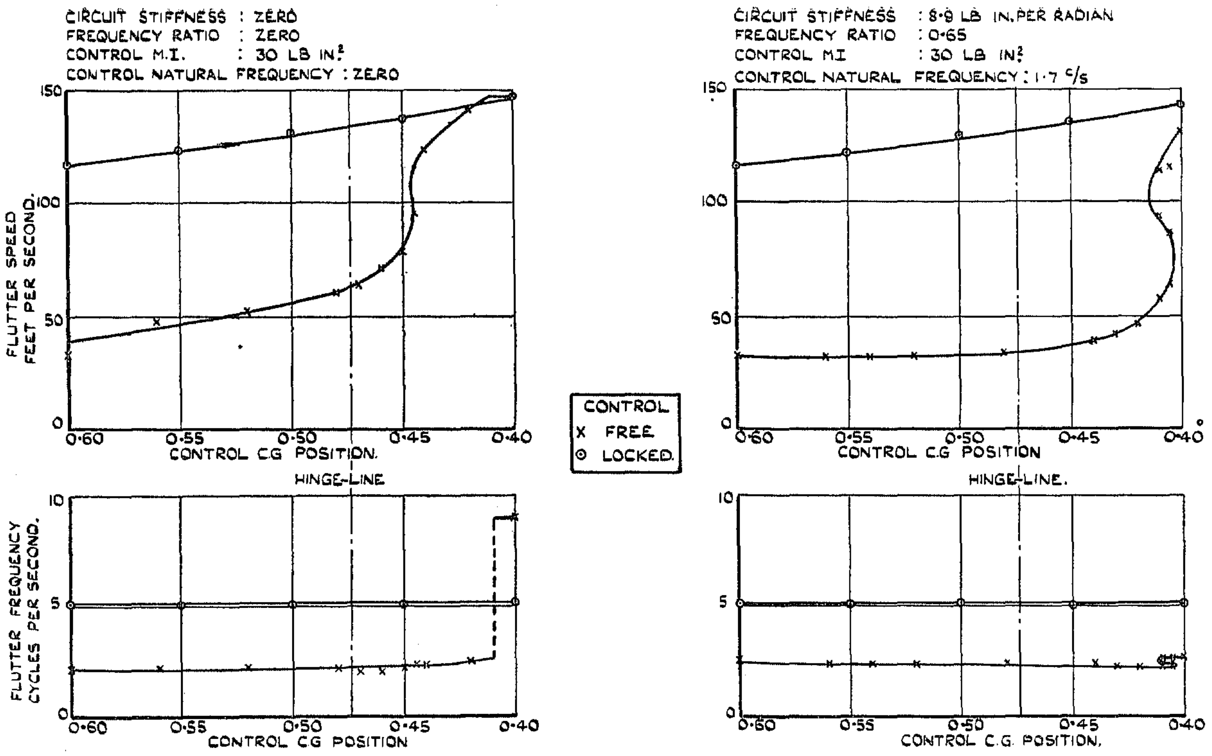

Fig. 3. The effect of control c.g. position on flutter speed and frequency (control plan-form A).

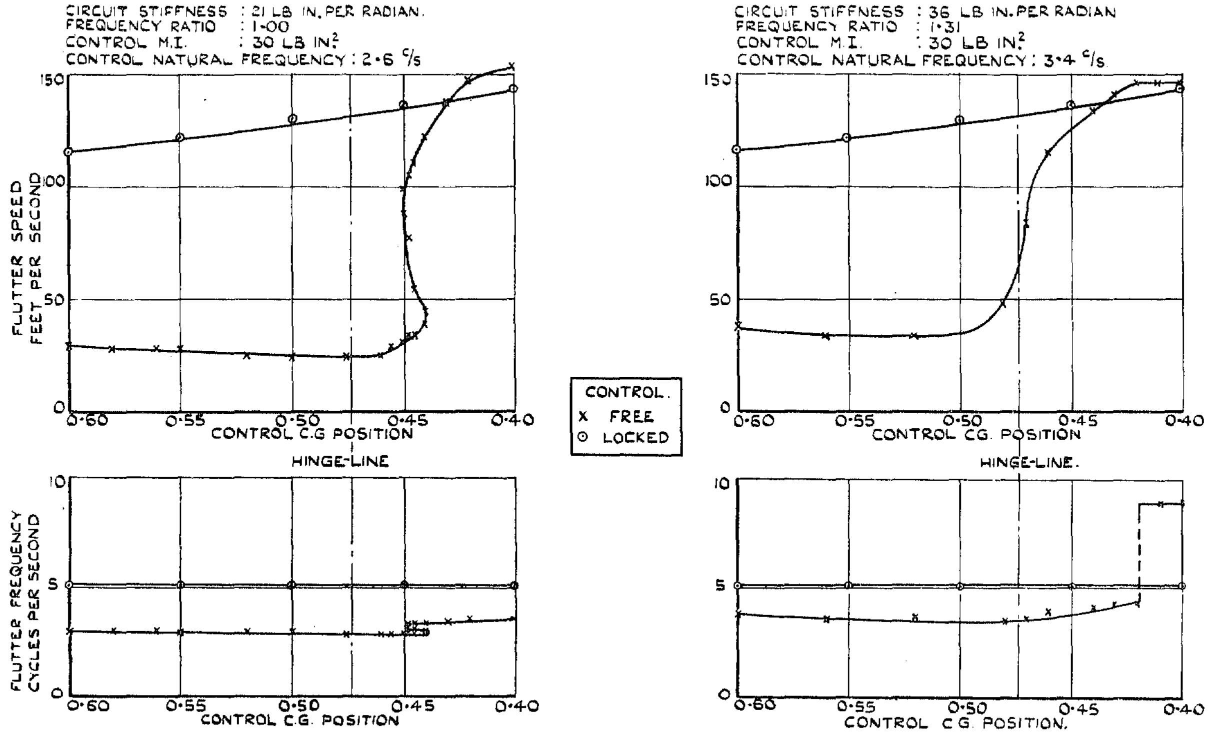

Fig. 4. The effect of control c.g. position on flutter speed and frequency (control plan-form A).

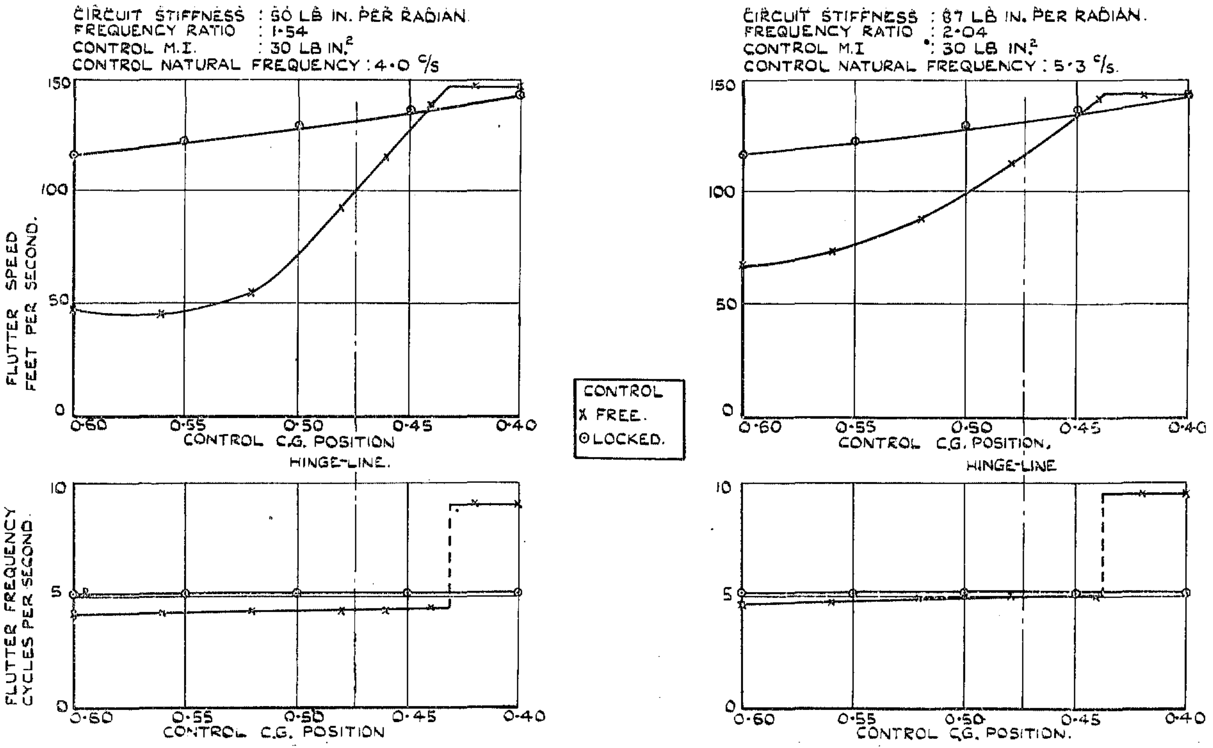

FIG. 5. The effect of control c.g. position on flutter speed and frequency (control plan-form A).

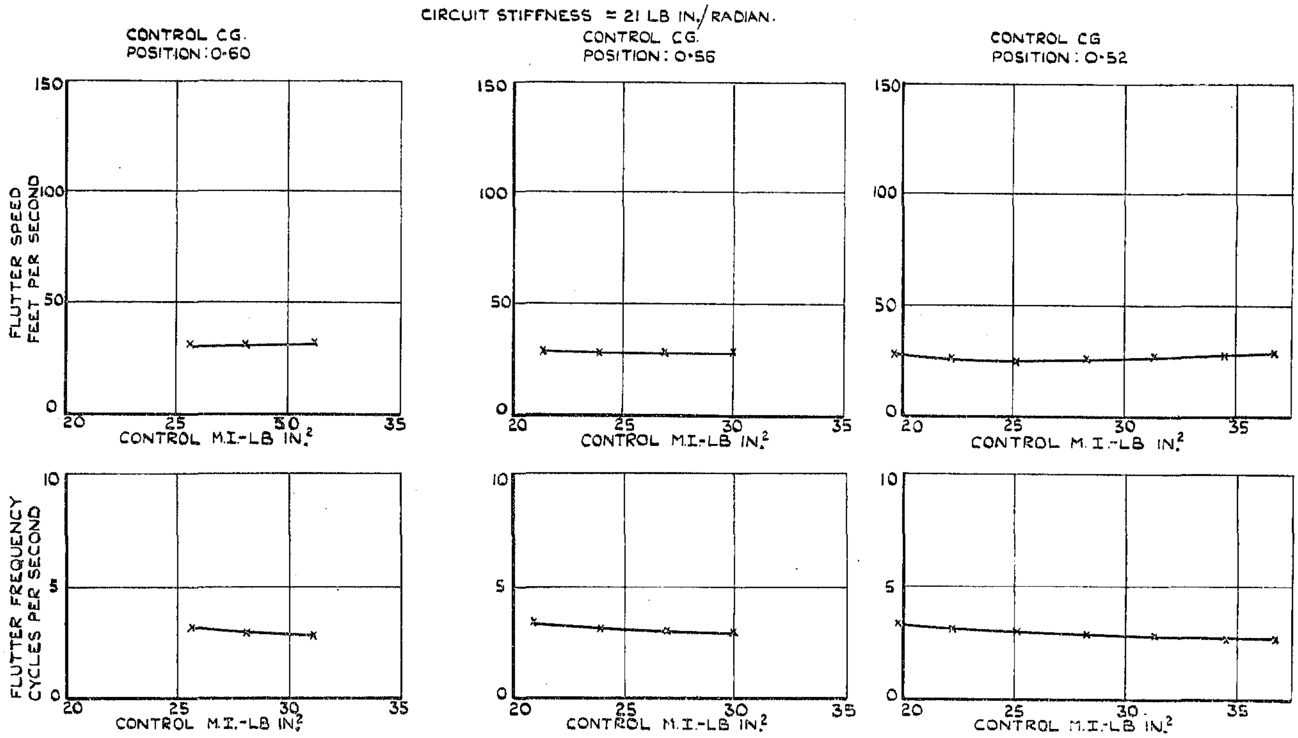

FIG. 6. The effect of control moment of inertia on flutter speed and frequency (control plan-form A).

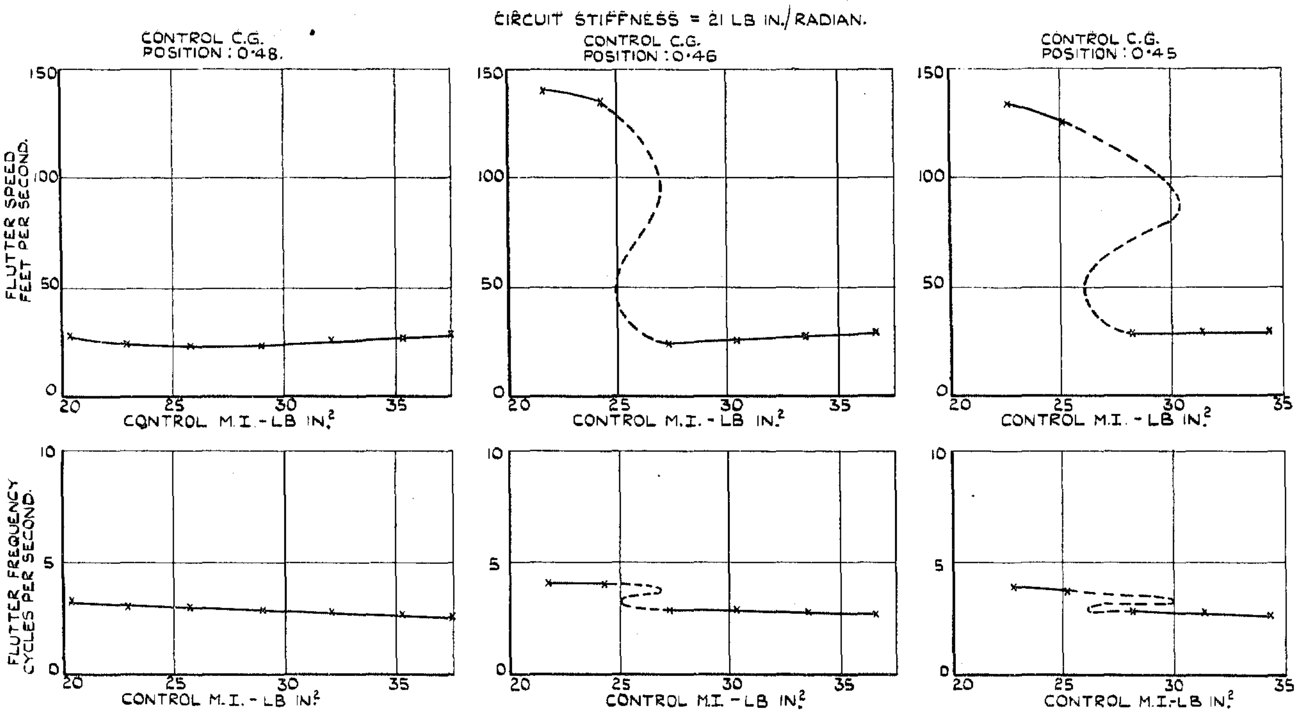

FIG. 7. The effect of control moment of inertia on flutter speed and frequency (control plan-form A).

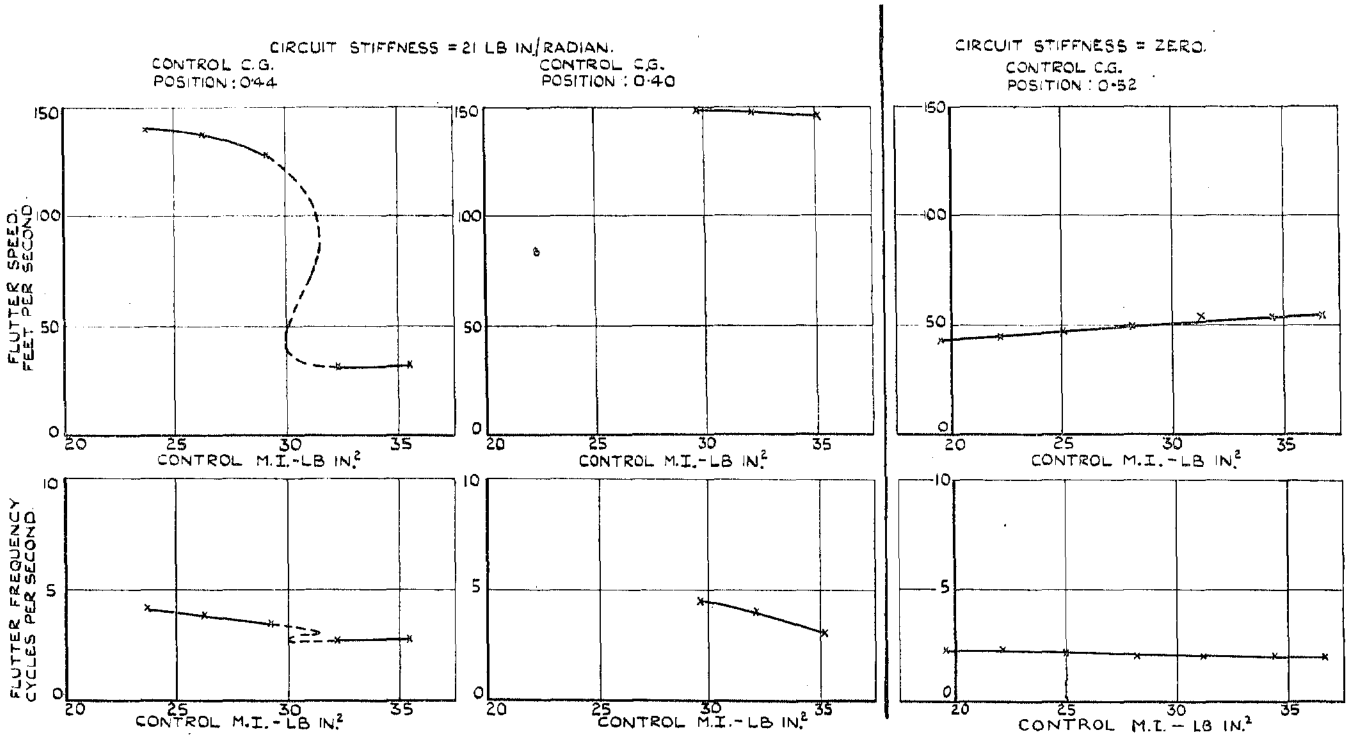

FIG. 8. The effect of control moment of inertia on flutter speed and frequency (control plan-form A).

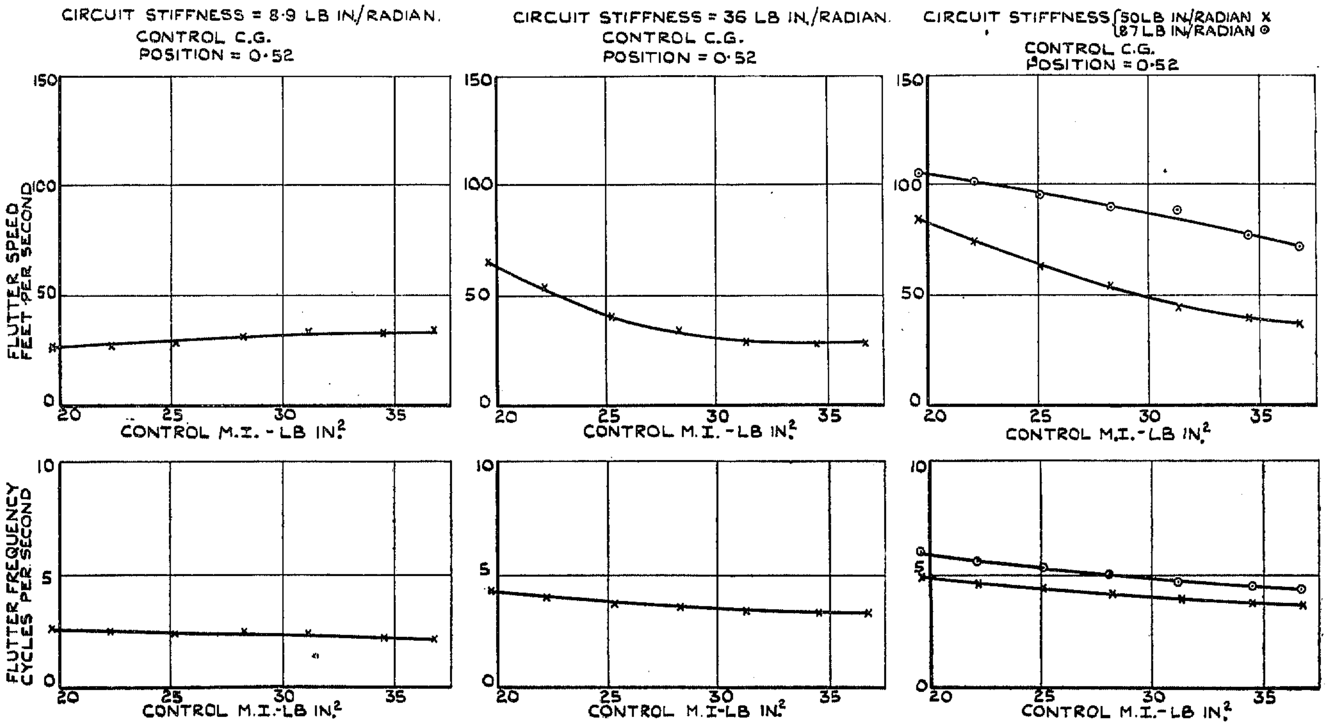

Fig. 9. The effect of control moment of inertia on flutter speed and frequency (control plan-form A).

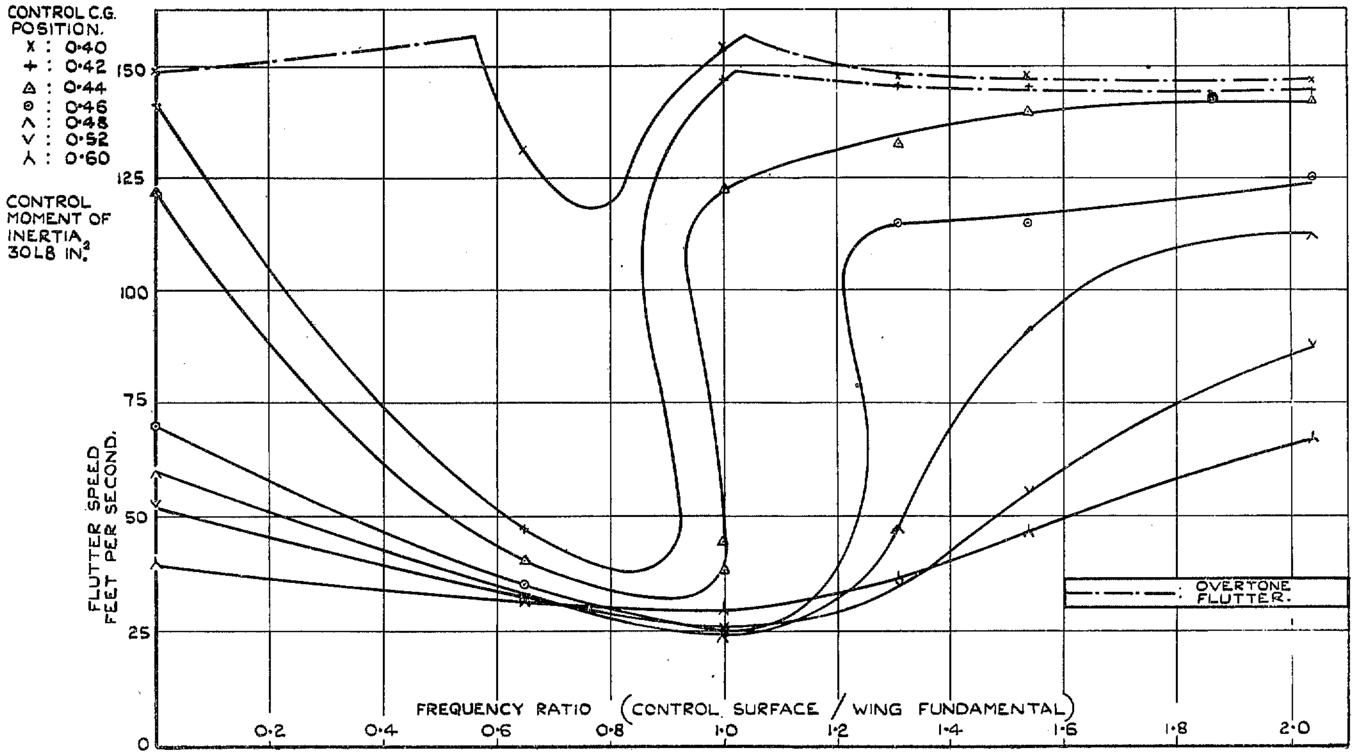

Fig. 10. The effect of frequency ratio on flutter speed (control plan-form A).

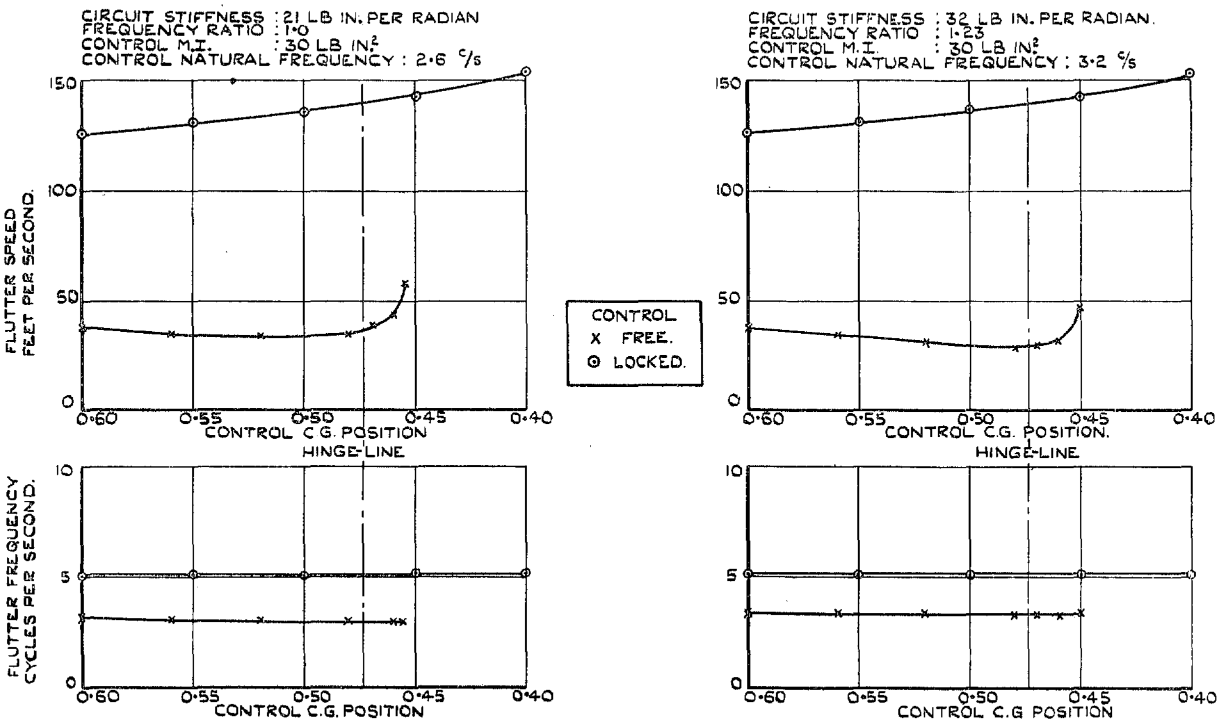

Fig. 11. The effect of control c.g. position on flutter speed and frequency (control plan-form B).

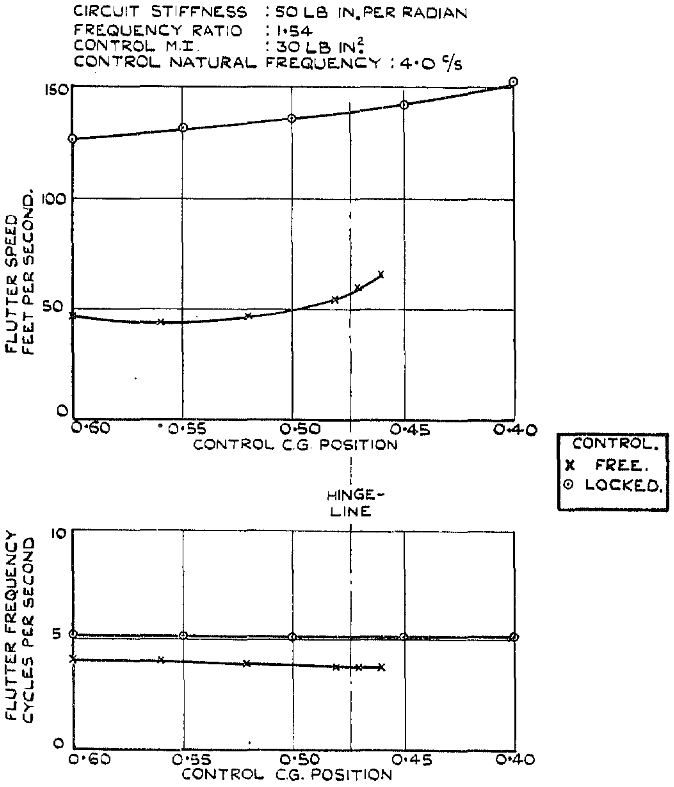

Fig. 12. The effect of control c.g. position on flutter speed and frequency (control plan-form B).

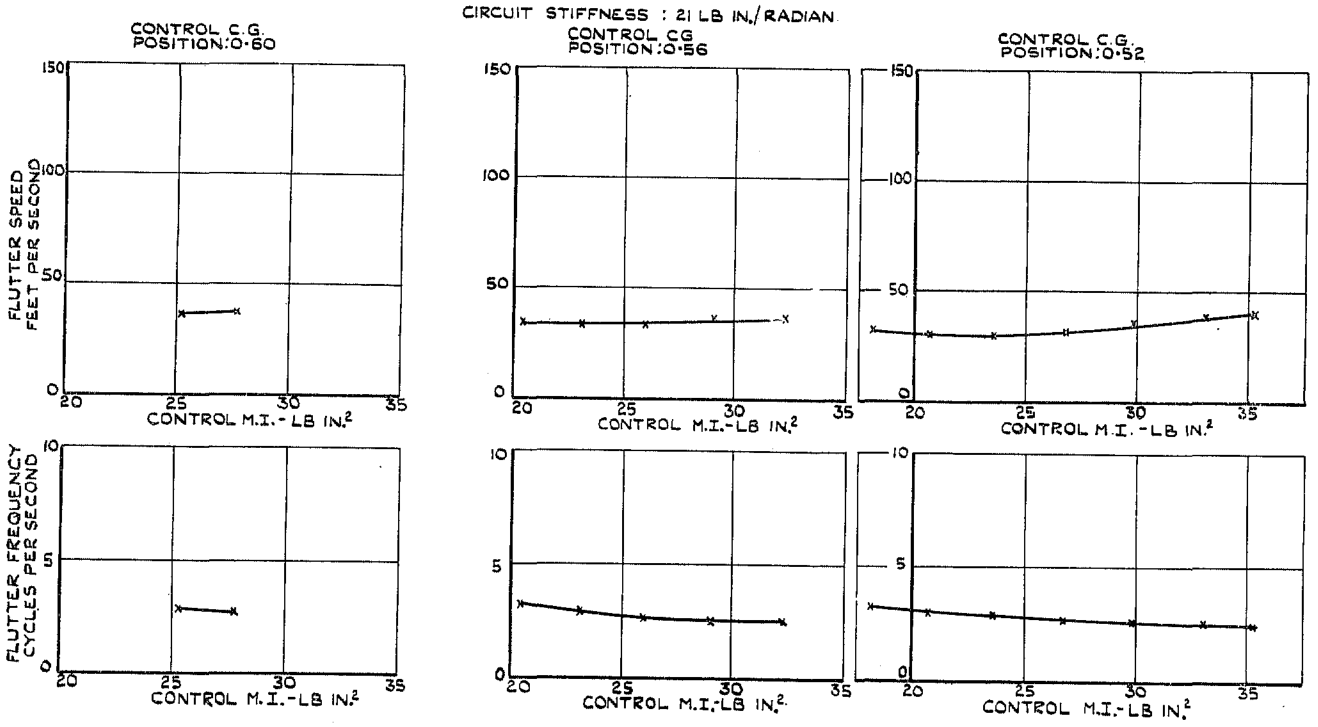

FIG. 13. The effect of control moment of inertia on flutter speed and frequency (control plan-form B).

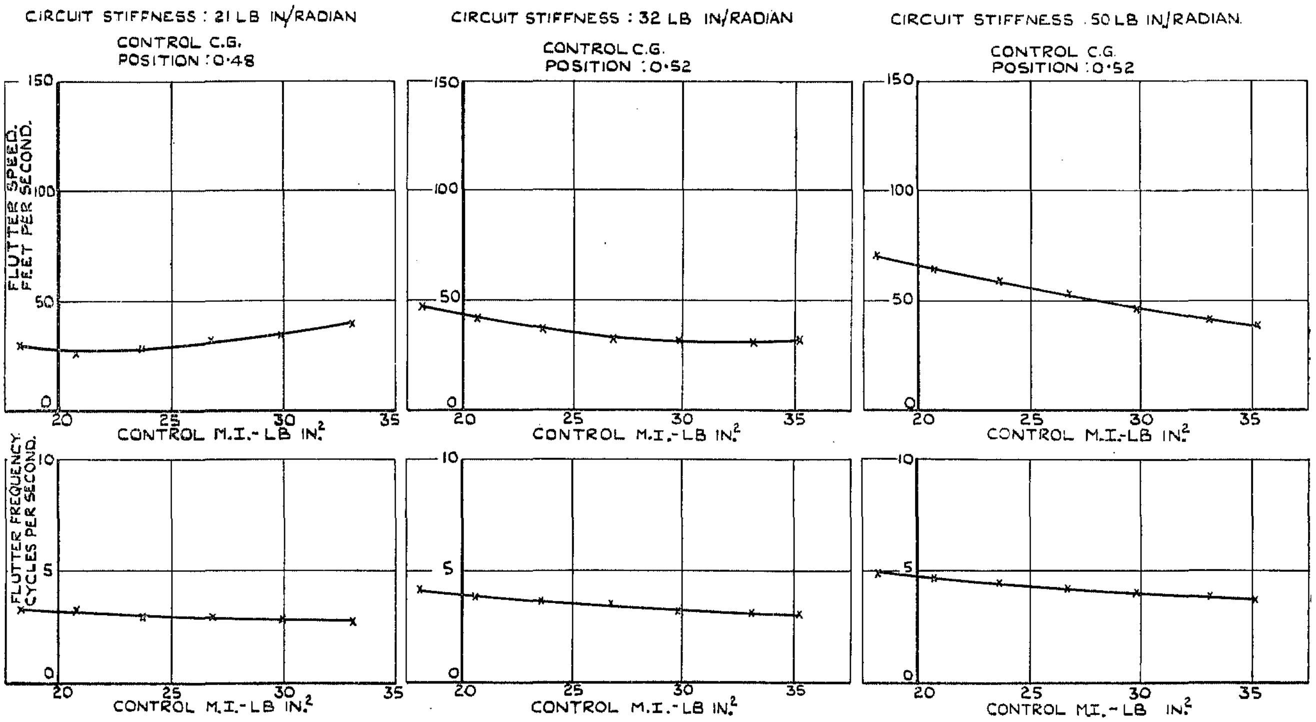

FIG. 14. The effect of control moment of inertia on flutter speed and frequency (control plan-form B).

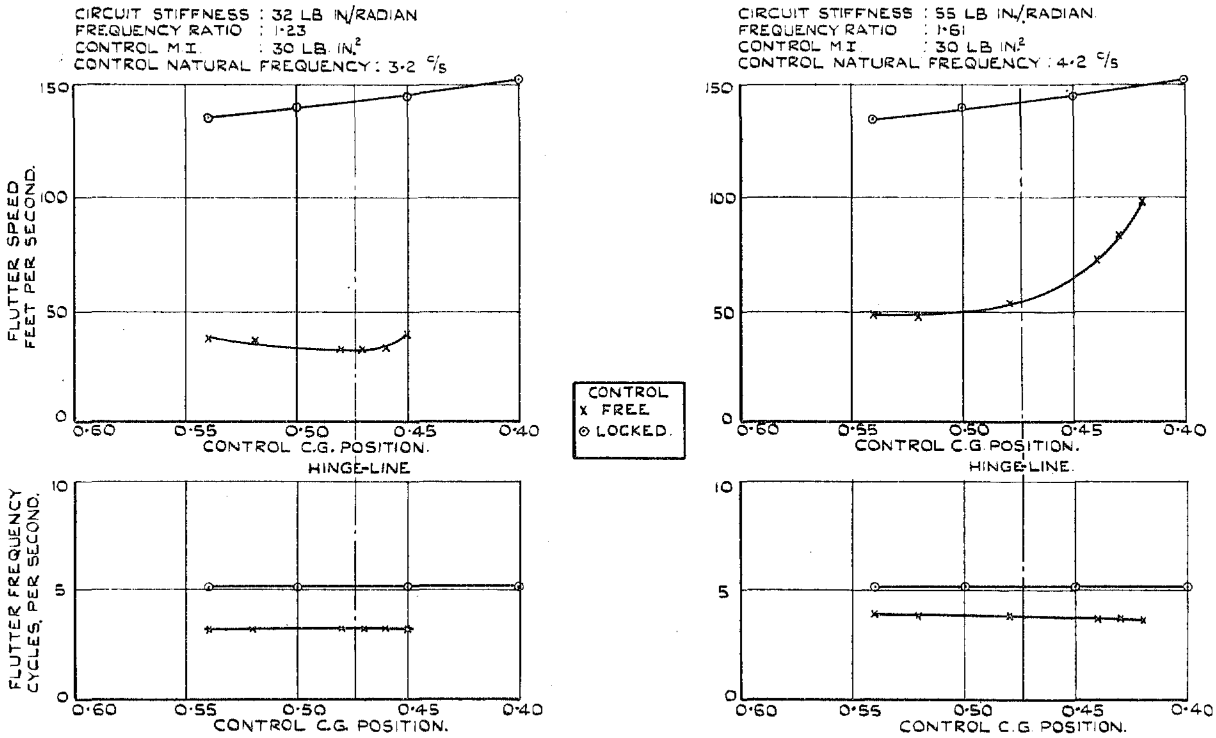

Fig. 15. The effect of control c.g. position on flutter speed and frequency (control plan-form C).

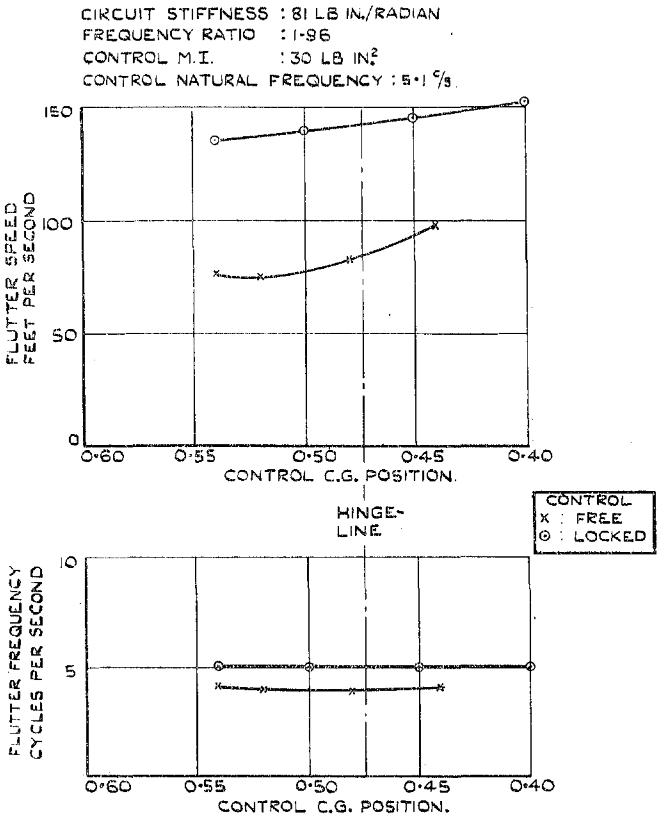

Fig. 16. The effect of control c.g. position on flutter speed and frequency (control plan-form C).

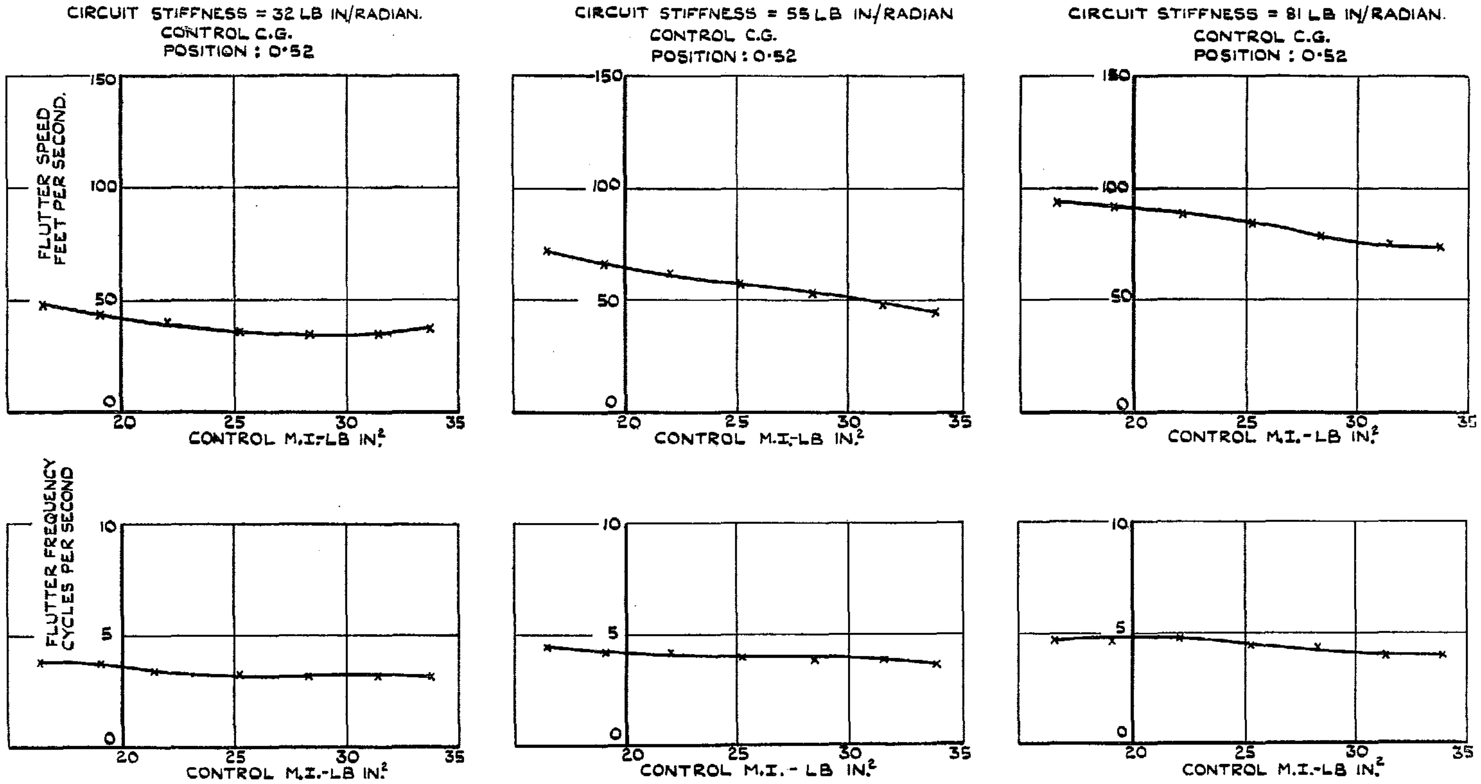

FIG. 17. The effect of control moment of inertia on flutter speed and frequency (control plan-form C).

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