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Part I. Fixed Root Flutter Tests
Part II. Anti-Symmetric Flutter Tests
Part III. Symmetric Flutter Tests

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Wind-Tunnel Tests on the Effects of an Added Mass on the Flutter of a Model Delta Wing

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COMMUNICATED BY THE DEPUTY CONTROLLER AIRCRAFT (RESEARCH AND DEVELOPMENT),
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Summary. A comprehensive investigation of the fixed root, anti-symmetric and symmetric flutter characteristics of a model delta wing carrying an added mass has been made. The parameters that were varied in the tests were the mass value, the spanwise and chordwise position of the mass and its pitching radius of gyration. In the body freedom tests the fuselage inertia characteristics were also varied. Five different types of flutter were obtained depending on these parameters and the particular root condition.

The test results indicate that either symmetric or anti-symmetric flutter may be critical depending on mass value and c.g. position and that the optimum position of an added mass, from the flutter aspect, is in the neighbourhood of 0·75 span and well forward in the chord. It is felt that the results of a general investigation of this nature cannot be applied in detail to assess the effect of an added mass on the flutter characteristics of a particular aircraft.

1. *General Introduction.* An experimental investigation of the effects of an added mass on the flutter of a sweptback wing has already been made at the Royal Aircraft Establishment[1, 2]. The present Report extends this work to a wing of delta planform. There were three separate investigations made:

(i) Flutter with fixed root.
(ii) Anti-symmetric flutter with rolling body freedom.
(iii) Symmetric flutter with body freedoms in pitch and vertical translation.

The flutter characteristics were in all three cases obtained for a range of parameters of the mass and in the body freedom cases for a range of fuselage inertia characteristics.

The results show that the flutter characteristics of a fixed root delta wing carrying an added mass can be considerably modified by the introduction of body freedoms. The body freedom cases become similar to the fixed root for very high values of fuselage moment of inertia. The results should be regarded as giving a broad general indication of possible flutter characteristics of a delta wing.

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2. *The Scope of the Investigation.* The parameters that have been varied in the tests, for all root conditions, are mass value, its pitching radius of gyration and spanwise and chordwise position. Mass value was varied between 0·25 and 0·73 of the mass of the bare wing for two values of pitching radius of gyration namely, zero and 0·45 of the wing mean chord. Tests were made at 0·25, 0·5 and 0·75 span.

Considerable trouble was experienced in the symmetric body freedom case with gravitational and aerodynamic instabilities of the model. To overcome these problems it was necessary to have a large fuselage pitching moment of inertia. It was also necessary to use springs to stabilise the model during the tests[3] and at certain flutter frequencies these cause a large reduction in the effective fuselage mass.

For the anti-symmetric investigation there were only minor problems of aerodynamic instability and the gravitational instability was easily overcome by the supporting springs. Large variations in the fuselage rolling moment of inertia were possible.

Over 700 flutter tests have been performed in the investigation and these allow the general effects of an added mass and of rigid body freedoms on the flutter characteristics to be established.

3. *Model and Test Equipment.* 3.1. *Model Wing.* The model used in the tests was to the same design as that used in earlier tests to determine the flutter characteristics of a delta wing under fixed and free root conditions[4]. The half-span model had a span of 45 in., root chord 48 in. and tip chord 3 in. thus having a leading-edge sweepback of 45 deg. Fig. 1 shows the structural details and dimensions. A single square-sectioned spar of spruce at 35 per cent of chord tapered both in width and depth in proportion to wing taper. Spruce ribs were glued to the spar parallel to the airflow at intervals of 1 in. The ribs were 0·31 in. thick and were shaped to aerofoil section RAE 101 having a 10 per cent thickness/chord ratio. A lead block was built into each rib to give an overall wing inertia axis at 40 per cent chord and there were cartridge-paper shrouds over the leading and trailing edges. The spar was stiffened at half and three-quarter span by wood blocks glued to the spar and ribs (Fig. 1)*. At these stations three ribs were joined by these blocks. There were thus two local increases in stiffness over the span. The whole wing was covered with silk and doped with a solution of Vaseline in chloroform. The wing weight was 16·5 lb.

3.2. *Loading Technique.* The 'remote loading' method for investigating the effects of added masses on wing flutter has been fully described elsewhere[1], but a short description is given here. 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 wings by universal joints at a spanwise section. The other ends of the rods are outside the airstream and are connected to a loading platform by bearings permitting only motion 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 the airstream. Under these conditions a mass on the loading platform is equivalent to the same mass at the corresponding chordwise position on the wing section for oscillatory motion in pitch and vertical translation.

4. *Presentation of Results.* The fixed root, anti-symmetric and symmetric test results are described in Parts I, II and III of this Paper respectively.

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* It is proposed to use the model in further tests during which large loads will be applied at these stations and spar stiffeners were accordingly fitted.

A comprehensive theoretical investigation of the problem of the flutter of wings carrying an added mass has been made[5], in which all types of main surface flutter that are theoretically possible are considered. Classification of each type depends on the relative amplitude of motions of the body and the mass in the flutter oscillation. The several types of flutter found in the present investigation have been classified in the same way; type letters are used throughout this Report to differentiate between various kinds of flutter. The type letters correspond to those used in Ref. 5.

Three types of flutter occurred in the fixed root tests, four in the anti-symmetric and two in the symmetric. The three types in the fixed root case were:

Type A

The fundamental type of flutter for the wing mass combination involving considerable movements of the mass in pitch and vertical translation.

Type B

An overtone type of flutter (which only occurs at the 0·25 span loading position) involving the fundamental modes outboard of the mass coupled with considerable pitching of the mass. There is however, little or no vertical translation of the mass.

Type D

An overtone type of flutter occurring at all spanwise positions of the mass in which the mass is stationary in both pitch and vertical translation. The flutter involves the fundamental modes outboard of the mass, there being little visible motion inboard of the mass.

In the anti-symmetric case, flutter of types B and D occurred, when the fuselage, although free to roll did not appear to do so, and there were two further types E and C. *Type* E flutter involved roll of the fuselage and distortion of the wing in what appeared to be primarily a flexural overtone mode with a node at approximately 2/3 span. There was considerable pitch and vertical translation of the mass. *Type* C flutter involves translation of the mass, zero pitch of the mass and no roll of the fuselage.

Only two types of flutter occurred in the symmetric case; namely, types A and D, and again there was little or no fuselage motion in the flutter. The symmetric tests were much more restricted than the anti-symmetric in that a wide range of fuselage inertia conditions was covered in the latter case whereas in the former the fuselage inertia conditions were dictated by stability considerations and only one case was tested, (modified by negative inertia contribution from stabilising springs of fixed stiffness). It should not be inferred, however, that the symmetric case is of any less significance in the full scale flutter problem.

The flutter speed and frequency of the bare wing with the root fixed are adopted as standards and flutter speed and frequency for all other conditions are expressed as ratios of these in plotting the flutter curves. The anti-symmetric tests were made immediately following the fixed root tests but there was an interval of two months before the symmetric tests were carried out. There was a change in the flutter characteristics of the wing during this interval, so that comparison of the three sets of results can only be made when they are referred to the bare wing fixed root characteristics. The mean standard flutter speed and frequency were respectively 86 ft/sec and 6·3 c.p.s. during the fixed root and the anti-symmetric tests and for the symmetric tests the values were 95 ft/sec and 5·5 c.p.s.

The fixed root normal modes for a mass having a radius of gyration of 0·45 of the wing mean chord situated on the spar at 0·25 span and 0·75 span were obtained. Nodal lines and frequencies are shown in Figs. 3 and 4.

PART I

5. *Fixed Root Flutter Tests.* 5.1. *The Test Rig.* Fig. 2 shows the wing set up for a fixed root flutter test. The rig was that used for the anti-symmetric tests (described in Part II) with the wing root held fixed against roll by a solid linkage. To simulate fixed root flutter of the symmetric type a reflector plate should be fitted at the wing root to simulate the symmetric flow conditions. In practice none was used, previous tests having shown that a reflector plate had little or no effect on the flutter characteristics in this particular case.

5.2. *Range of Tests.* Five values of the added mass were tested varying between 4·07 lb and 12·07 lb, representing a variation between 0·25 and 0·73 of the wing mass. Two values of the radius of gyration of the added mass, in the pitching sense were tested, equal to 0·45 of the wing mean chord and a negligibly small value. The tests were made at three spanwise positions of the mass 0·25, 0·5 and 0·75 of span and at each spanwise position, about ten chordwise positions of the mass were selected.

The bare wing fixed root flutter speed and frequency were measured at frequent intervals throughout the tests to check whether any variations in stiffness were taking place whilst the tests were carried out, and to provide reference characteristics with which the other results could be compared.

5.3. *Test Results.* 5.3.1. *Mass at* 0·25 *span.* The results for all the tests in which the added mass had a radius of gyration of 0·45 of the wing mean chord are shown in Fig. 5. An added mass having this pitching radius of gyration will hereafter for convenience be referred to as a *localised mass.* Either two or three types of flutter occur depending on the mass value.

For mass values less than 0·4 of the wing mass three types of flutter occur depending on the chordwise position of the mass. The flutter associated with the further aft positions of the mass is Type B and both flutter speed and frequency are above those of the bare wing. The flutter frequency is reasonably constant with variation in chordwise position of the mass but the flutter speed varies reaching a maximum just before the transition to Type A flutter when the mass is slightly aft of the spar. The point at which transition occurs moves forward with increasing mass. For mass positions near the spar, the flutter is Type A and both the flutter speed and frequency are in general lower than those of the bare wing. The flutter speed falls to a minimum just forward of the spar, and then increases sharply and a second transition takes place. The chordwise position of the minimum moves aft with increasing mass. Type D flutter occurs for all positions of the localised mass forward of this point. The flutter speed and frequency are both higher than those of the bare wing and do not vary with chordwise position of the mass forward of the transition. This second transition point moves aft with increasing mass.

For mass values greater than 0·5 of the wing mass only two types of flutter occur, Types B and D. The two transition points have moved closer together and merged for a mass approximately 0·5 that of the wing and Type A flutter is eliminated. The flutter speeds and frequencies are above the bare wing values. The single transition point moves aft as the mass is increased up to the maximum value tested. All Type D flutter speeds are dependent on mass value and decrease with increasing mass.

The results for the tests in which the added mass had a negligibly small radius of gyration are shown in Fig. 6 together with comparable localised mass cases. An added mass having a negligibly small pitching radius of gyration will hereafter for convenience be referred to as a *concentrated mass.* A detailed chordwise variation in the position of the mass was not possible, only three positions could be tested. Depending on the mass value and position two types of flutter occur. The fundamental Type A flutter occurs for all mass values when the mass is situated at 0·08 of the local chord on either side of the spar. The flutter speeds and frequencies are roughly the same for these two mass positions, the speeds being approximately that of the bare wing. For an aft position of the mass, at approximately 0·25 of the local chord from the spar, two types of flutter occur. For small mass values, less than 0·25 of the wing mass, the fundamental Type A flutter occurs but for mass values greater than this an overtone Type B flutter occurs. The flutter speed is practically independent of mass value but there is a change of frequency at the transition.

Comparison of concentrated and localised mass results gives the effect of a change in the pitching radius of gyration of the mass on the flutter characteristics. For the furthest aft position of the mass, Type B flutter occurs in both cases for mass values greater than 0·25 of the mass of the wing. There are considerable differences when the mass is situated 0·08 of the local chord aft of the spar. For the concentrated mass, only Type A flutter is found whereas for the localised mass Types A, B, D are found depending on the mass value. Differences also occur for the mass 0·08 of the local chord forward of the spar, Types A and D flutter are obtained depending on the localised mass value whereas only Type A flutter occurs for all concentrated mass values.

5.3.2. *Mass at* 0·5 *span.* The results for the localised mass are shown in Fig. 7. Only two types of flutter now occur, Types A and D, for all the mass values tested.

If the mass is placed so that its c.g. is aft of a point just forward of the spar then Type A flutter occurs. The flutter speed is generally lower than that of the bare wing, but for masses placed well aft in the section the flutter speed is greater. The flutter frequency is in all cases lower than that of the bare wing and is invariant with c.g. position. As the mass is moved forward the flutter speed falls gradually to a minimum and then increases sharply and transition to Type D flutter occurs. Both the minimum and transition points move aft in the section with increasing mass value. The flutter speeds and frequencies of the Type D flutter are above those of the bare wing. Type D flutter speeds are independent of chordwise position of the mass and decrease with increasing mass value.

The results for the concentrated mass are plotted in Fig. 8 together with comparable localised mass cases. For all mass values the fundamental-type flutter is found when the mass is situated at either 0·08 or 0·31 of the chord aft of the spar, the flutter speeds being higher and the frequencies lower than those of the bare wing. When the mass is situated 0·15 of the chord forward of the spar Type A flutter occurs for mass values less than 0·4 of wing mass whilst for higher mass values Type D flutter is found having both flutter speed and frequency greater than the bare wing values.

Comparison of concentrated and localised mass results gives the effect of change of radius of gyration on the flutter characteristics. For the mass at 0·08 or 0·31 of the chord aft of the spar, Type A flutter occurs for all mass values in both cases. At the forward mass position 0·15 of the chord in front of spar, Types A and D flutter occur in both cases and the transition takes place at roughly the same mass value. However, Type A flutter speeds are in general below the bare wing for the localised mass whereas for the concentrated mass they are always greater.

5.3.3. *Mass at* 0·75 *span.* The results are shown in Fig. 9 for a localised mass and are very similar to those for the loading at 0·5 span. The Type D flutter was not encountered in the tests as the speed at which it probably occurs was outside the limit of 200 ft/sec. At this speed skin ballooning begins to have a serious effect on the model characteristics.

The Type A flutter speeds and frequencies are lower than the bare wing values and the minimum speeds are lower than those obtained at 0·25 and 0·5 span. The c.g. position at which the minimum occurs moves only slightly aft with increasing mass for this spanwise loading position and remains close to the spar for all mass values.

There were only two positions at which the concentrated mass could be applied, and the results are shown in Fig. 10 together with comparable localised mass cases. At the rear loading position, 0·27 of the chord aft of the spar, Type A flutter occurs. The flutter speeds increase slightly and the frequencies decrease slowly with increasing mass value. At the forward loading position, 0·13 of the chord forward of the spar a type of flutter occurs which appears to be purely wing bending at a flutter frequency less than that of the bare wing, the flutter speed increases with increasing mass and is greater than that of the bare wing. The flutter frequencies are similar to those for the aft position of the mass and this suggests that the flutter may, in fact, be Type A but with greatly reduced amplitudes in torsion.

Comparison of concentrated and localised mass results gives the effect of radius of gyration. For the aft position of the mass both values of radius of gyration give Type A flutter but the flutter speeds are lower than the bare wing for the larger and above for the smaller. The comparison is difficult at the forward position due to the uncertainty over the concentrated mass results. The normal Type A flutter occurs for the larger radius of gyration at mass values less than 2/3 of the mass of the bare wing and above this value Type D flutter is presumed to occur (no flutter encountered within the speed limit set for the tests).

5.4. *Discussion.* The test results for a localised mass show that the chordwise position of the transition from the fundamental Type A flutter to either of the overtones Type B or D is dependent on the mass value and spanwise position. The locus of the transition point is shown in Fig. 11 in terms of mass value and chordwise position (in terms of the local chord) for masses between 0·25 and 0·73 of the wing mass. Results were obtained at only a limited number of chordwise positions for a concentrated mass so that it is not possible to draw a transition curve in this case.

The shape of the transition curve for masses placed at 0·5 and 0·75 span is similar. Transition is in all cases from Type A to D flutter. Both types of flutter are possible for all mass values tested, the chordwise position of the transition moving aft with increasing mass. At 0·25 span however, Types A, B and D flutter are found. Type A flutter is only possible for mass values less than 0·44 of the wing mass. For higher mass values the flutter will be Type B or D depending on the chordwise position of the mass. Type B flutter occurs in general for mass positions aft of the spar whilst Type D may occur at either forward or aft positions depending on the mass value.

The results obtained show that it is possible to improve the fixed root flutter characteristics of the delta wing by a judicious choice of the localised mass value and its position. By a correct positioning of the mass the system will lie within the Type D flutter region where the flutter speed is invariably greater than that for the fixed root bare wing. The highest flutter speeds occur with the mass at 0·75 span and well forward in the chord and are at least 2·4 times the bare wing value. Type D flutter occurs over a much wider range of c.g. positions of the localised mass (expressed in terms of the local chord) at 0·25 span than at either of the other two spanwise loading stations but the flutter speed for this type of flutter is lower than that obtained at other spanwise stations.

5.4.1. *Comparison of the fixed root flutter characteristics of a swept and delta wing.* The flutter characteristics of the fixed root delta wing are compared with those of a swept wing having comparable leading-edge sweepback[1] in Fig. 12. The ordinates are the non-dimensional flutter speed (critical speed divided by that of the bare wing), and the abcissae the non-dimensional mass value, (localised mass value divided by wing mass). The results presented are for a localised mass situated on the spar. Type A flutter only is obtained for all spanwise positions of the mass for the swept wing and the same is true for the delta wing except for the case of a mass at 0·25 span where both Types A and D flutter are obtained. At 0·5 and 0·75 span the swept wing has a higher relative flutter speed providing that the mass value is less than 0·8 of that of the bare wing but at 0·25 span the delta has the better characteristics when the mass value is greater than 0·45 that of the wing. A similar comparison for masses placed slightly aft or forward of the spar gives corresponding trends except that at 0·25 span for slightly aft positions of the mass Type B flutter replaces Type D for the delta. From a general comparison of the two sets of results we can say that for mass values less than about 0·75 that of the bare wing the swept wing, on the whole, has the better relative flutter characteristics for masses placed close to the spar whilst for masses placed well forward in the chord the delta has the better.

PART II

6. *Anti-Symmetric Flutter Tests.* 6.1. *The Test Rig.* The model wing was attached to a rig that permitted body freedom in roll about an axis corresponding to the centre-line of the aircraft (Fig. 13). A linkage system allowed the rolling moment of inertia of the rig to be varied by attaching weights to a rod outside the tunnel working section. The wing was mounted vertically in the tunnel with the tip uppermost, and stabilizing springs fitted to the linkage provided a restoring moment when the model was displaced in roll. For a steady oscillatory condition 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 provided by the restraining springs.

6.2. *Range of Tests.* The same range of added mass parameters was covered as for the fixed root tests (Part I). For each mass loading the rolling moment of inertia of the fuselage was varied. In general, the range of moment of inertia covered was between − 200 lb in^2 and + 1,000 lb in.^{2}. The bare wing rolling moment of inertia was 4,100 lb in.^{2}.

The effective value of the fuselage rolling moment of inertia was dependent on the flutter frequency, since the negative mass effect of the springs contributed a negative moment of inertia that was inversely proportional to the square of the frequency. Variation of the chordwise position of the added mass without any corresponding variation in rolling moment of inertia of the fuselage was thus practically an impossibility because of the resulting change of frequency. The test method adopted was to fix on a chordwise position for the added mass and then vary the rolling moment of inertia. Interpolation of the results of these tests gave the variation of flutter speed and frequency with chordwise added mass position for particular values of fuselage rolling moment of inertia. Results are presented for two values; namely, 0·1 and 0·2 of the wing rolling moment of inertia. (Figs. 20 to 22.)

6.3. *Test Results.* 6.3.1. *Mass at* 0·25 *span.* The variation of flutter speed and frequency with fuselage rolling moment of inertia for three values of the localised mass is shown in Fig. 14. Two types of flutter E and D occur depending on the c.g. position of the mass and the fuselage inertia. As the mass moves forward in the section the transition from Type E to Type D flutter occurs at a lower value of fuselage inertia. Forward of a certain point in the section it is only possible to obtain Type D flutter. Flutter speeds and frequencies at a fixed localised mass position and fuselage inertia decrease with increased mass value.

For concentrated masses, only three chordwise positions of the mass could be investigated, and the variation of flutter speed and frequency with fuselage inertia is shown in Fig. 15. Three types of flutter B, D and E are possible depending on the mass value, its chordwise position and the fuselage inertia. The greatest complexity occurs with the mass 0·08 of the chord aft of the spar when all three types are found. All the flutter speeds are greater than that of the bare wing and the frequencies of Types B and D flutter are higher than the bare wing.

6.3.2. *Mass at* 0·5 *span.* There are no marked differences between the results for loading of 0·25 span and those at 0·5 span (Fig. 16) for a localised mass. Types D and E flutter were found, the type of flutter occurring for a particular localised mass depends on its chordwise position and on the fuselage inertia. There is a decrease in flutter speed with increasing mass value at a particular mass position and fuselage inertia.

The results for a concentrated mass (Fig. 17) differ from those for the mass at 0·25 span. Types C, D and E flutter were found, the transition from one type to another for a particular mass value and position depending on the fuselage inertia. Type C flutter occurs at roughly the same speed as Type D and at a slightly higher frequency. The types of flutter occurring at similar mass position relative to the spar at 0·25 and 0·5 are not the same over the whole range of fuselage inertias tested.

6.3.3. *Mass at* 0·75 *span.* The results for a localised mass are shown in Fig. 18. Type E flutter occurs for aft positions of the mass and for more forward positions no flutter at all was obtained.

No results were obtained for a concentrated mass. Attempts were made to determine the flutter characteristics with a small mass at chordwise positions both forward and aft of the spar. In both cases a violent instability of the model was set up at certain wind speeds and the tests were not continued.

6.3.4. *Bare wing.* Tests on the effect of roll freedom on the flutter of the bare wing were made (Fig. 19), to compare with the results of Ref. 6 and some differences were obtained. In the earlier tests two types of flutter were obtained namely 'body freedom' corresponding with Type E and 'disturbed root' corresponding with Type A. Type E occurs for values of fuselage rolling moment of inertia up to $\bar{I}_R = 0 \cdot 27$ when there is a transition to Type A. The present tests yield a transition from Type E flutter at a smaller value of $\bar{I}_R = 0 \cdot 053$. After the transition the flutter mode changes gradually with increase of $\bar{I}_R$. The fuselage amplitude in roll is small for all values of $\bar{I}_R$ beyond the transition but the amplitudes in wing flexure and torsion gradually increase as the wing approaches the fixed root condition. The flutter speed beyond the transition is approximately constant and the flutter frequency falls steadily with increase of fuselage inertia. The difference between the two models used for these tests lies in the local increase of spar stiffness at 0·50 and 0·75 span of the present model. This changed stiffness distribution has a pronounced effect on the normal mode frequencies of the wing as is shown in Table 1.

In particular the frequencies of the overtone bending and torsion modes are considerably greater than for the original wing.

6.4. *Discussion.* The anti-symmetric test results are the most complex of those reported here; four types of flutter B, C, D and E having been found.

Figs. 20 to 22 show the effect of chordwise position of localised mass on the flutter speed and frequency of the delta wing for two values of fuselage rolling moment of inertia at three spanwise stations. Comparison with the fixed root characteristics shows the effects of the addition of the rolling freedom. Whereas in the case of fixed root Type D flutter the speed is practically constant with chordwise position of the mass, in the case with rolling freedom, speeds decrease gradually with forward movement of the mass. Type D flutter speeds in the case with rolling freedom also vary slightly with fuselage rolling moment of inertia and decrease with increased localised mass value.

TABLE 1

	Normal Mode Frequencies—Fixed Root		
Model	Fundamental	Overtone bending	Torsion
Original Wing	3·3 c.p.s.	4·8 c.p.s.	6·0 c.p.s.
Present Wing	3·5 c.p.s.	7·3 c.p.s.	12·6 c.p.s.

From a comparison of the fixed root and roll freedom results for a wing carrying a localised mass at three spanwise stations the following points emerge:

(*a*) *Mass at* 0·25 *span.* In the body freedom case only Types E and D flutter occur, compared with Types A, B and D in the fixed root case. Type B flutter is entirely suppressed by the introduction of the rolling freedom and for most of the range of chordwise positions of the mass there is only Type D flutter. With roll freedom present the effect of increase of mass is to move forward the chordwise position of the transition from E to D type flutter. This is directly contrary to the fixed root case where increase of mass moves the corresponding transition point from A to D flutter aft. Reduction of fuselage rolling moment of inertia has the effect of moving the transition point forward in the chord.

(*b*) *Mass at* 0·5 *span.* The results in the body freedom case are similar to those for fixed root. Types E and D flutter occur with body free and A and D with fixed root. With roll freedom present the transition point appears to be largely independent of the mass value. There is a similarity with the results for the mass at 0·25 span in that the transition point for the roll freedom case is much further aft in the chord than in the corresponding fixed root case, where it is always forward of the spar.

(*c*) *Mass at* 0·75 *span.* The results are again similar, Type E flutter occurring in the body freedom case and Type A in the fixed root. Type D flutter was obtained in neither case but the transition point was readily found. It appeared to be practically independent of both mass value and fuselage rolling moment of inertia. The point is situated much nearer to the corresponding fixed root cases than at either of the other two spanwise positions.

Curves of transition points for these three spanwise positions and for two values of rolling moment of inertia are shown in Fig. 23. The curves for mass positions at 0·5 and 0·75 span are quite similar to those for the fixed root case but there is a radical change in the curves for mass placed at 0·25 span due to the introduction of the rolling body freedom.

It is not possible to make a direct comparison between the fixed root and the anti-symmetric results for a concentrated mass using the method adopted above as results are available for a severely limited number of chordwise positions.

Summarising, therefore, the introduction of the anti-symmetric body freedom has a marked beneficial effect on the flutter characteristics when the localised mass is added at 0·25 span. The fundamental Type A flutter is replaced by Type D having a higher flutter speed over a wide range of mass positions for low mass values. Type B flutter is replaced by the Type D flutter also but here the increase in critical speed is marginal. The beneficial effect is repeated at 0·5 span where again Type D has replaced Type A flutter over quite a large range of mass positions. Over the remainder of the c.g. range covered in the fixed root tests Type E flutter now occurs and the flutter speeds are considerably higher than the corresponding Type A fixed root values. At 0·75 span again Type E flutter speeds are higher than their counterparts in the fixed root case. With root fixed or free only Type E flutter is obtained at this spanwise loading position.

For wings carrying concentrated masses the addition of the rolling freedom is again in general beneficial. At 0·25 span flutter speeds are increased at all three mass positions tested, the flutter with the rolling freedom being mainly the Type D although Type B is also found for the larger masses placed slightly aft of the spar. At 0·5 span there is little overall difference between the flutter speeds found in the fixed root and the body freedom cases. Such differences as do occur are in the types of flutter found, in the fixed root case Types A and D and in the body free case C, D and E. No accurate assessment of the effect of the rolling body freedom was possible at 0·75 span but the indications are that the flutter speeds are slightly increased.

In both the fixed root and the anti-symmetric flutter tests an optimum position for the localised mass has been found at 0·75 span and well forward in the chord. This ensures that flutter, if encountered, will be in the Type D overtone region. The minimum value of the localised mass which would achieve this condition was not determined in the tests, but it will be less than 0·25 of the mass of the wing.

PART III

7. *Symmetric Flutter Tests.* 7.1. *The Test Rig.* The rig is shown in Fig. 24. It consisted of a body 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 deflection 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. Due to the effect of the leg support the system was gravitationally unstable, and accordingly two stabilizing springs were fitted close to the overall centre of gravity. This overcame the gravitational instability but increased the stiffness in the body freedoms. This resulted in a rigid body instability at a particular wind speed, which could only be avoided by increasing the fuselage pitching moment of inertia considerably and by introducing friction into the system*.

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* In practice this measure was only effective up to a speed of approximately 120 ft/sec. and above this speed the rigid body oscillation was again encountered. The flutter tests were accordingly limited to speeds below this.

The restraining springs act as negative masses during an oscillation[3], the mass value depending on the flutter frequency, so that the fuselage characteristics were changing throughout the tests. As springs were fitted close to the overall c.g. of the system the effect on the fuselage pitching moment of inertia about this axis was small but the effect on fuselage mass was quite pronounced in certain cases.

7.2. *Range of Tests.* The same range of added mass parameters was covered as for the fixed root and anti-symmetric tests. The fuselage pitching moment of inertia varied by up to 2 per cent from the basic value of 7,900 lb in.^{2} (equivalent to a pitching radius of gyration of $0 \cdot 76c_m$) due to variations in the flutter frequency. Fuselage mass, however, for certain localised mass positions was effectively lowered to $0 \cdot 36$ of its basic value of $21 \cdot 25$ lb. and effective fuselage masses between these extremes were tested. The basic fuselage c.g. position is $0 \cdot 02c_m$ forward of the aerodynamic centre of the wing alone. The method of testing was the same as that in the fixed root case.

7.3. *Test Results.* 7.3.1. *Mass at* $0 \cdot 25$ *span.* The results for a localised mass are shown in Fig. 25. Two types of flutter are obtained depending on the localised mass value and its chordwise position. For small mass values Type A flutter occurs in the majority of c.g. positions tested. The flutter is similar to the Type A flutter for the fixed root wing, though there is a small pitching motion of the fuselage in addition. For small mass values well forward in the chord, and for masses greater than $0 \cdot 5$ of the mass of the bare wing, the flutter is mainly Type D. This flutter corresponds exactly with the fixed root Type D flutter. The transition position moves aft in the chord with increasing mass. It should be noted that because of the frequency change the two types of flutter occur at different fuselage effective mass values and these are indicated on the graphs.

Results for a concentrated mass together with comparable results for a localised mass are shown in Fig. 26 for three positions of the mass. Type A flutter is found in all cases, the flutter speeds and frequencies being in general, lower than the bare wing values.

There are marked differences between the localised and concentrated mass results. In the first case Types A and D flutter are found whereas in the second only Type A. The transition from A to D takes place at a higher mass value for the further aft positions of the mass.

7.3.2. *Mass at* $0 \cdot 5$ *span.* The results for a localised mass are shown in Fig. 27 and are very similar to those obtained at $0 \cdot 25$ span. The main difference between the two cases is that fuselage pitching amplitudes in the Type A flutter are less than at $0 \cdot 25$ span.

Results for the concentrated mass together with comparable results for a localised mass are shown in Fig. 28. The results for this loading position are different from those at $0 \cdot 25$ span as in this case two types of flutter, A and D, are obtained. The transition between the two occurs at a higher mass value for the aft positions of the mass.

Comparison of concentrated and localised mass results shows the effect of variation of radius of gyration on the flutter characteristics. For the furthest aft position of the mass the results are similar but for more forward mass positions two types of flutter occur for the lower value of radius of gyration whereas there is only one for the higher.

7.3.3. *Mass at* $0 \cdot 75$ *span.* Results for a localised mass are shown in Fig. 29. Only Type A flutter was obtained. The fuselage mass varies considerably during the tests as indicated on the graphs. The amplitudes in the fuselage pitching motion are smaller than in either of the other two spanwise loading positions. The minima of the Type A flutter speed curves at this spanwise position are in general much further aft in the chord than at the other two loading sections. This effect is associated with the marked reduction in fuselage mass with this loading section and consequently with a change in the overall c.g. position which does not occur at the other two spanwise positions.

Results for a concentrated mass together with comparable results for a localised mass are shown in Fig. 30. Only two chordwise positions of the mass could be investigated. Type A flutter occurs with the mass aft of the spar, the speeds and frequencies being respectively higher and lower than the bare wing. No flutter was found within the available speed range with the mass forward of the spar.

Comparison of concentrated and localised mass results shows that only Type A flutter is found in both cases.

7.4. *Discussion.* The symmetric test results are the simplest in that only Types A and D flutter occur. There are slight root movements associated with the Type A flutter, but it is classified in the same way as the corresponding fixed root flutter.

The transition curves, from Type D flutter, for a localised mass at the three spanwise sections are shown in Fig. 31. At 0·25 span the transition takes place at similar mass values and chordwise positions to the fixed root case and similarly at 0·5 span. Only one point was obtained at 0·75 span, but the other results are sufficient to indicate that the trends at this section are similar to those at the others.

Owing to the method of testing, the fuselage effective mass is not the same at each spanwise loading position and a comparison between the fixed and free root tests cannot be made for a particular fuselage mass. At 0·25 span, Type A flutter exists, in general, for all mass positions aft of the spar (at speeds less than the bare wing), whereas in the fixed root tests Type B flutter is obtained for the mass positions further aft (at speeds greater than the bare wing). For a localised mass at 0·5 span however, the results are similar in the root fixed and free conditions, though transition from Type A flutter occurs at a somewhat further aft position in the root free case. At 0·75 span where the largest changes in fuselage effective mass occur, there are the biggest differences between the root fixed and free results. For a localised mass 0·25 of that of the bare wing the results are similar, the root free flutter speeds being higher than the root fixed, but for higher mass values the results are quite different. The Type A flutter speeds with the root fixed show a decrease with forward movement of the localised mass whereas the same movement in the root free case causes the flutter speed to increase.

Compared with the fixed root, the effect of the symmetric body freedom appears to be to improve the flutter characteristics for masses placed outboard of 0·5 span and to have a detrimental effect for masses placed inboard of this position. There seems to be little difference between the two cases for masses placed at 0·5 span. In the fixed root and anti-symmetric flutter tests an optimum position has been found for a localised mass so that the best flutter characteristics are obtained, namely at 0·75 span and well forward in the chord. This same position is found from these symmetric body freedom tests to give the best flutter characteristics for the wing mass combination.

8. *Comparison of the Symmetric, Anti-Symmetric and Fixed Root Tests.* In a specific flutter investigation on a particular wing-localised mass system it will be necessary to consider both symmetric and anti-symmetric flutter. Comparison of the symmetric and anti-symmetric results of these tests yields the following points. (1) For masses placed at, or inboard of, half span, symmetric

flutter is more critical, particularly for smaller masses whose c.g. is aft, but for more forward c.g. positions both types are important. (2) The comparison is difficult when masses are placed outboard due to variation in the fuselage characteristics in the symmetric case but it seems likely that the symmetric flutter will be more critical. (3) The optimum position for a localised mass in the symmetric, anti-symmetric and fixed root tests can be used as a guide in the correct positioning of a localised mass for the avoidance of flutter. These tests show the position to be at 0·75 span and well forward in the chord. It has been shown theoretically[5, 7] that the optimum position for a localised mass is in the region of the nodal line of the overtone torsion mode for the fixed root bare wing. The nodal lines of the higher frequency modes for this wing are shown in Fig. 32. It can be seen that the nodal line of the overtone torsion mode, which occurs at 14·8 c.p.s., crosses the spar somewhat outboard of the optimum position. However, theoretical predictions were based on uncoupled modes of the wing whereas the measured modes are coupled ones which may account for the discrepancy. (4) Chordwise positions of the mass near the spar should be avoided as these lead to low flutter speeds for the symmetric types of flutter.

It is shown that fixed root tests do not give an accurate indication of the results to be expected when body freedoms are present. In particular, in certain instances the fixed root results are shown to give a conservative estimate of flutter speed compared with that actually obtained when the body freedoms are included.

9. *Conclusions.* A comprehensive investigation of the fixed root, anti-symmetric and symmetric flutter characteristics of a model delta wing with an added mass has been made. The main conclusions to be drawn from this investigation are:

(1) That either symmetric or anti-symmetric body freedom flutter may be more critical depending on mass value and position.

(2) That the lowest flutter speeds are associated with the symmetric types of flutter and for certain chordwise positions of the mass. For this wing the minimum generally occurs when the mass is situated on or near the spar.

(3) The introduction of body freedoms into the tests causes a modification of the fixed root flutter characteristics and the fixed root results cannot be taken as a reliable guide to the body free case.

(4) There appears to be an optimum position for a localised mass on a delta wing. This would seem to be in the region of 0·75 span and well forward in the chord, a more forward position being required with a small mass than a large one. Provided the optimum conditions are realised flutter speeds greater than twice that of the fixed root bare wing may be achieved.

(5) A total of five different forms of flutter are possible depending on the mass value and root condition.

LIST OF SYMBOLS

c_l	Local chord
c_m	Mean chord
I_R	Fuselage rolling moment of inertia
$\bar{I}_R$	$\frac{\text{Fuselage rolling moment of inertia}}{\text{Bare wing rolling moment of inertia}}$
k	Pitching radius of gyration of added mass
M	Added mass value
$\bar{M}$	$\frac{\text{Added mass}}{\text{Wing mass}}$
m	$\frac{\text{Fuselage mass}}{\text{wing mass}}$
V	Flutter speed
$\bar{V}$	$\frac{\text{Flutter speed}}{\text{Bare wing, fixed root, flutter speed}}$
ω	Flutter frequency
$\bar{\omega}$	$\frac{\text{Flutter frequency}}{\text{Bare wing, fixed root, flutter frequency}}$

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2	D. R. Gaukroger and E. W. Chapple . .	Wind tunnel test on the effect of body freedoms on the flutter of a model wing carrying a localised mass. A.R.C. R. & M. 3081. May, 1956.
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4	D. R. Gaukroger, E. W. Chapple and A. Milln	Wind tunnel flutter tests on a model delta wing under fixed and free root conditions. A.R.C. R. & M. 2826. September, 1950.
5	W. G. Molyneux	Flutter of wings with localised masses. *J. R. Aero. Soc.* Vol. 61. No. 10. p. 667. October, 1957.
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7	D. R. Gaukroger	A theoretical treatment of the flutter of a wing with a localised mass. *J. R. Aero. Soc.* Vol. 63. No. 2. p. 95. February, 1959.

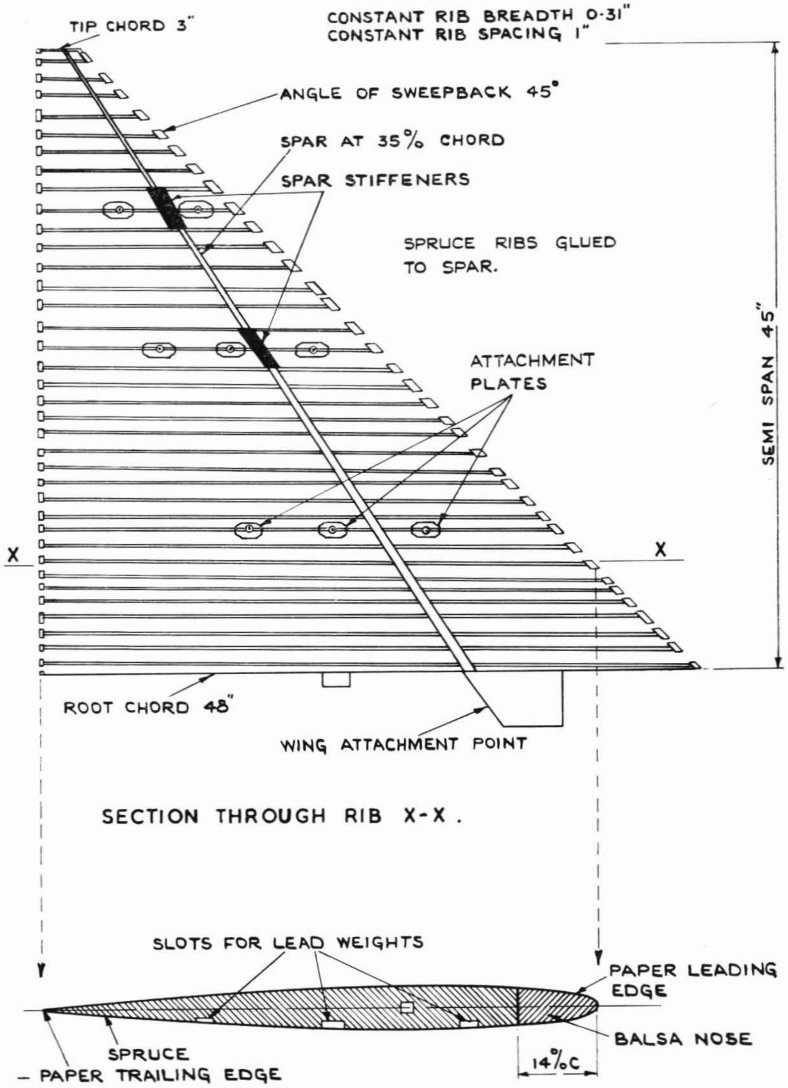


FIG. 1. Model wing details.

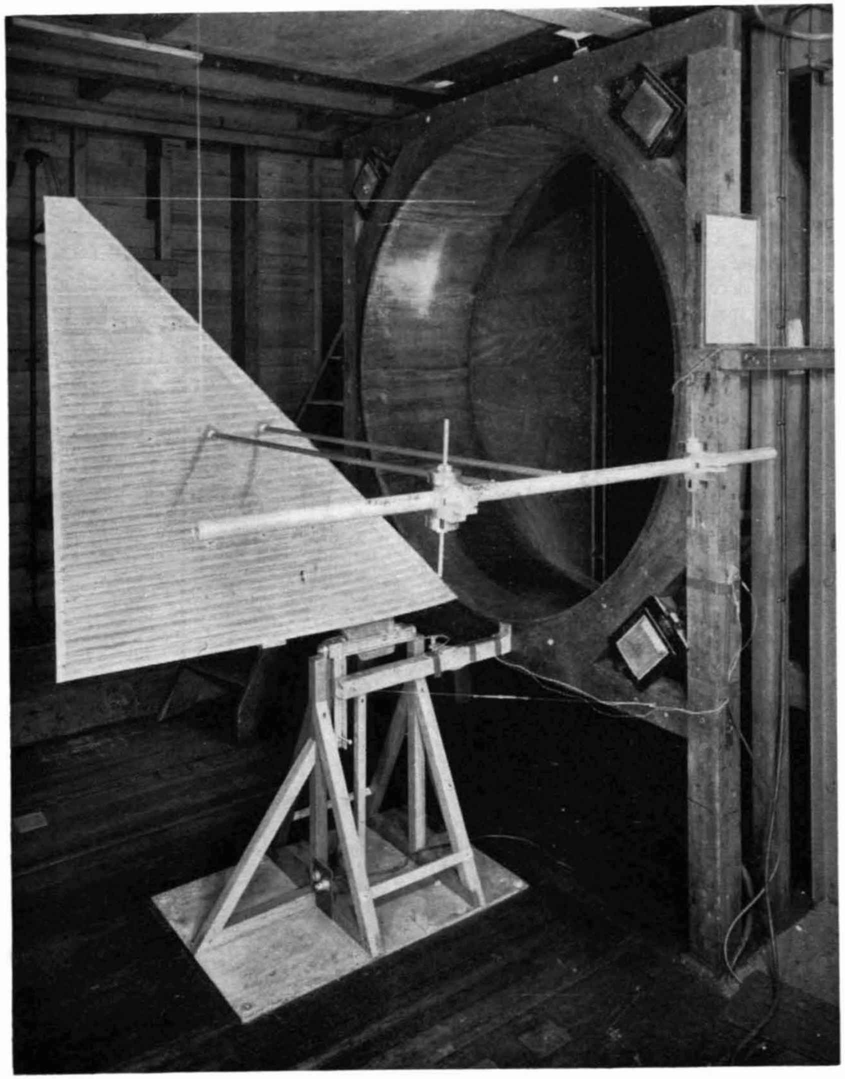


FIG. 2. The flutter rig in wind tunnel.

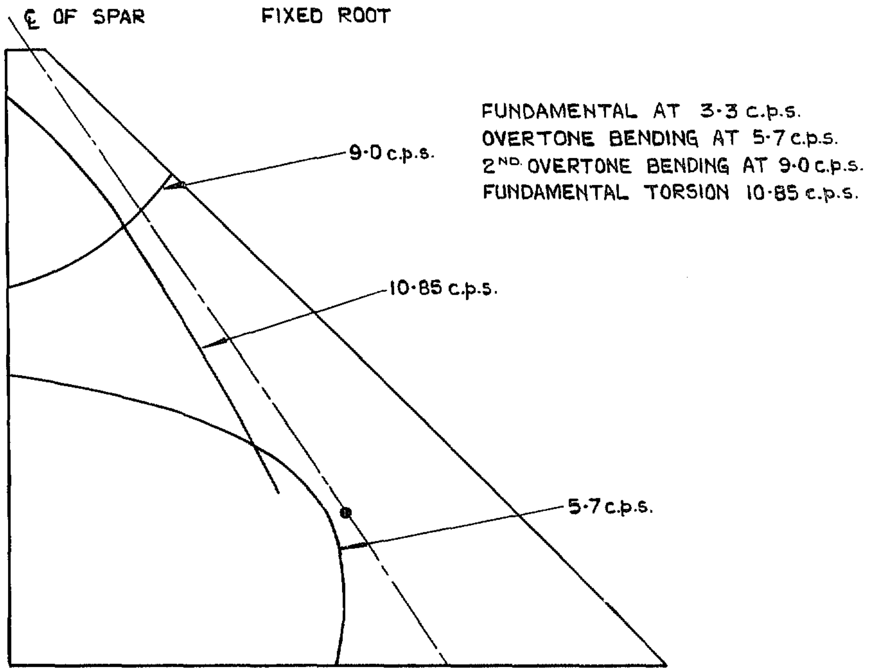


FIG. 3. Normal mode frequencies and nodal lines for a localised mass 8·07 lb at 0·25 span.

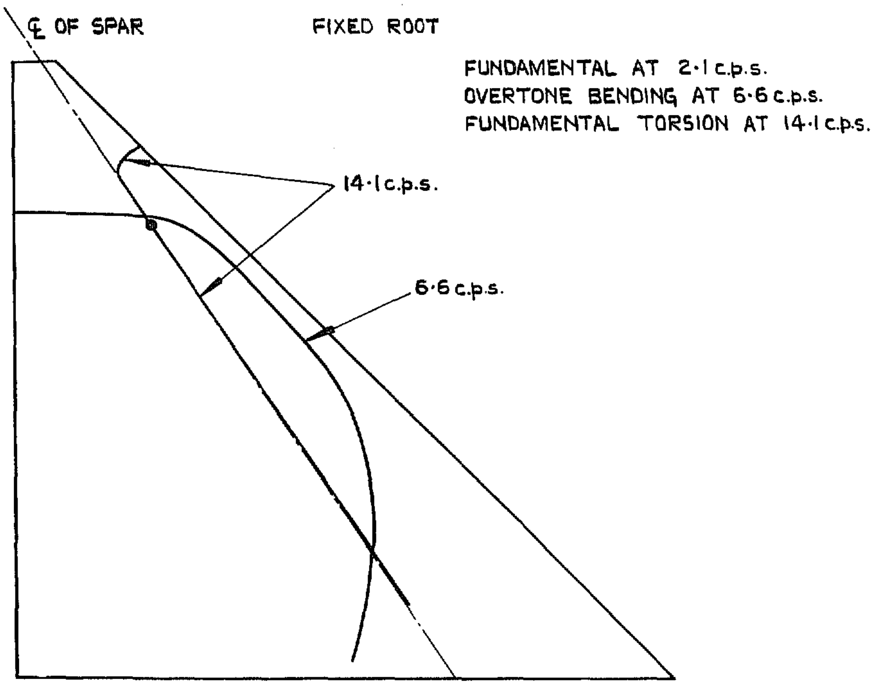
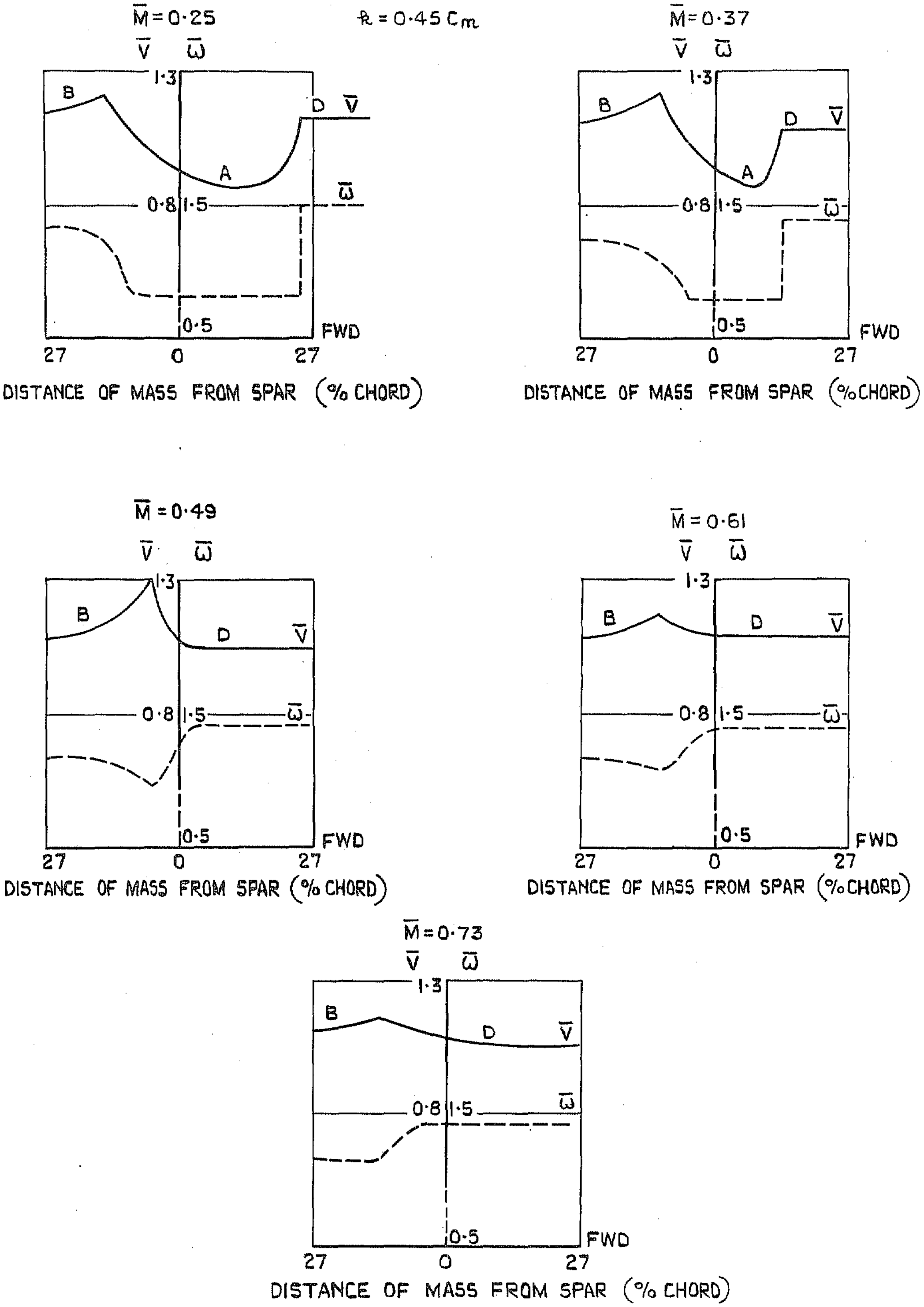


FIG. 4. Normal mode frequencies and nodal lines for a localised mass 8·07 lb at 0·75 span.



FIXED ROOT FLUTTER—LOCALISED MASS.

FIG. 5. The effect of chordwise position on flutter speed and frequency for a localised mass at 0·25 span.

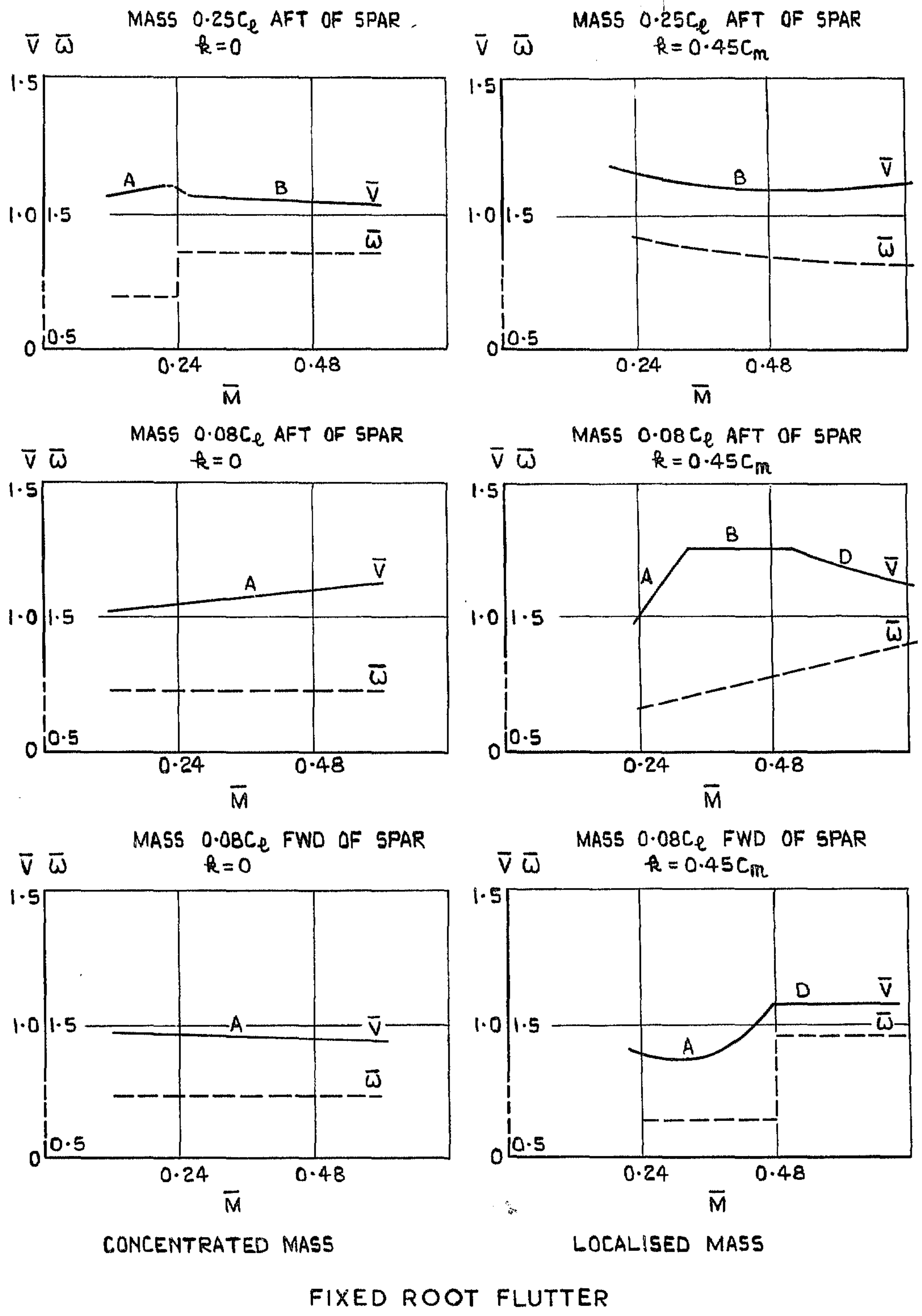
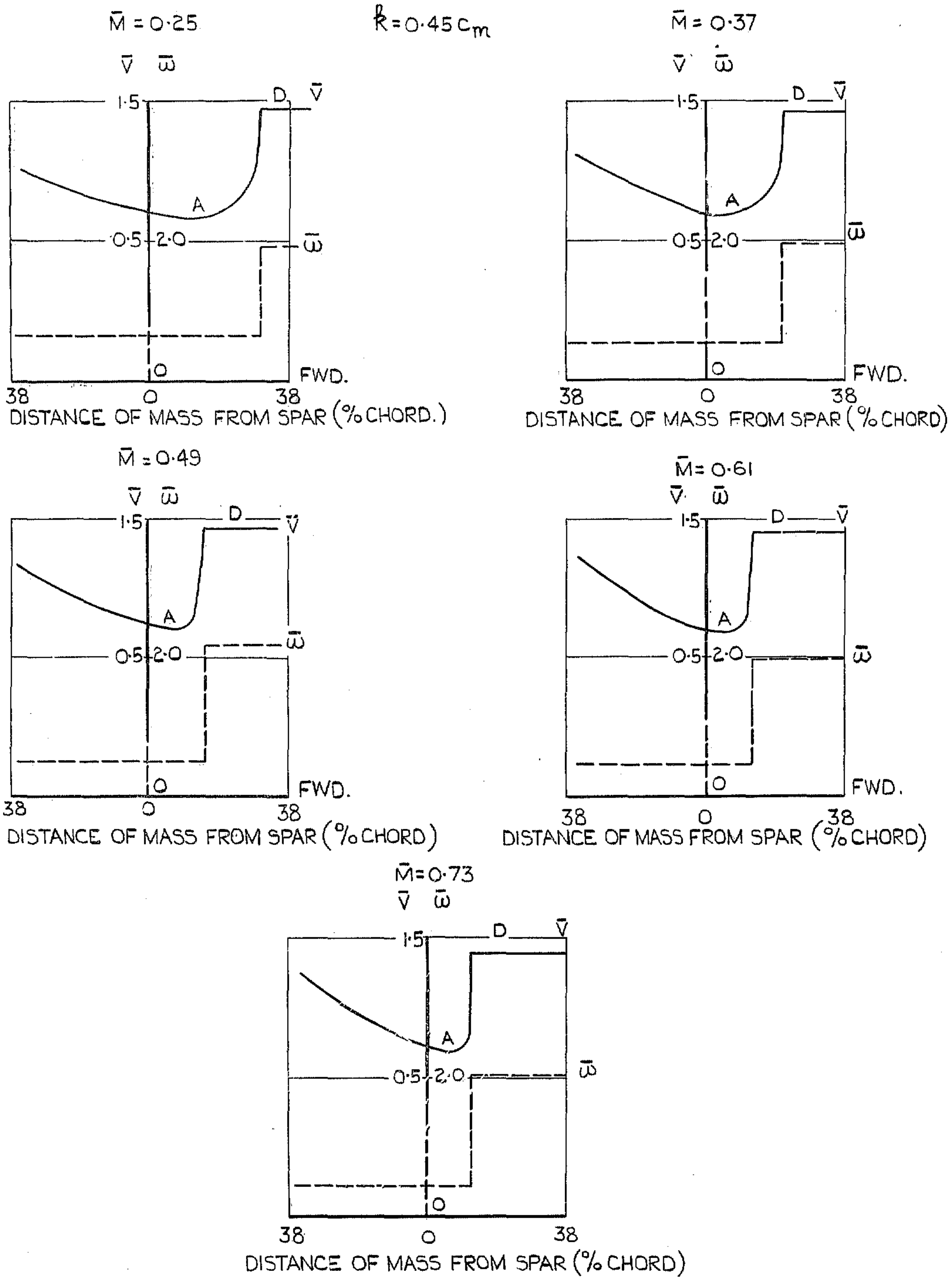
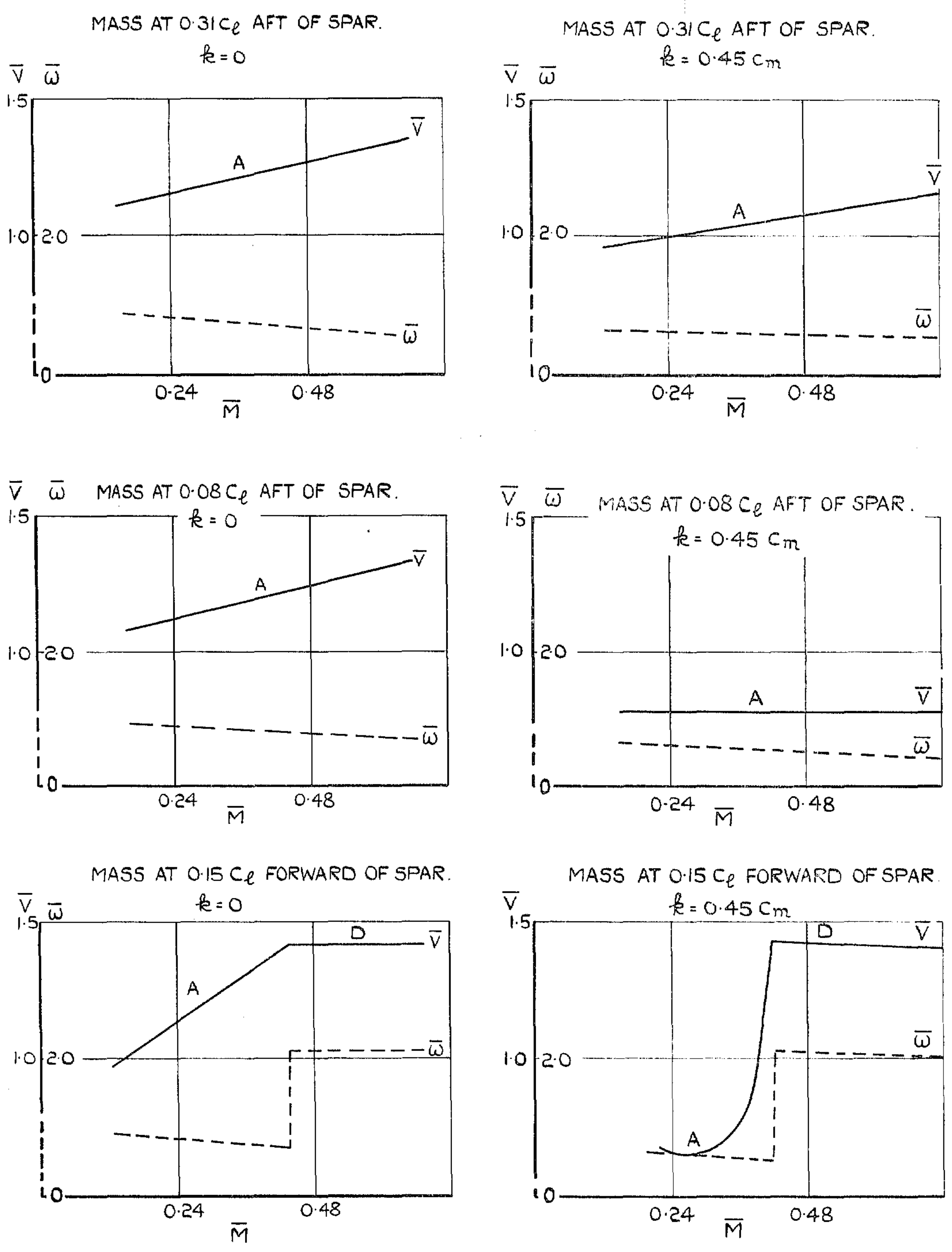


FIG. 6. The effect of mass value on flutter speed and frequency for a mass at 0·25 span.



FIXED ROOT FLUTTER - LOCALISED MASS.

FIG. 7. The effect of chordwise position on flutter speed and frequency for a localised mass at 0·5 span.

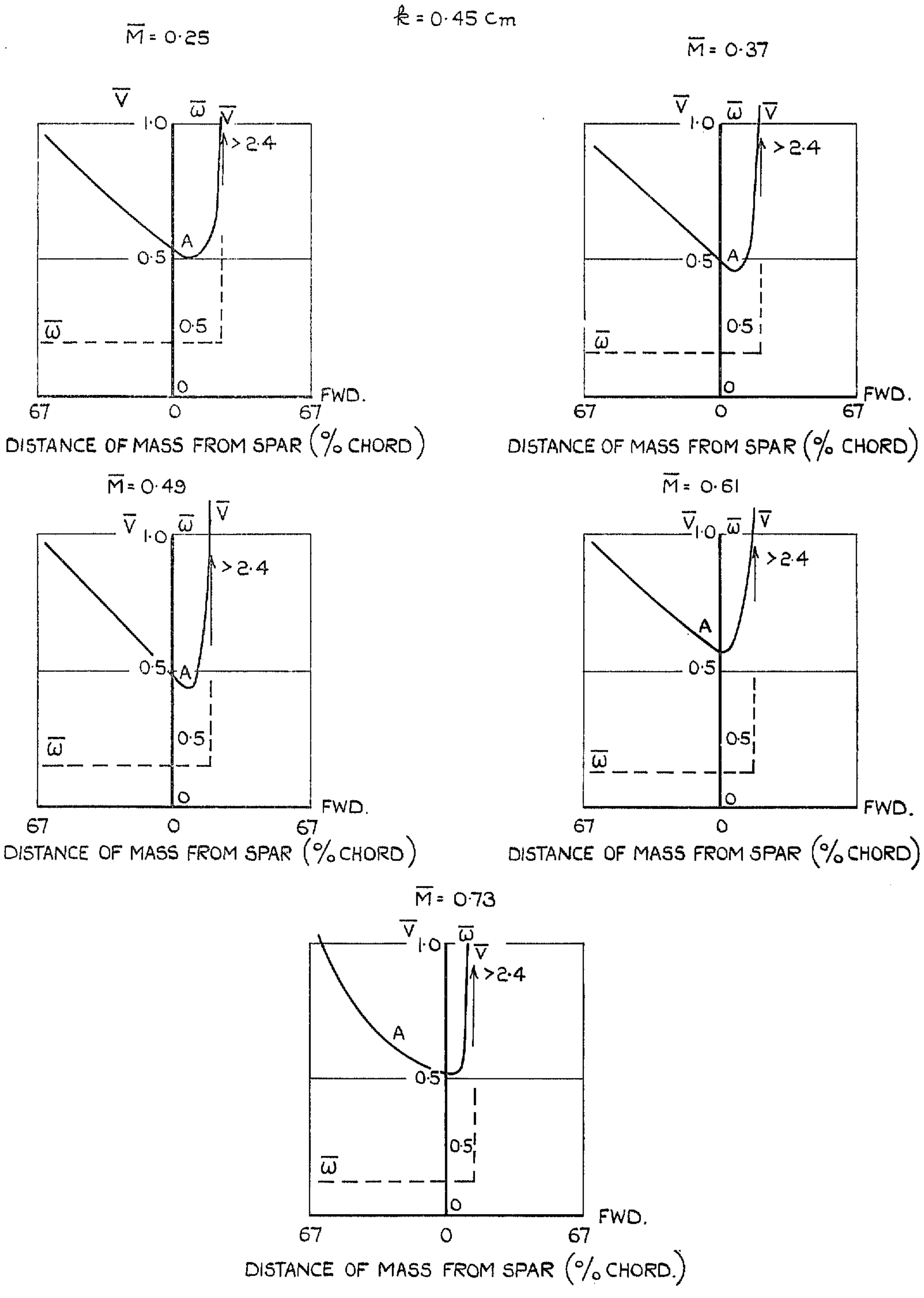


CONCENTRATED MASS.

LOCALISED MASS

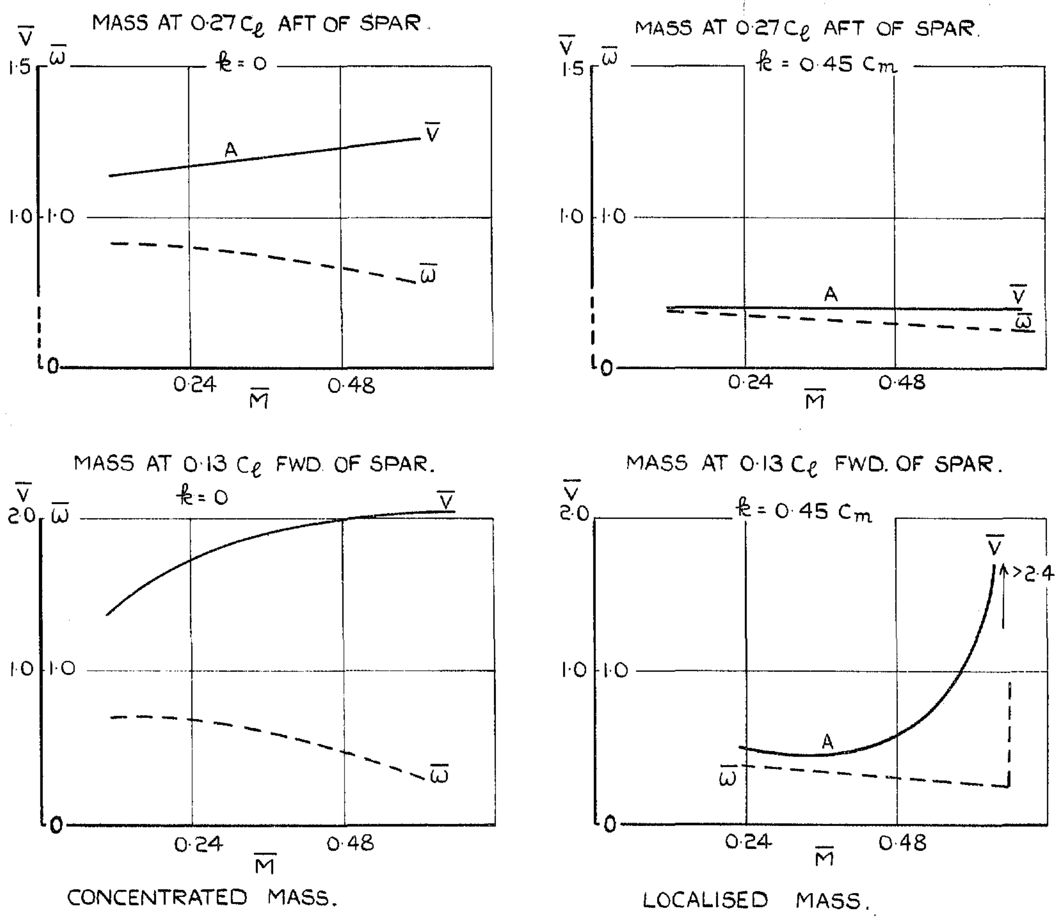
FIXED ROOT FLUTTER.

FIG. 8. The effect of mass value on flutter speed and frequency for a mass at 0·5 span.



FIXED ROOT FLUTTER – LOCALISED MASS.

FIG. 9. The effect of chordwise position on flutter speed and frequency for a localised mass at 0·75 span.



FIXED ROOT FLUTTER.

FIG. 10. The effect of mass value on flutter speed and frequency for a mass at 0·75 span.

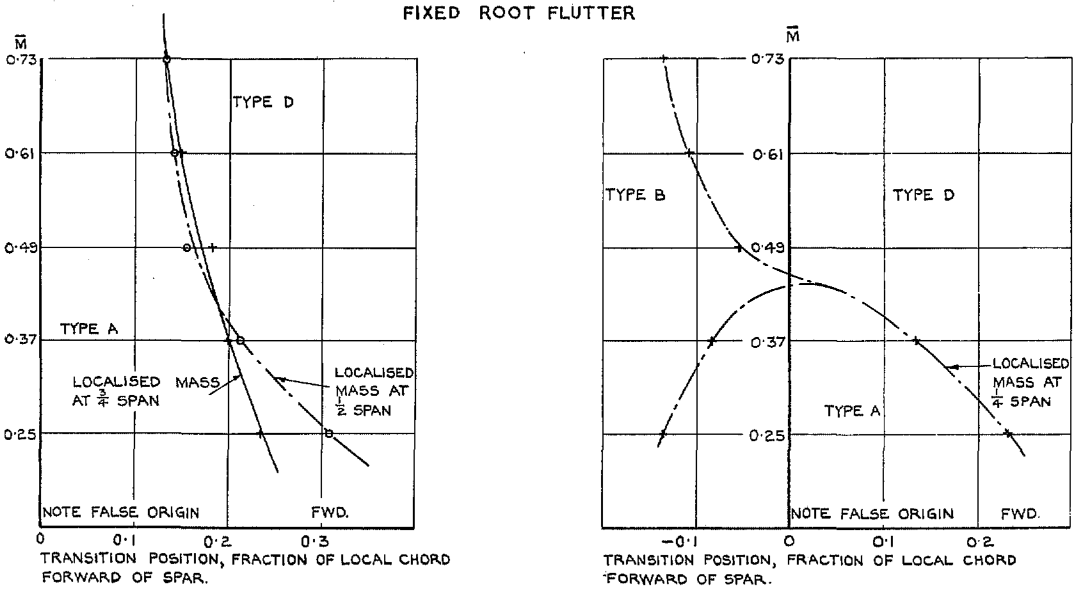


FIG. 11. Transition curves for a localised mass at various spanwise sections.

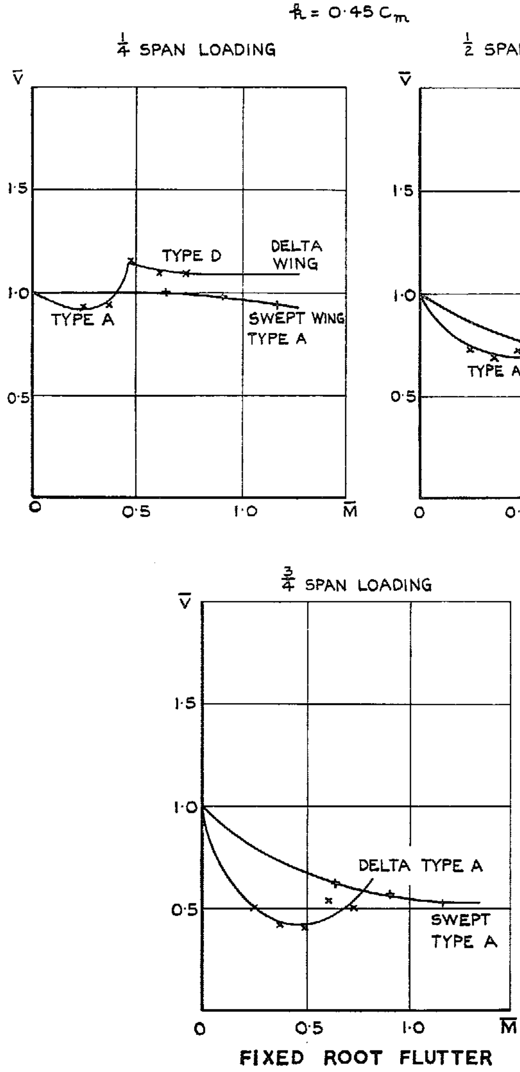


FIG. 12. A comparison of the fixed root flutter characteristics of a delta and swept wing of comparable sweepback carrying a localised mass on the wing spar.

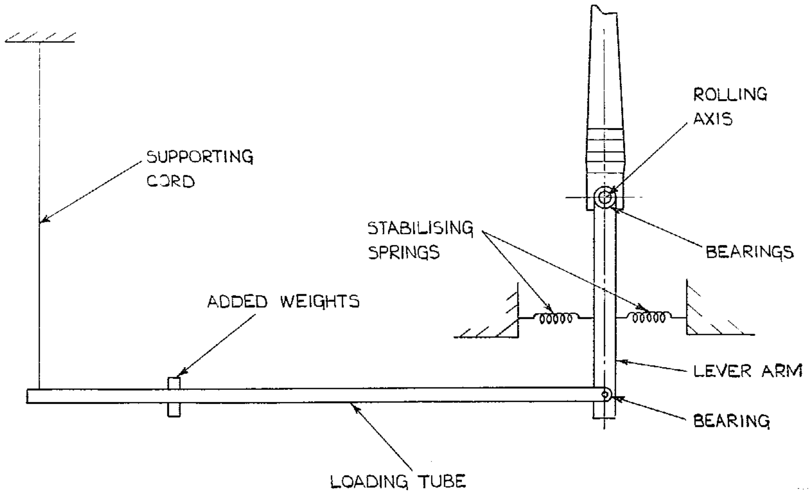
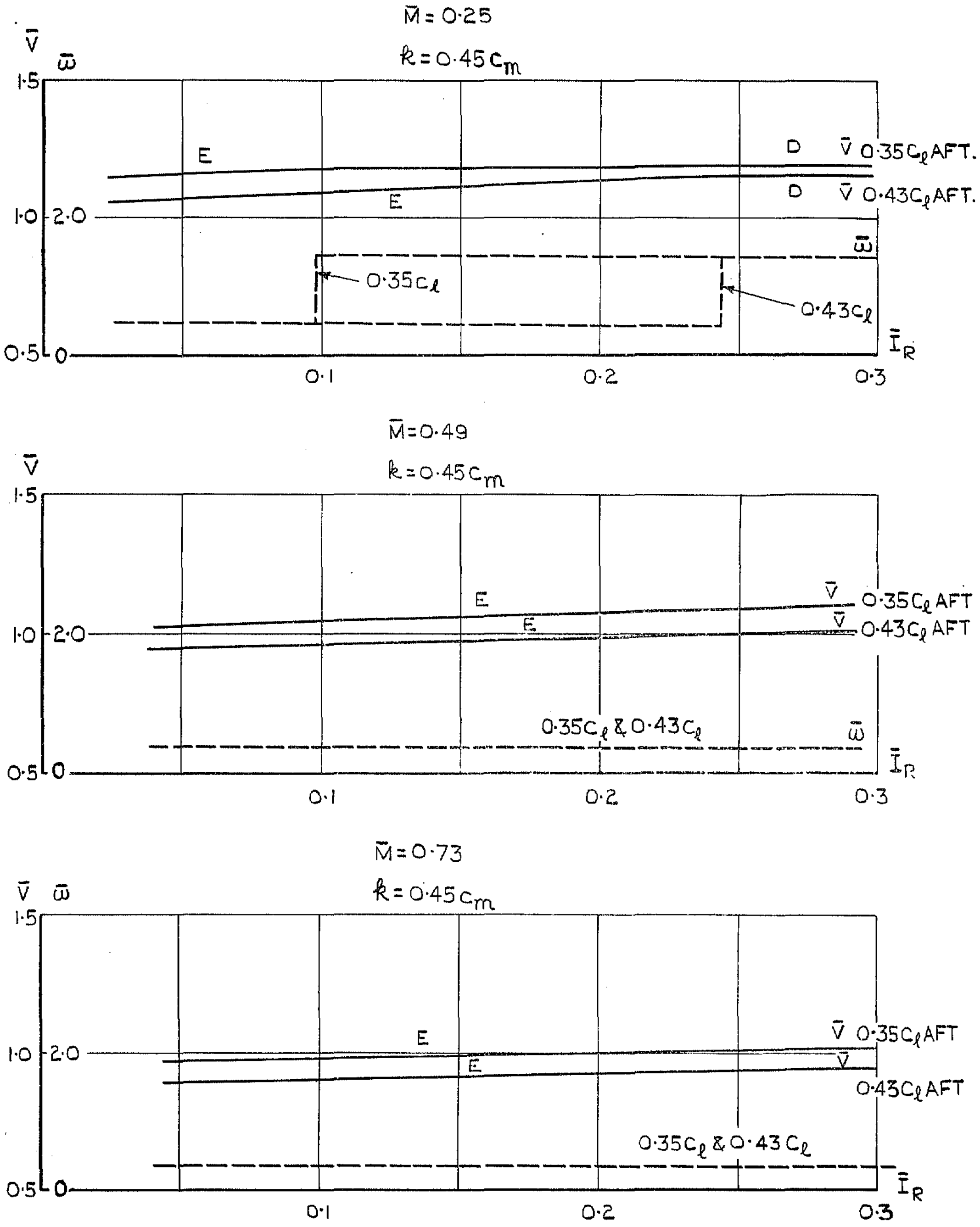


FIG. 13. Arrangement of anti-symmetric rig.



ANTI-SYMMETRIC FLUTTER-LOCALISED MASS.

FIG. 14. The effect of fuselage rolling moment of interia on flutter speed and frequency for a localised mass at 0·25 span.

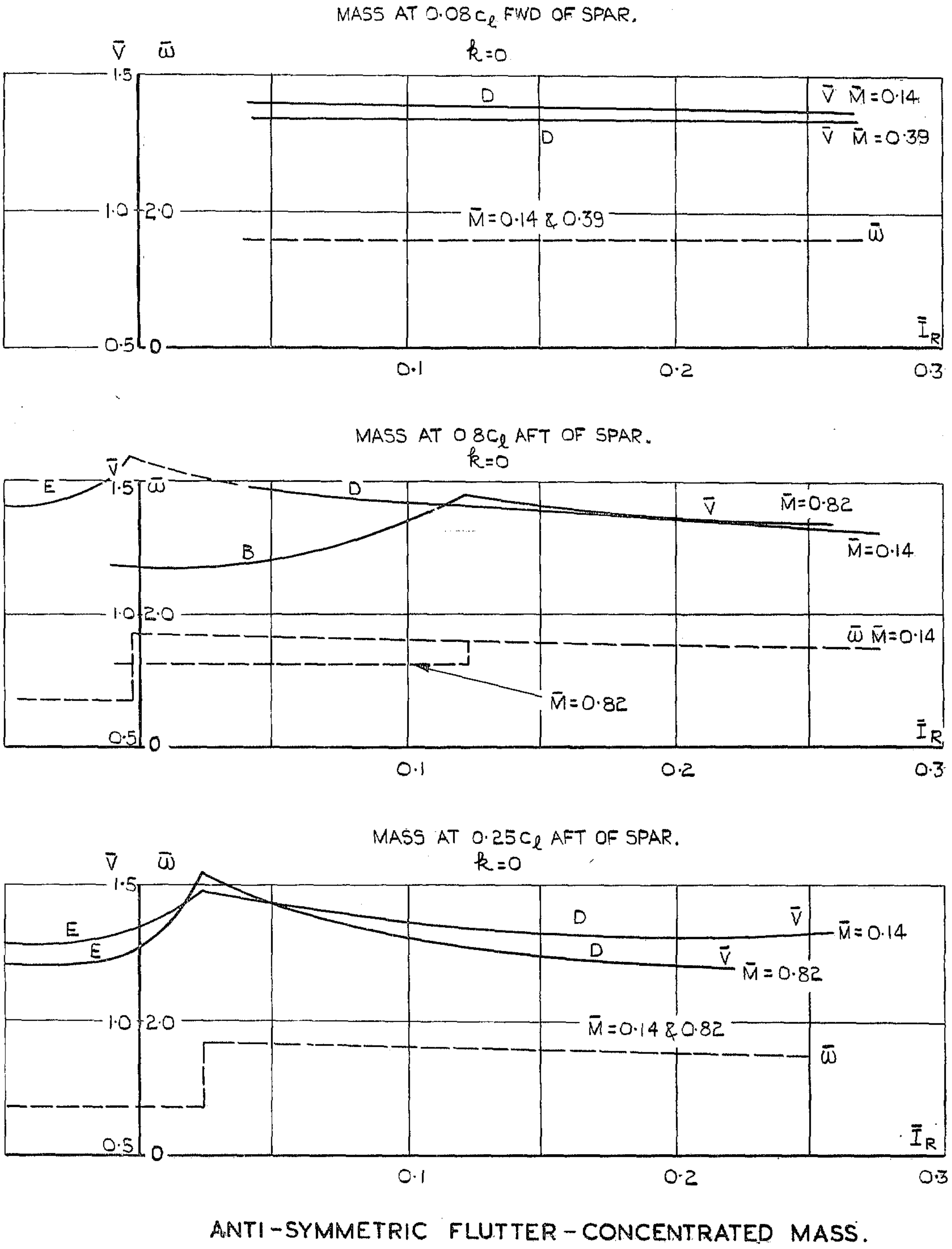
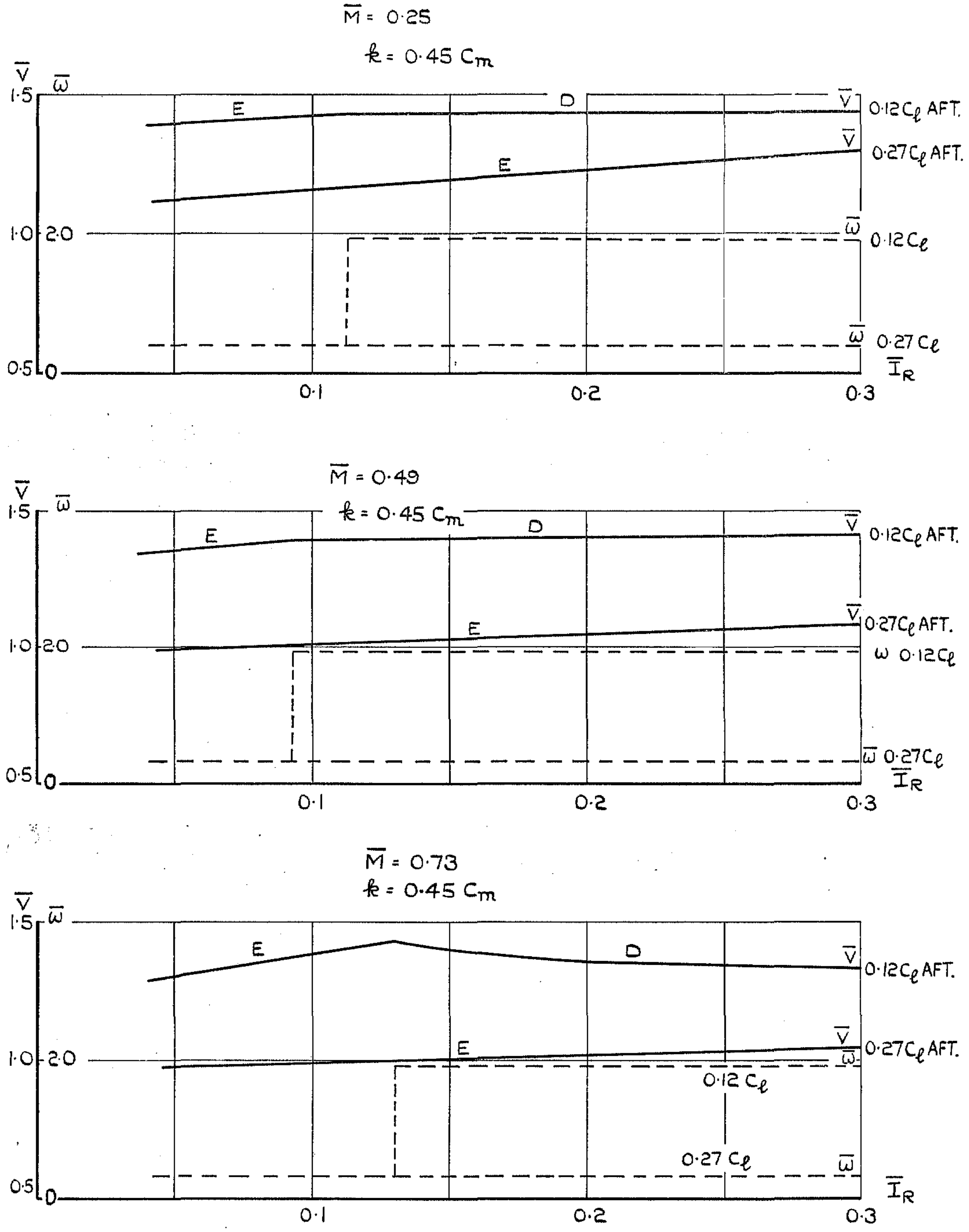
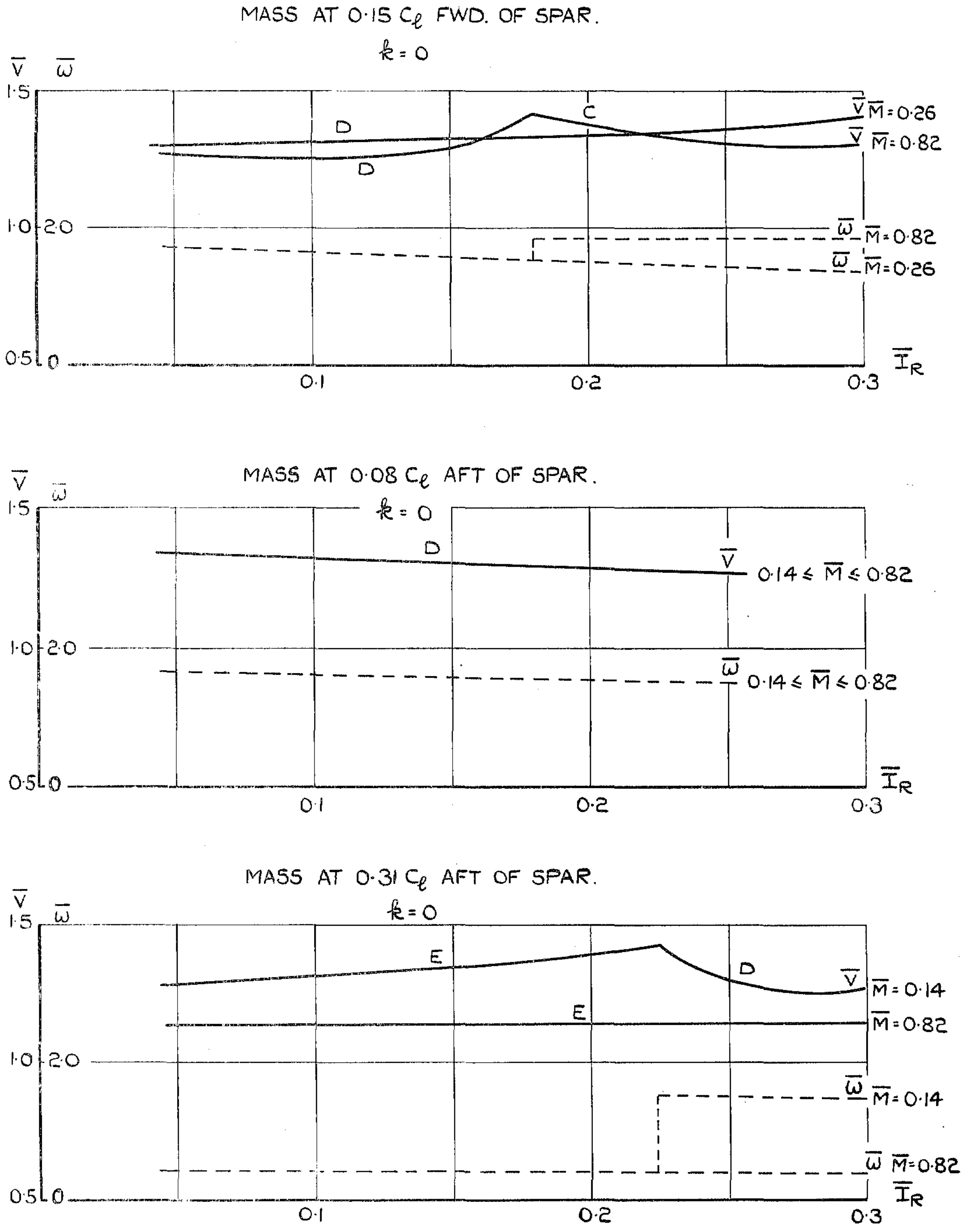


FIG. 15. The effect of fuselage rolling moment of interia on flutter speed and frequency for a concentrated mass at 0·25 span.



ANTI-SYMMETRIC FLUTTER — LOCALISED MASS.

FIG. 16. The effect of fuselage rolling moment of inertia on flutter speed and frequency for a localised mass at 0·5 span.


MASS AT 0·15 C_ℓ FWD. OF SPAR.

$k = 0$

MASS AT 0·08 C_ℓ AFT OF SPAR.

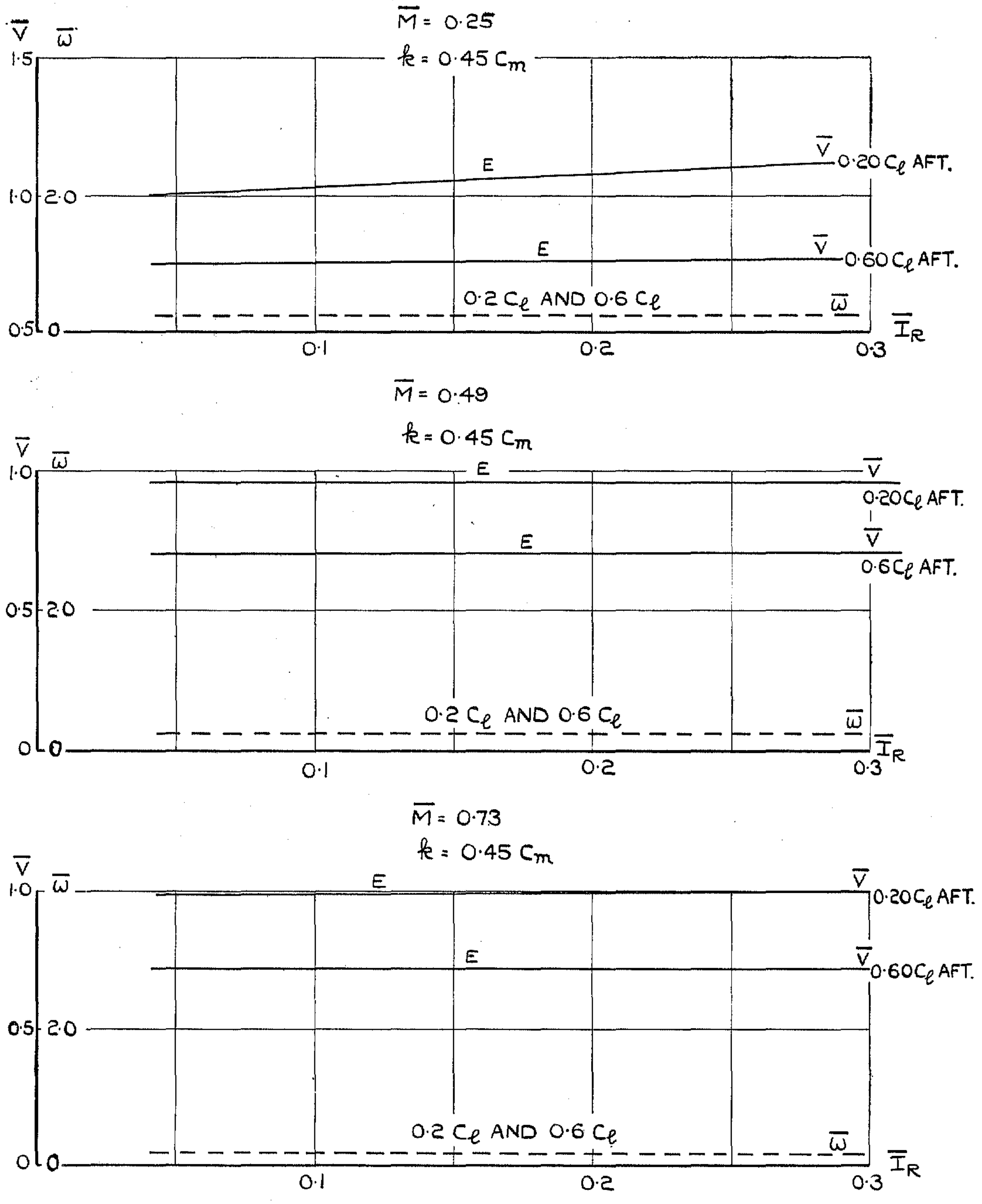
$k = 0$

MASS AT 0·31 C_ℓ AFT OF SPAR.

$k = 0$

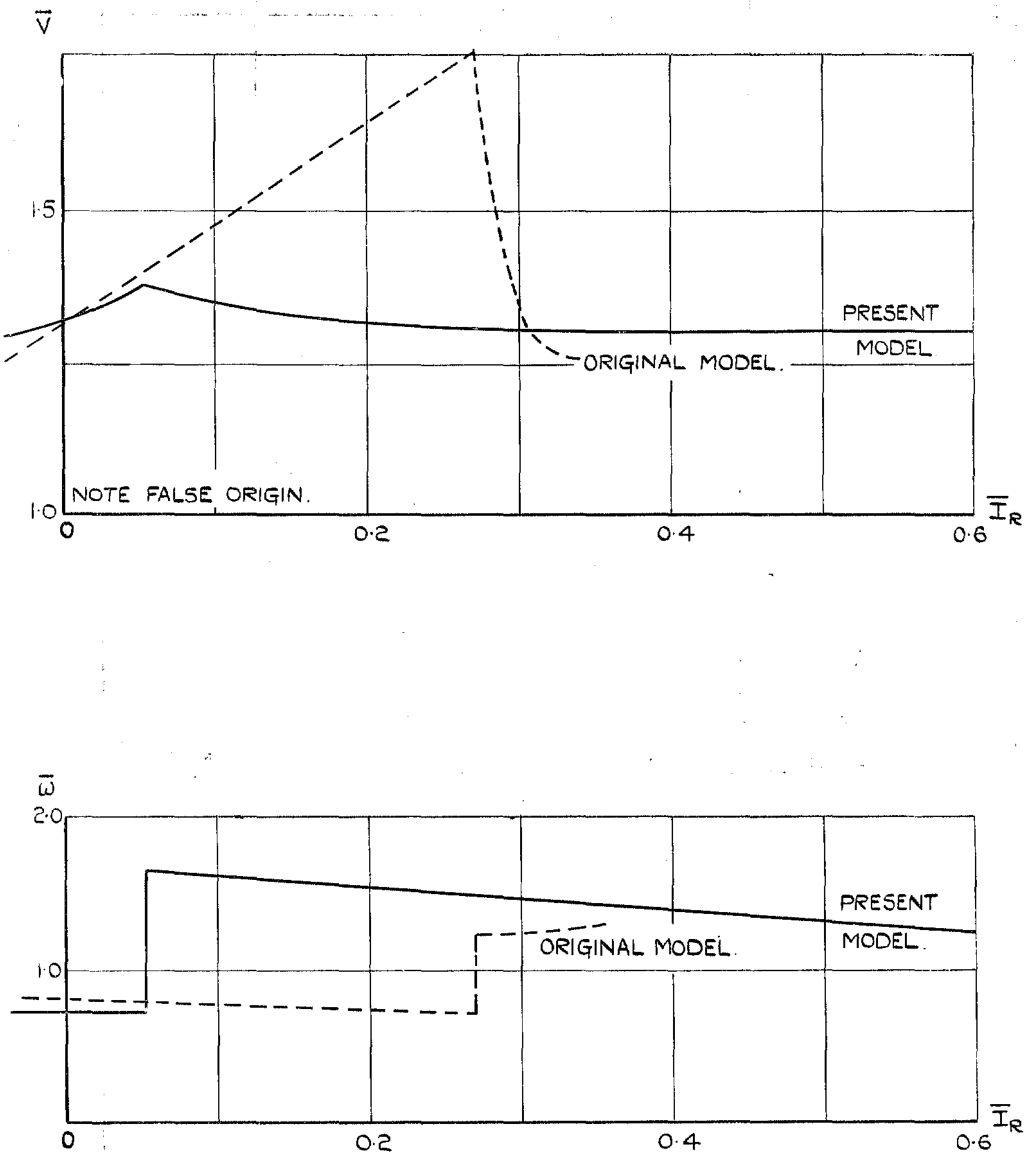
ANTI-SYMMETRIC FLUTTER - CONCENTRATED MASS.

FIG. 17. The effect of fuselage rolling moment of inertia on flutter speed and frequency for a concentrated mass at 0·5 span.



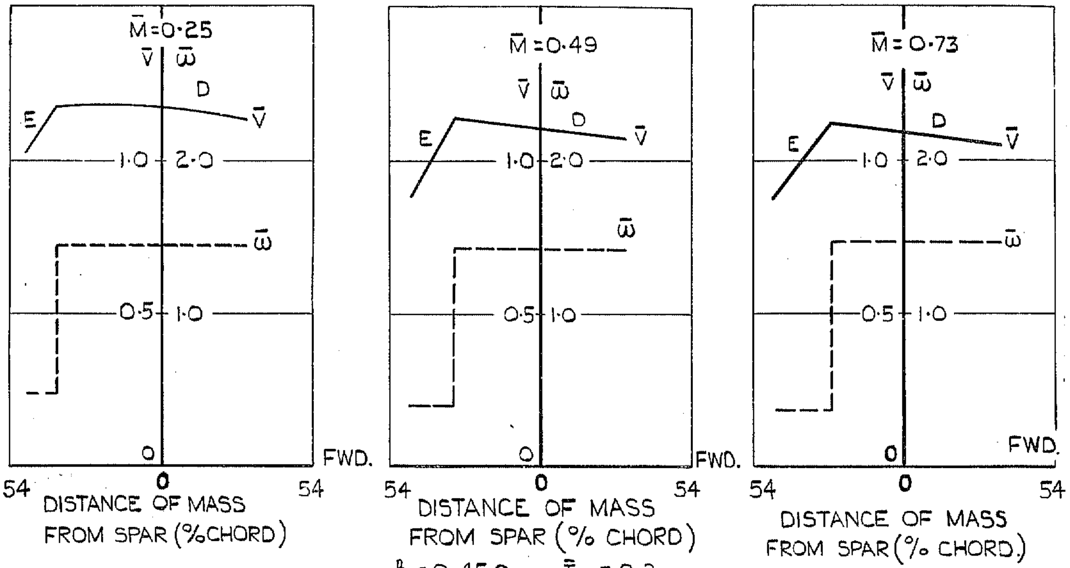
ANTI-SYMMETRIC FLUTTER — LOCALISED MASS.

FIG. 18. The effect of fuselage rolling moment of inertia on flutter speed and frequency for a localised mass at 0·75 span.

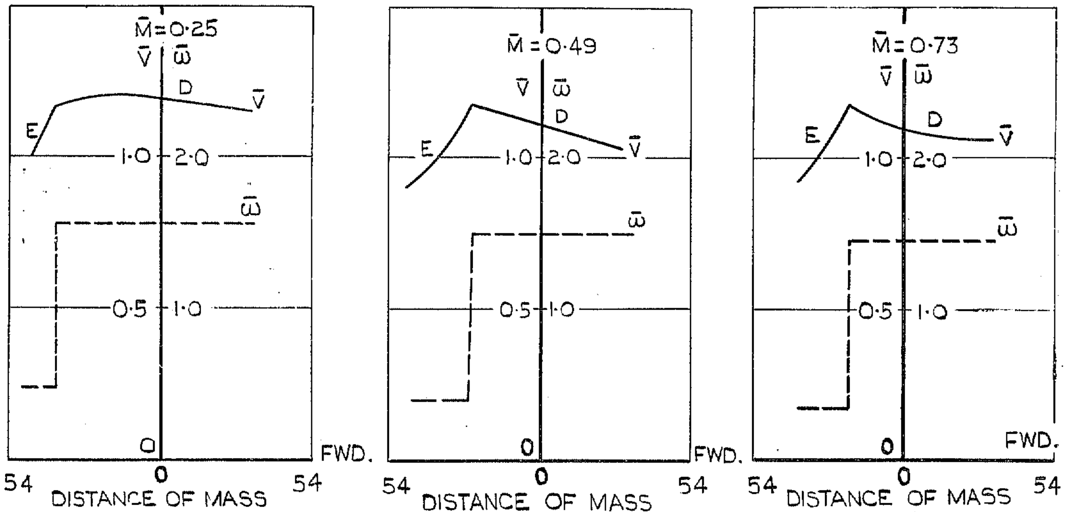


ANTI-SYMMETRIC FLUTTER.

FIG. 19. The effect of fuselage rolling moment of inertia on the flutter speed and frequency of a delta wing.



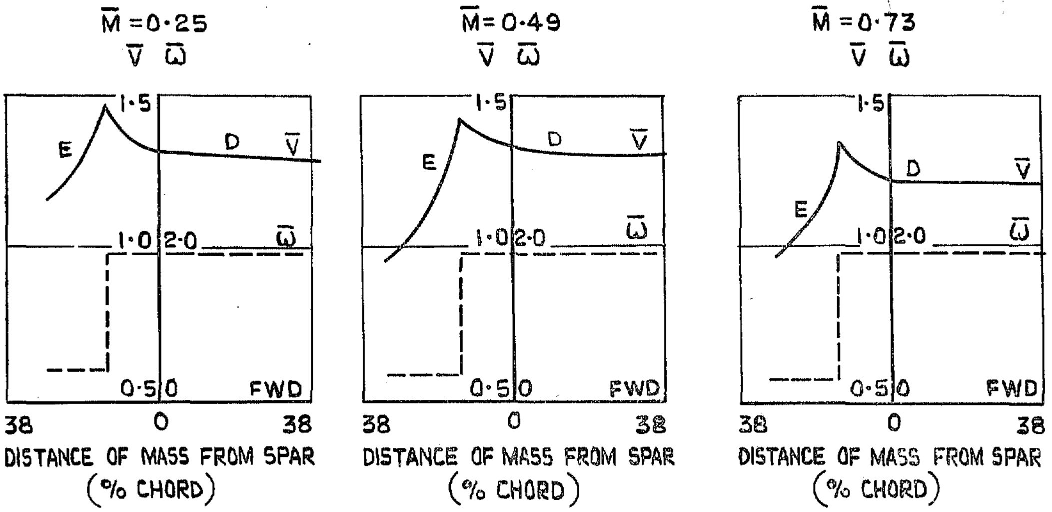
$k = 0{\cdot}45\,c_m,\ \bar{I}_R = 0{\cdot}2$



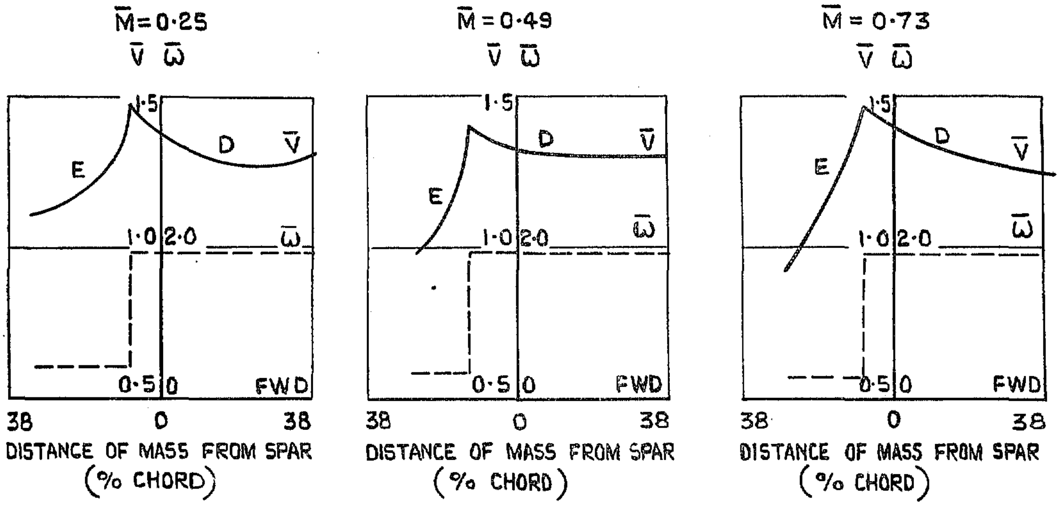
$k = 0{\cdot}45\,c_m,\ \bar{I}_R = 0{\cdot}1$.

ANTI-SYMMETRIC FLUTTER-LOCALISED MASS

FIG. 20. The effect of chordwise position on flutter speed and frequency for a localised mass at 0·25 span.



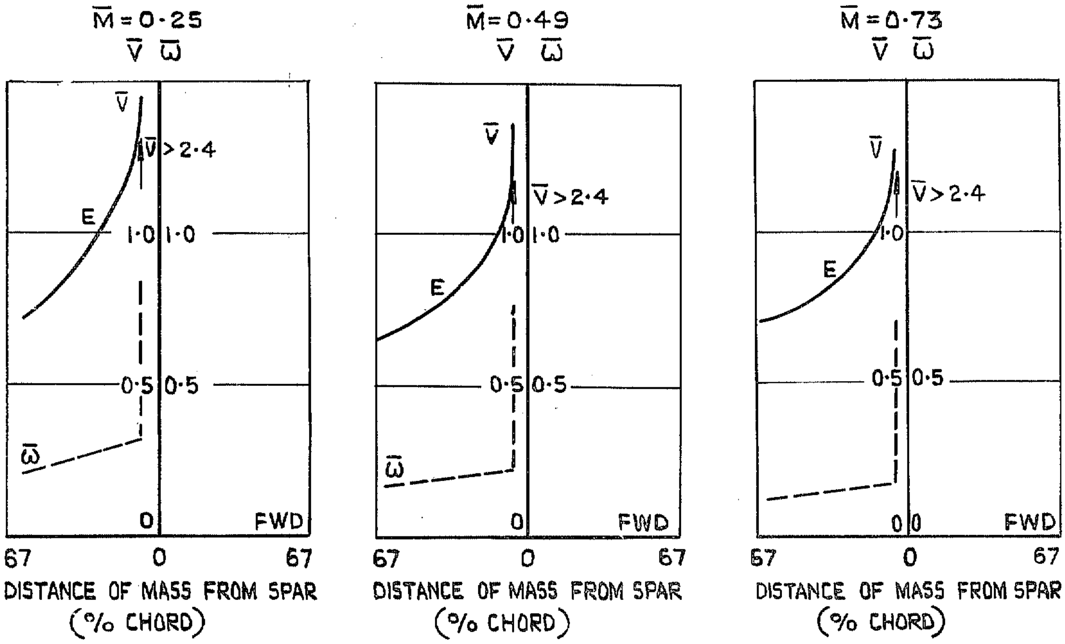
$k = 0{\cdot}45 c_m$, $\bar{I}_R = 0{\cdot}2$



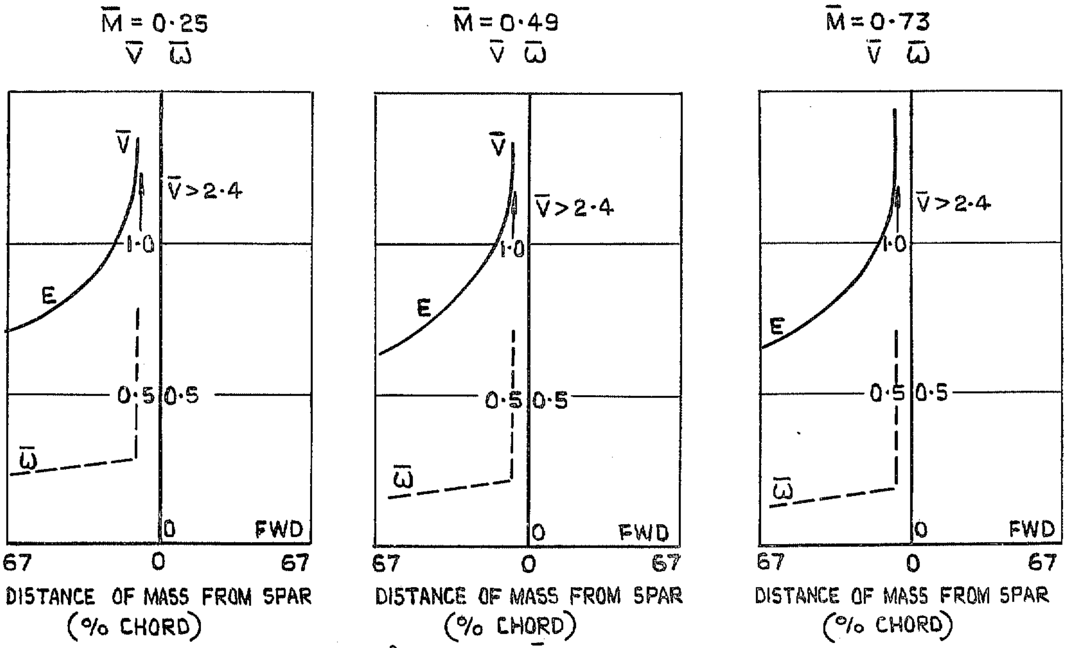
$k = 0{\cdot}45 c_m$, $\bar{I}_R = 0{\cdot}1$

ANTI-SYMMETRIC FLUTTER—LOCALISED MASS.

FIG. 21. The effect of chordwise position on flutter speed and frequency for a localised mass at 0·5 span.



$k = 0{\cdot}45 c_m,\ \bar{I}_R = 0{\cdot}2$



$k = 0{\cdot}45 c_m,\ \bar{I}_R = 0{\cdot}1$

ANTI—SYMMETRIC FLUTTER—LOCALISED MASS.

FIG. 22. The effect of chordwise position on flutter speed and frequency for a localised mass at 0·75 span.

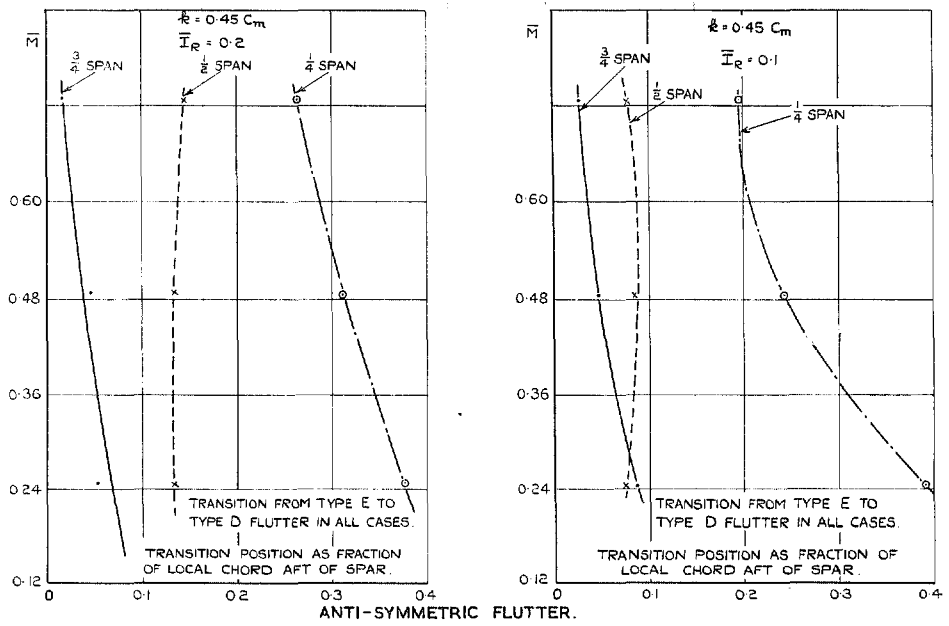


FIG. 23. Transition curves for a localised mass at various spanwise stations.

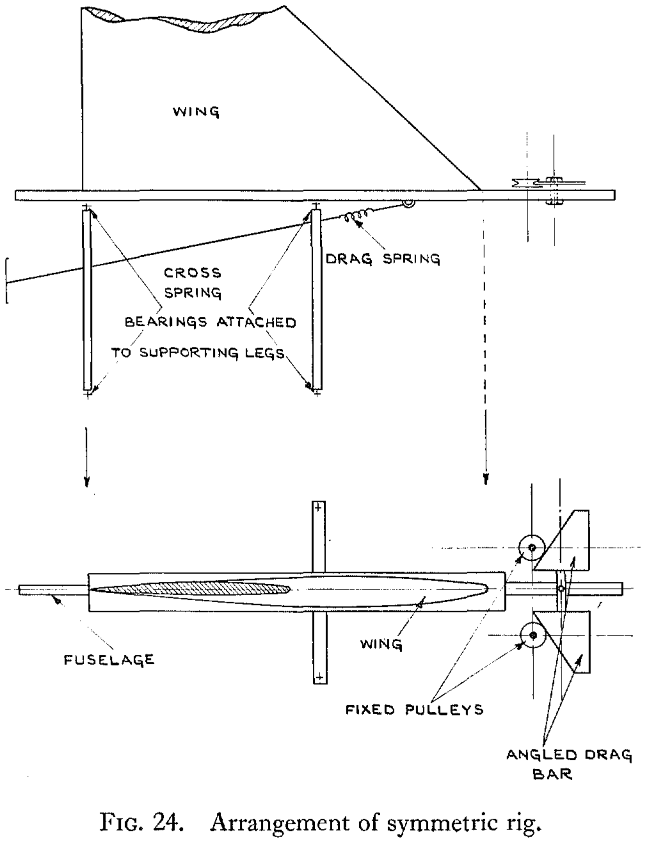
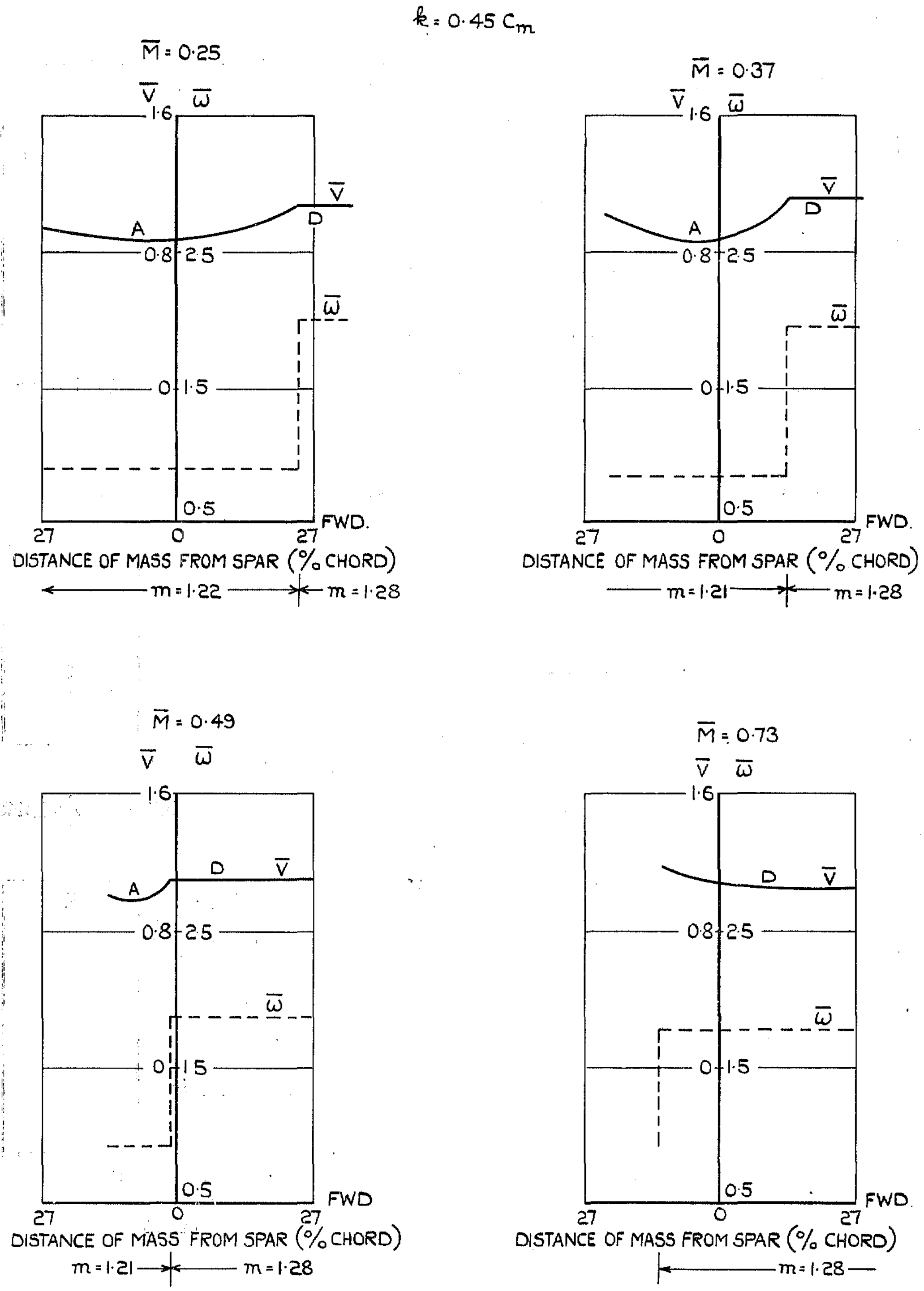
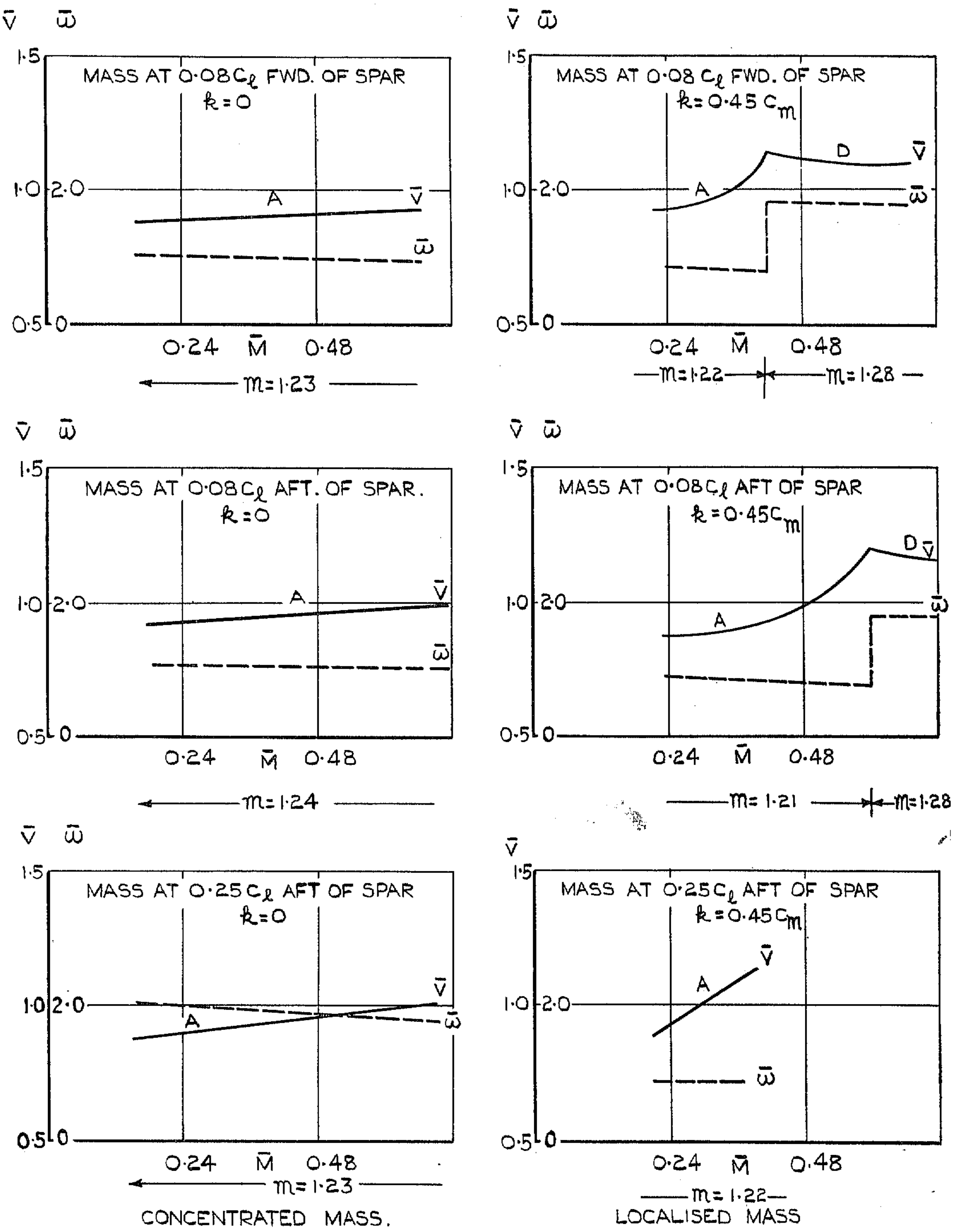


FIG. 24. Arrangement of symmetric rig.



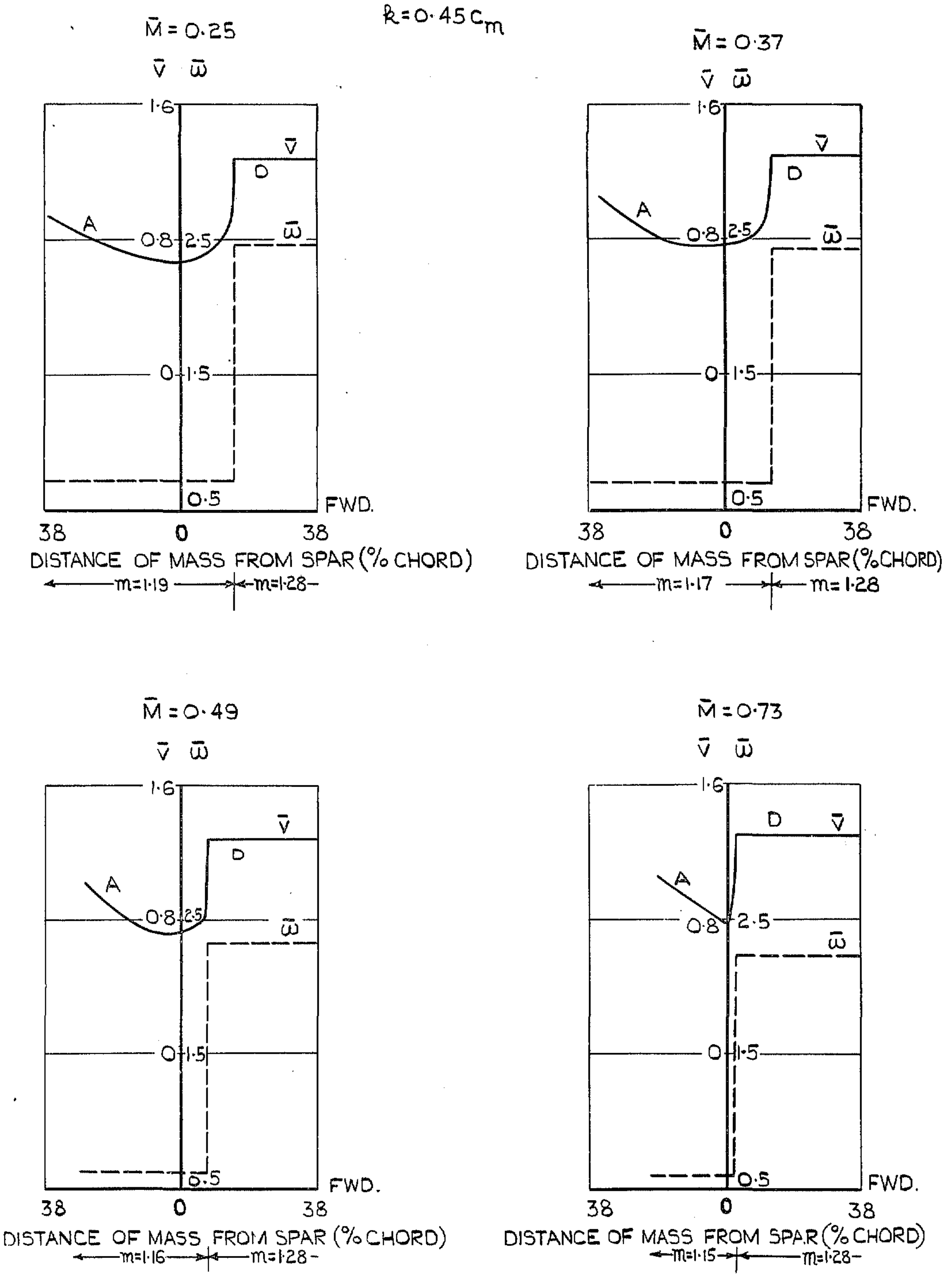
SYMMETRIC FLUTTER — LOCALISED MASS.

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



SYMMETRIC FLUTTER

FIG. 26. The effect of mass value on flutter speed and frequency for a mass at 0·25 span.



SYMMETRIC FLUTTER - LOCALISED MASS.

FIG. 27. The effect of chordwise position on flutter speed and frequency for a localised mass at 0·5 span.

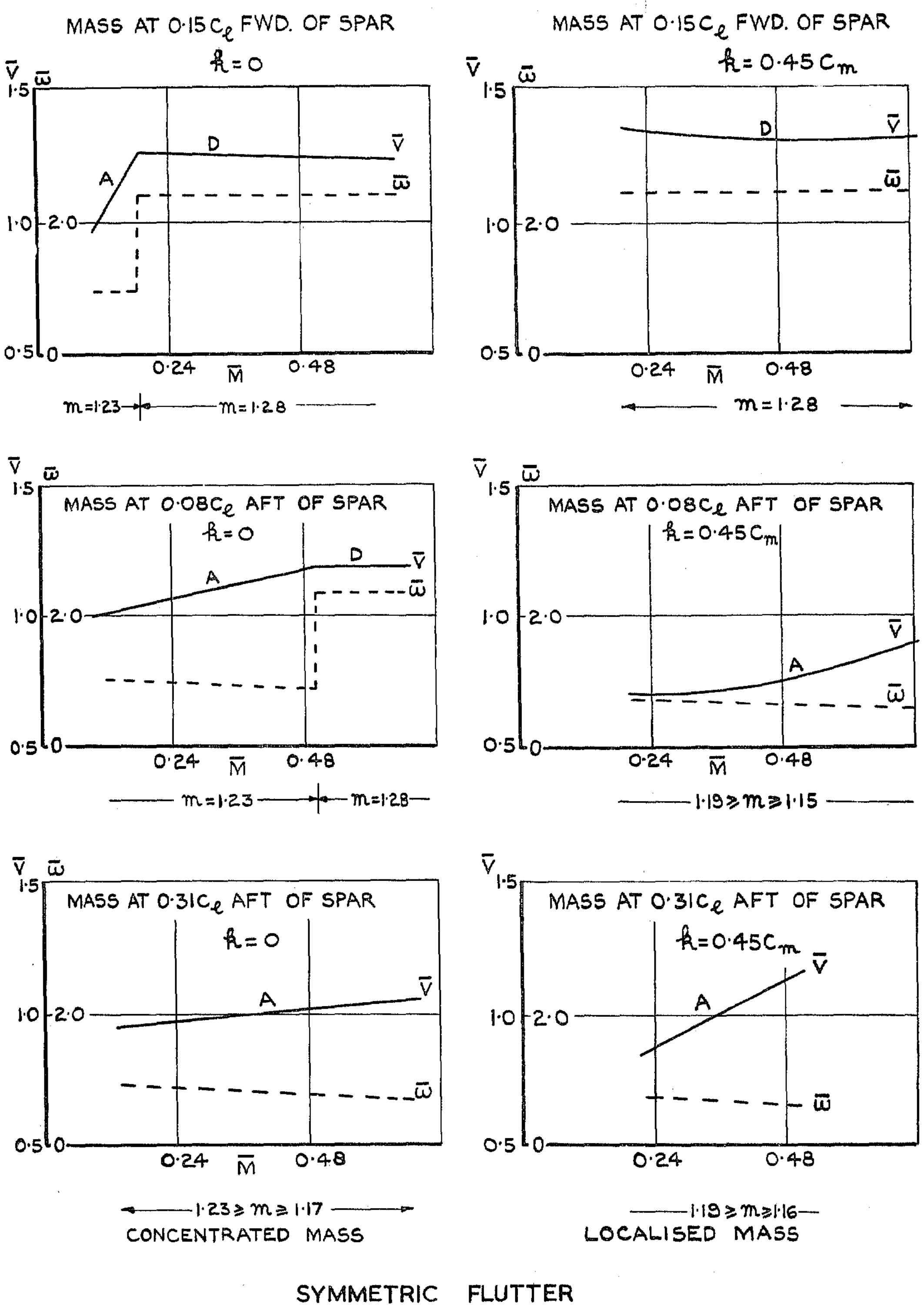
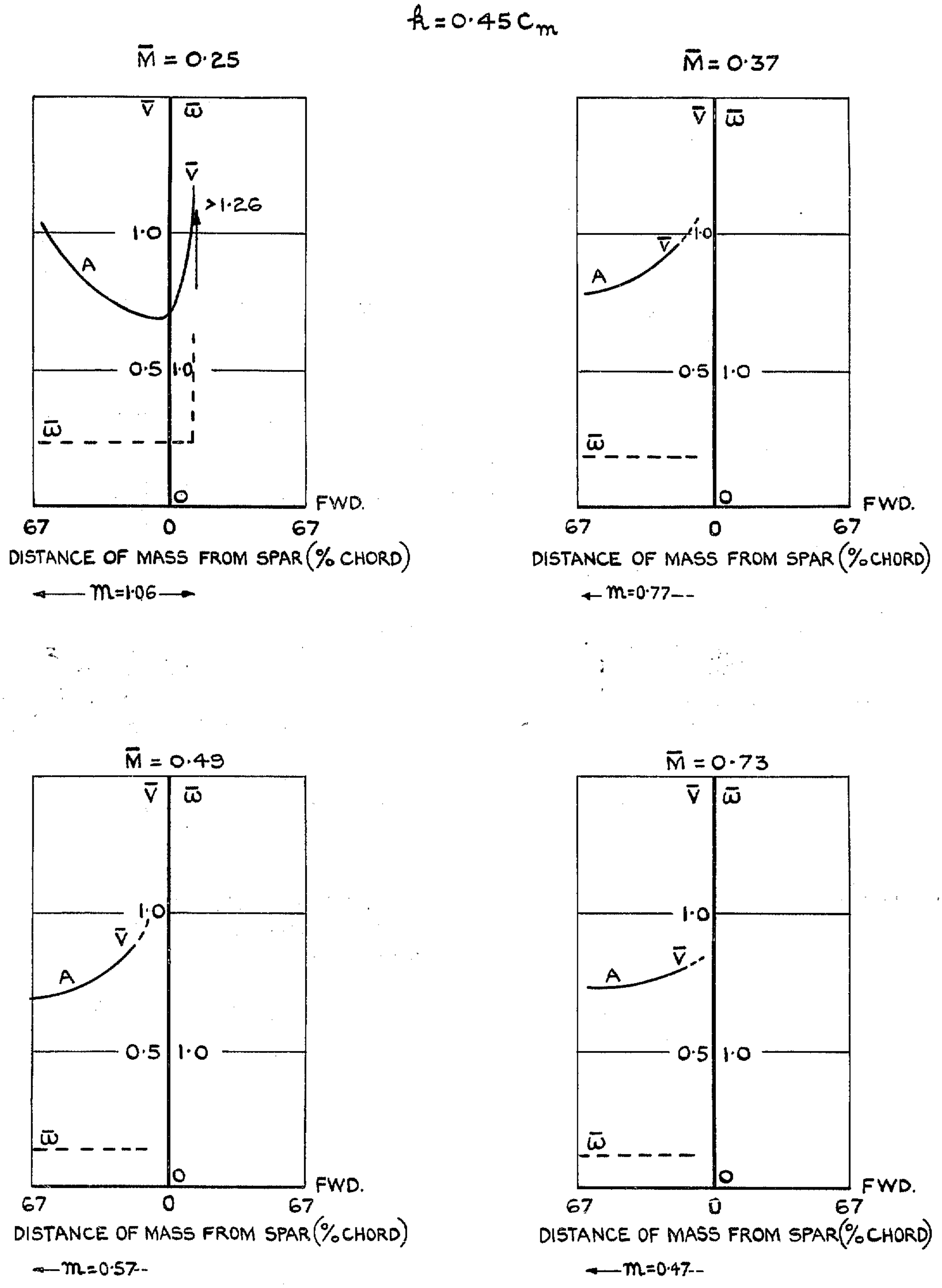
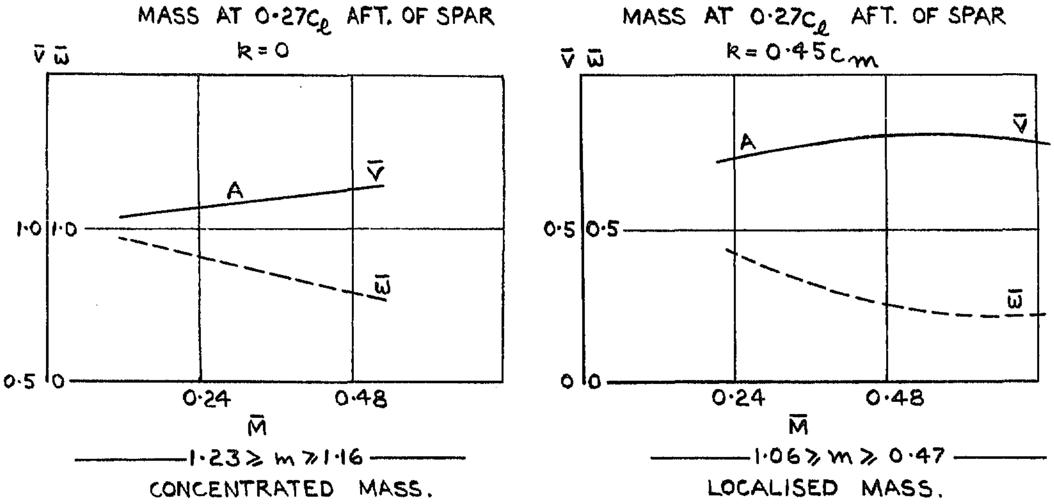


FIG. 28. The effect of mass value on flutter speed and frequency for a mass at 0·5 span.



SYMMETRIC FLUTTER — LOCALISED MASS

FIG. 29. The effect of chordwise position on flutter speed and frequency for a localised mass at 0·75 span.



MASS AT 0·13cℓ FWD. OF SPAR.

NO FLUTTER OBTAINED
BELOW $\bar{V}$ = 1·26 FOR ANY
MASS VALUE.

MASS AT 0·13cℓ FWD. OF SPAR.

NO FLUTTER OBTAINED
BELOW $\bar{V}$ = 1·37 FOR ANY
MASS VALUE.

FIG. 30. The effect of mass value on flutter speed and frequency for a mass at 0·75 span.

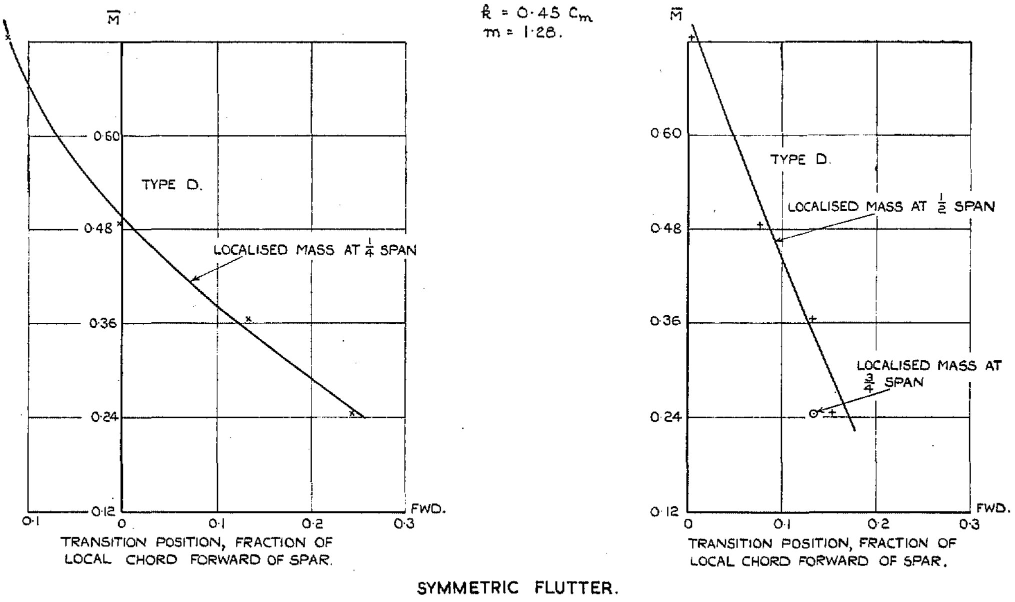


FIG. 31. Transition curves for a localised mass at various spanwise sections.

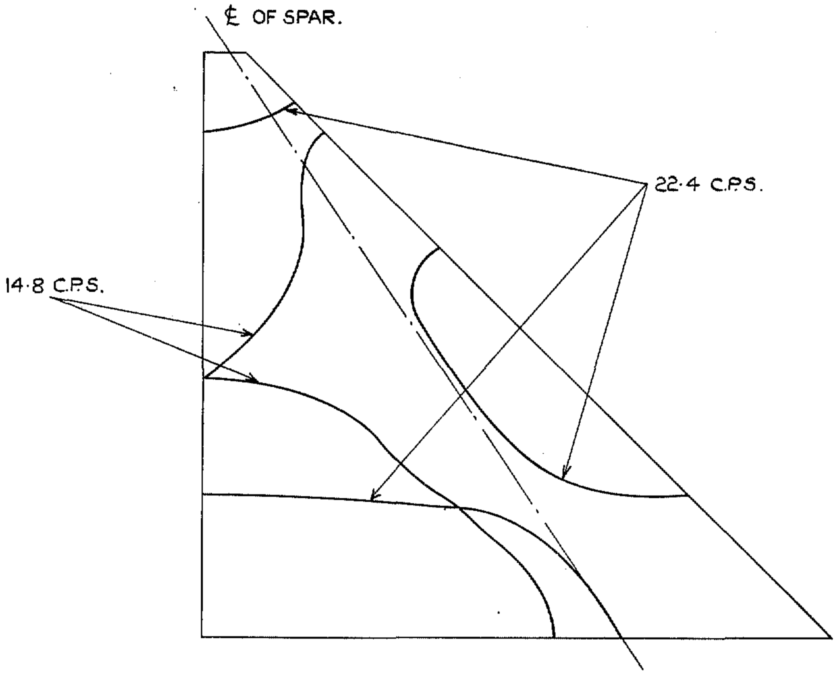


FIG. 32. The nodal lines of the higher frequency modes, bare wing, fixed root.

(83826) Wt. 67/1876 K.5 2/62 Hw.

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