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By F. J. Hawkins, M.Sc. and R. F. Mousley

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Summary.

A ground resonance test has been conducted on a Beagle B206 light aircraft.

The modes of vibration in the frequency range up to 47·4 *Hz* were investigated with multipoint excitation using the GRAMPA equipment. The modes obtained are discussed in the Report. Comment is also made on the short time and small effort required to conduct these tests.

CONTENTS

1. *Introduction.*

Resonance tests were conducted on a Beagle B206 Series 1, a twin-engined aircraft of 46 ft span and 33 ft 4 in. overall length, weighing, as tested, about 5000 lb. Ailerons, elevators and rudder are controlled through mechanical linkages (rods) and the flaps by hydraulic jacks.

The tests were performed using automatic ground-resonance testing equipment, GRAMPA[1], controlling up to six electromagnetic exciters stationed at a suitable selection of the fourteen available attachment points; it was found necessary to use different excitation points for some modes in order to obtain satisfactory responses.

*Replaces RAE Technical Report 66 309—A.R.C. 29 150.

Eleven modes of vibration were discovered, ten of which were measured in detail; the remaining mode defined the natural frequency of the symmetric aileron rotation.

The aircraft had not previously been resonance tested and as details of its mass distribution were not available it was not possible to check the orthogonality of the modes of vibration obtained.

2. *Aircraft Condition for Testing.*

The aircraft, Serial No. G–ATDD, was flown into R.A.E. Farnborough in June 1966, taxied to the test laboratory and was resonance tested without further modification. It has been fitted prior to arrival with exciter attachment brackets at ten points on the tailplane, wings and engine nacelles; four further excitation points were used, two on the propeller spinners and two on the ailerons.

The aircraft was tested whilst standing on its tricycle undercarriage with partially deflated tyres; this condition produced natural frequencies below 4 *Hz* in pitch, heave and roll; the lowest structural natural frequency was 6·7 *Hz*.

The flaps and ailerons were clamped by blocks bolted to the main surfaces. The rudder was clamped to the fin at its horn. The elevator arrangement raised some difficulty in that it was spring-loaded to deflect downwards against a mechanical stop. The elevator was brought into line with the tailplane by introducing packing at the mechanical stop; backlash did not occur at this point as the spring load was not overcome at the vibration levels employed. All the tests were performed with the tailplane in this condition, then the symmetric mode in which the elevator motion predominated was investigated without the packing but with the spring load counteracted by a light spring on the control column.

The wing fuel tanks contained approximately fifty per cent of full load on each side.

3. *Excitation Forces.*

Provision was made for controlling six electromagnetic exciters using the automatic control equipment GRAMPA[1]. The GRAMPA control system provides automatic frequency control at one exciter – using phase as a resonance criterion – whilst the other exciters have their force amplitudes controlled either manually or automatically; in general, quick and satisfactory performance was achieved by manual control of the relative force levels. The exciters could be fixed at any of the fourteen available attachment points (Fig. 1) but most of the tests were conducted with the exciters attached as in Fig. 8. In the mode involving antisymmetric engine nodding it was necessary to move two exciters to the propeller spinners (Fig. 6).

The symmetric aileron mode was excited by applying force through push rods held in contact with the ailerons by suction pads.

4. *Measurement of Aircraft Response.*

The modes of vibration were defined by measurements at 150 points on the aircraft (Fig. 2).

Measurements were made with a single wandering accelerometer which was held in contact by a small suction pad. The accelerometer signal was fed (Fig. 3) to a resolver and plotting table to record its phase and amplitude relative to the force datum.

5. *Modes of Vibration.*

5.1. *General.*

Initially, using single-point excitation at tailplane, wing tip and engine nacelles in turn, vector plots – like that in Fig. 4 – were produced for several points on the aircraft. From these plots all the apparent natural frequencies[2] were noted for subsequent investigation using multipoint excitation.

To establish each mode of vibration the acceleration responses at the excitation points were induced to move in phase with one another and also in quadrature with the excitation. Further spot checks on the phase of the structure at other points were made to assess the overall phase behaviour. If there was considerable phase scatter, other excitation points were tried and the most efficient excitation points used for exciting the mode.

Eleven modes of vibration were discovered in the frequency range 6·7 *Hz* to 47·4 *Hz*; six of these were symmetric and five were antisymmetric. The frequencies at which the modes occurred are shown in Table 1.

The associated mode shapes are illustrated in Figs. 5 to 33: the first figure for each mode is an isometric representation of the mode shape; the second figure shows the mode shape in detail and, for some modes, a third figure shows a vector diagram of the responses used to plot the mode and illustrates the amount of phase scatter.

5.2. *Detailed Discussion of Modes.*

5.2.1. *Antisymmetric wing bending, engine nodding – 6·7 Hz* (Figs. 5 and 6). This mode consists of antisymmetric wing bending and antisymmetric engine nodding, with each engine moving in phase with its nacelle; the engine vertical displacements are in antiphase with their respective wing tips. Tailplane and rear fuselage motion is very small and is not recorded.

5.2.2. *Symmetric wing bending – 6·7 Hz* (Figs. 7, 8 and 9). This, the fundamental wing bending, mode is essentially wing motion. Motion of other points of the aircraft is very slight and is not recorded.

5.2.3. *Fuselage torsion and antisymmetric wing bending – 9·1 Hz* (Figs. 10 and 11). This is the fundamental fuselage torsion mode in which all the components of the tail section are rotating in phase with each other; the excitation frequency is below the natural frequencies of any of the tail components. Some out-of-phase responses occur on the port wing but asymmetry is removed if quadrature components of the affected responses are plotted.

5.2.4. *Tailplane/fin antiflexure and antisymmetric wing bending – 11·1 Hz* (Figs. 12, 13 and 14). This mode involves some fuselage torsion with tailplane rolling and antisymmetric bending; the fin bends in antiphase with the rolling motion. The engines are again exhibiting antisymmetric nodding, but now (*c.f.* Section 5.2.1) the motion is in opposition to the nacelle motion (i.e. this is the second mode of the engine on its mounts).

5.2.5. *Symmetric elevator rotation and symmetric tailplane bending – 13·7 Hz* (Figs. 15, 16 and 17). As explained in Section 2, the elevator locking consisted of packing inserted against a mechanical stop, the elevator being held in position by the spring load which pushed the elevator down; however, the bracket against which the stop located proved to be fairly flexible, allowing some rotation of the elevator against both its spring stiffness and the bracket stiffness. To investigate the effect of removing the packing the spring load was equalised by attaching light rubber cord to the control column. The effect of this modification was to raise the natural frequency of the elevator rotation mode from 12·0 Hz to 13·7 Hz, without any significant change in mode shape. The condition in which the higher frequency was obtained is taken to be more representative of the flight condition, though the stiffness at the control column does not necessarily represent the aerodynamic stiffness at the elevator; balancing of the spring force only is achieved. This frequency (13·7 Hz) is not the fundamental for the elevator/control system; the fundamental mode was estimated to be at a very low frequency.

5.2.6. *Symmetric aileron rotation – 15·0 Hz* (Figs. 18 and 19). To find the natural frequency of symmetric aileron rotation (i.e. ailerons rotating on their hinges against the stiffness of the control linkage) the clamps were removed and an exciter connected to the aileron by a suction pad.

Wing bending responses were very small.

5.2.7. *Symmetric tailplane bending, fuselage bending and elevator rotation – 15·8 Hz* (Figs. 20, 21 and 22). Fuselage bending induces some tailplane pitch. Significant symmetric bending occurs in the tailplane and the elevator rotation is now in phase (*c.f.* Section 5.2.5) with the bending motion, indicating overbalance of the elevator.

There is evidence of symmetric wing first overtone bending (which becomes more pronounced in the next mode at 19·5 *Hz*).

5.2.8. *Symmetric wing overtone bending and tailplane bending – 19·5 Hz* (Figs. 23, 24 and 25). Bending of the wings has increased in this mode and tailplane bending is still present, though the tailplane tips now move antiphase to the wing tips. Fuselage bending is very much reduced, and elevator rotation is further diminished.

5.2.9. *Antisymmetric elevator bending and rotation – 26·0 Hz* (Figs. 26, 27 and 28). This mode involves torsion in the elevator connecting tube, but includes also simple bending of each elevator between the outboard hinge and the connecting tube. Antisymmetric rotation of the elevators is present, but very little torsion.

5.2.10. *Symmetric second-overtone bending of wing and overtone fuselage bending – 43·2 Hz* (Figs. 29 and 30). Second-overtone bending of the wings is evident in this mode but it is distorted by the torsion induced by the overhanging engines and nacelles. There is now no relative motion between the engines and their mountings. Elevators (which now show some torsion) and tailplane move significantly and are in-phase; some tailplane pitch arises from the rear fuselage bending.

5.2.11. *Antisymmetric wing torsion – 47·4 Hz* (Figs. 31, 32 and 33). This mode behaved in a curious manner.

Two exciters were deployed as shown in Fig. 32, after various exciter arrangements had been tried in an endeavour to achieve in-phase responses. The first step in each case was to achieve quadrature acceleration response relative to the input force at a wing exciter, using only the one exciter. A second exciter was introduced at the other wing tip in an attempt to produce a quadrature force/response relationship at this second point; however, a range of positive and negative forces, though causing marked amplitude change from in-phase to antiphase, produced no significant phase deviation of the response vectors: neither did changing excitation positions on the wing produce any improvement in the phase of the response. There was wide scatter in the phase of the responses on the wing and a plot of vector amplitude, without regard for phase, produced – as expected – a very confused mode. It was found, however, that a mode plot using only the quadrature components of response produced well balanced shapes for the two wings, though there was considerable differences in amplitude; these same shapes could be produced at a range of relative tip amplitudes, implying an independence between the two wings which is inconsistent with the assumption of linear behaviour necessary for obtaining normal modes. From the interior of the port wing loud rattling noises emerged which appeared to originate from the control linkage. The observed, curious behaviour could be caused by non-linearity arising from a resonating component in the wing.

The quadrature components of response were used in plotting the mode shape shown in Fig. 32 which, as mentioned earlier, shows similar shapes on both sides, but different amplitudes.

6. *Discussion.*

The resonance tests on the Beagle B206 aircraft produced eleven modes of vibration in the range 6·7 *Hz* to 47·4 *Hz*. Only one of these modes raised practical difficulties and these were resolved to the satisfaction of the authors. The combination of automatic control equipment for the excitation forces and a single wandering transducer for measuring mode shape proved to be a speedy and reliable technique. This equipment, (both excitation and response measuring) has been designed to eliminate spurious phase shifts; this, in combination with the single wandering transducer, removes the need for phase and amplitude calibration corrections and enables a considerable time-saving to be achieved.

The use of automatic frequency control to maintain only one exciter in the quadrature force/response condition greatly simplifies the problem of adjusting force levels of additional exciters even though force levels are adjusted manually. Convergence to a satisfactory phase response can be achieved very quickly, whereas convergence can be a long and tedious business when frequency also is controlled manually. Where overall phase response was not good enough for the vector amplitudes to be taken as the modal component, the quadrature component of the vectors was measured. Ideally, of course, one would like to have all points in phase, but this was found to be impossible even with six exciters and fourteen available attachment points. Suitable selection of excitation points enabled a best-phase condition to be obtained in which the points having the greatest motion showed good phase behaviour. The points exhibiting very poor phase response are generally those at smaller amplitudes and the poor phase coherence can be attributed to 'off-resonance' response (i.e. interfering modes). The fact that the points with large amplitudes are in phase indicates that the excitation frequency is a very good approximation to the natural frequency and it is therefore reasonable to extract the quadrature component of response from the points which have poor phase response.

The ground resonance tests involved two dynamics engineers for a period of less than two weeks. This represents a large saving in both manpower and cost over similar resonance tests in which the excitation equipment is wholly manually controlled and the correct excitation frequency and force-input distribution are determined by iterative procedures.

REFERENCES

No.	*Author(s)*	*Title, etc.*
1	F. J. Hawkins	GRAMPA. An automatic technique for exciting principal modes of vibration of complex structures. A.R.C. R. & M. 3588. July 1965.
2	C. C. Kennedy and C. D. P. Pancu	Use of vectors in vibration measurements and analysis. J. of Aero. Sci. *14*, No. 11, 603–630. 1947.

TABLE 1

Brief Summary of the Modes of Vibration.

Natural frequency *Hz*	S – Symmetric A – Antisymmetric	Brief description of mode
6·7	A	Antisymmetric wing bending and engine nodding
6·7	S	Wing bending.
9·1	A	Fuselage torsion and wing bending
11·1	A	Tailplane/fin antiflexure, wing bending.
13·7	S	Elevator rotation with tailplane bending.
15·0	S	Aileron rotation.
15·8	S	Tailplane bending and some first overtone wing bending.
19·5	S	First overtone wing bending with tailplane bending.
26·0	A	Elevator bending and rotation.
43·6	S	Second overtone wing bending with fuselage first overtone bending.
47·4	A	Wing torsion.

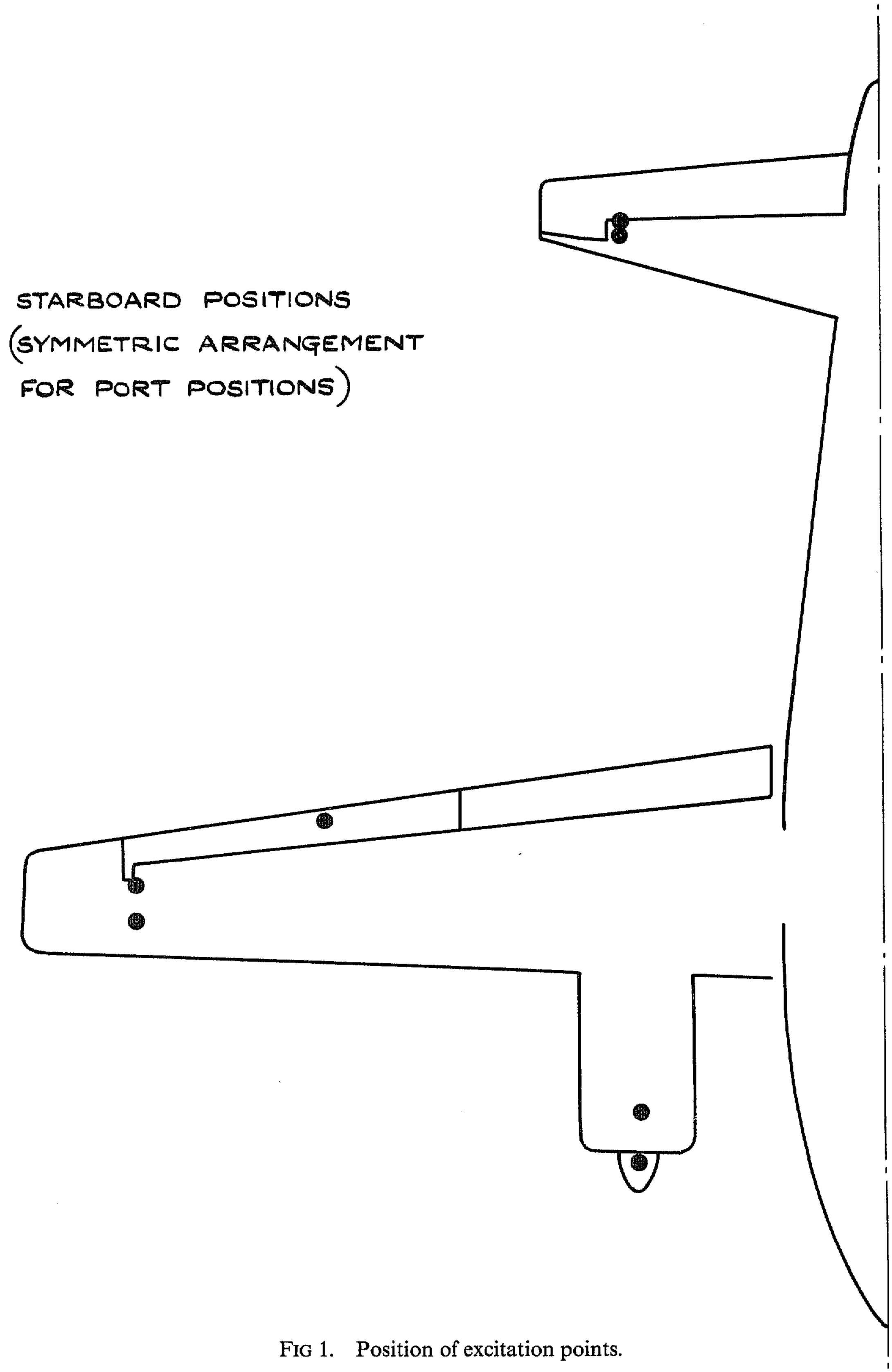

FIG 1. Position of excitation points.

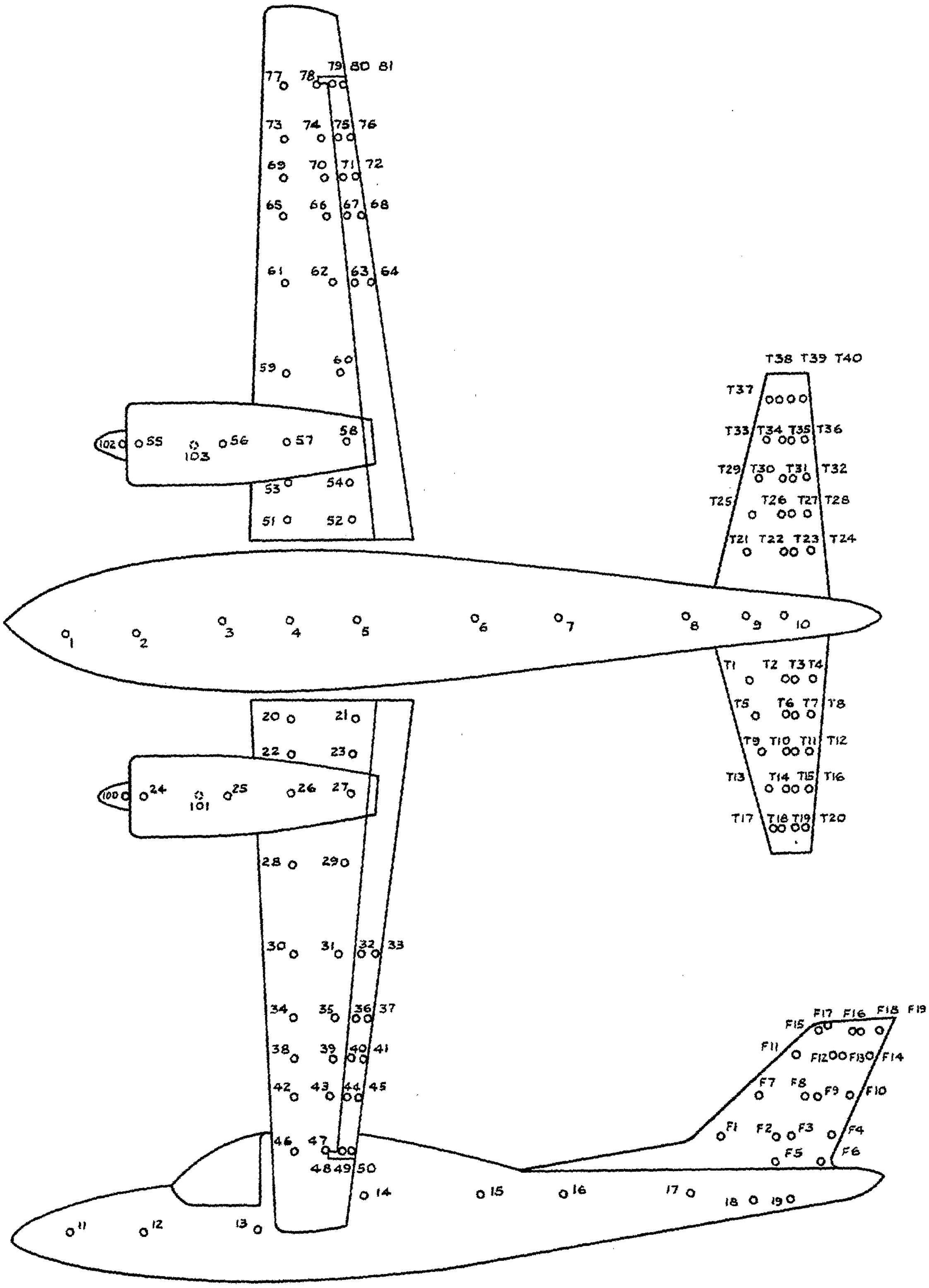

FIG. 2. Mode measuring points.

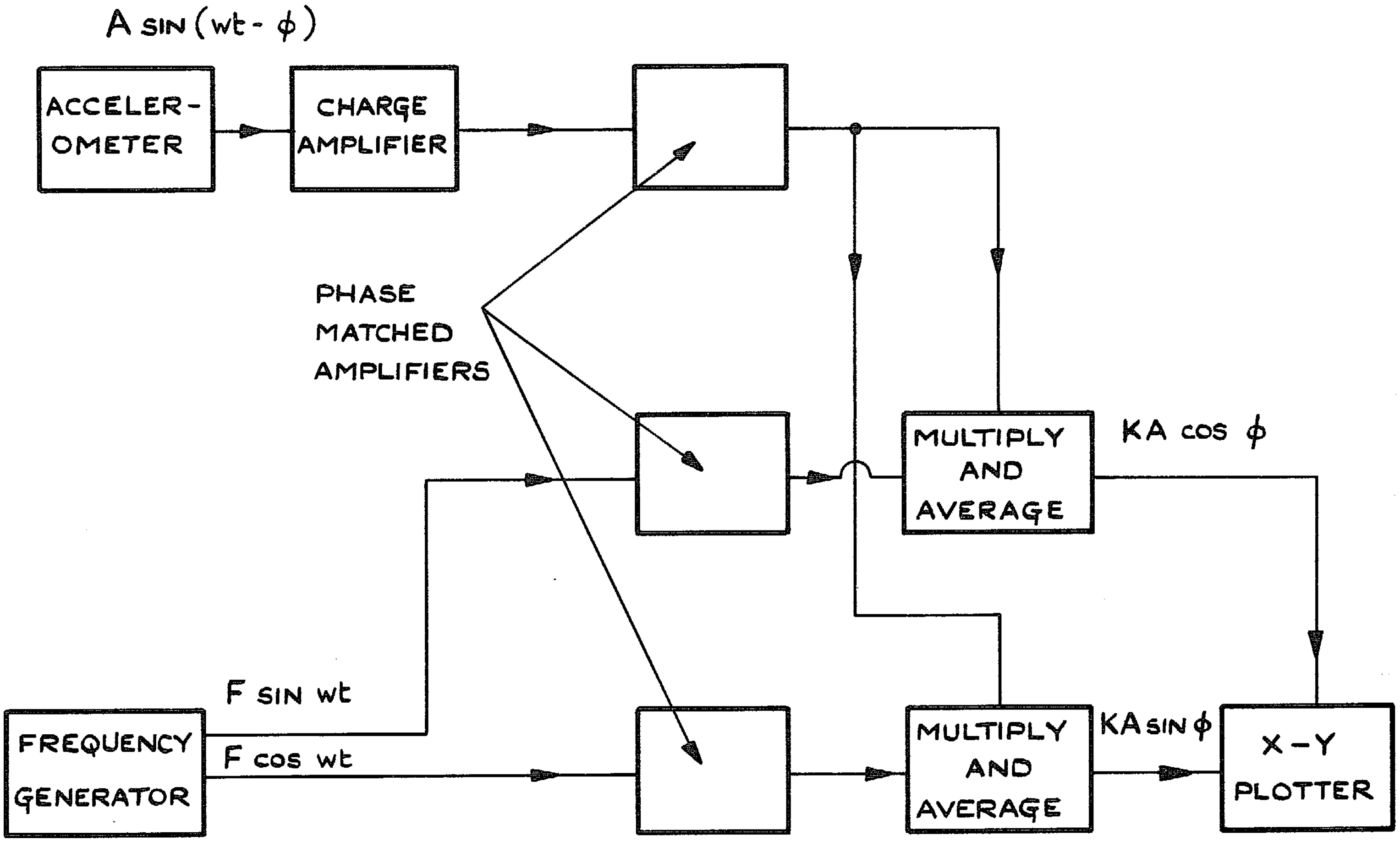

FIG. 3. Block diagram of mode measuring system.

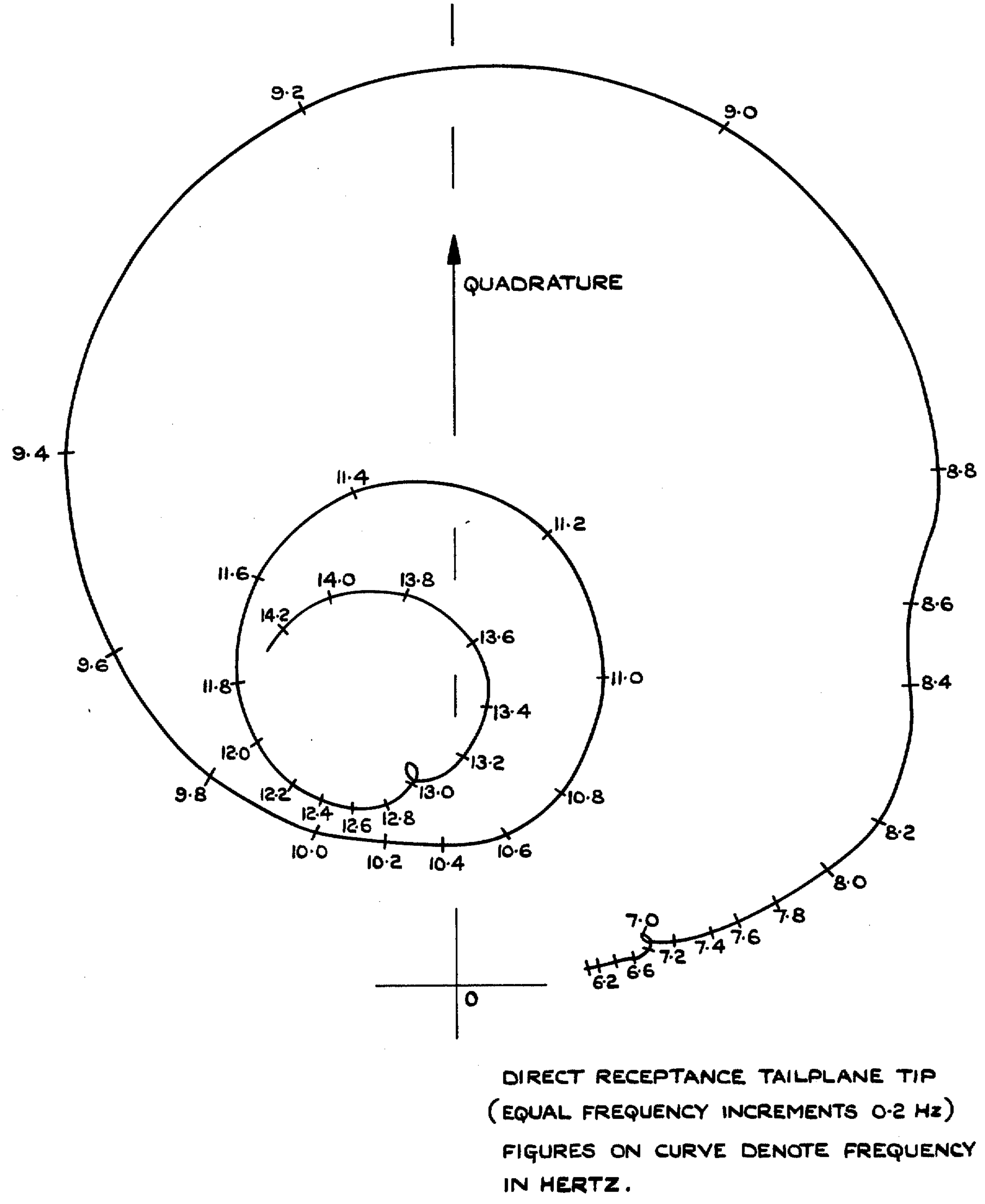

FIG. 4. Illustration of typical resonance search by plot of receptance locus.

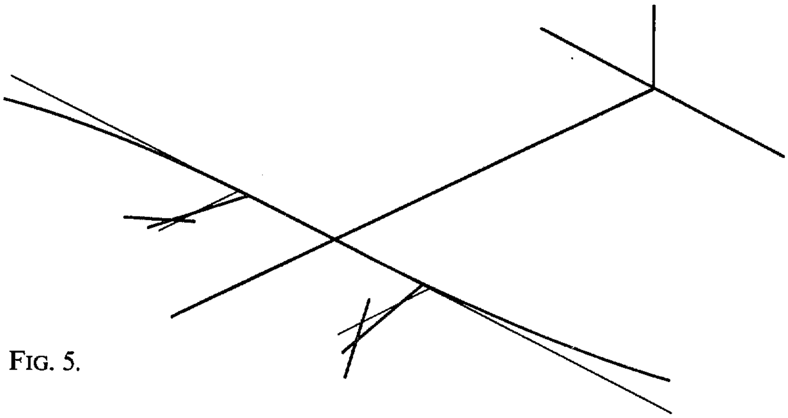

FIG. 5.

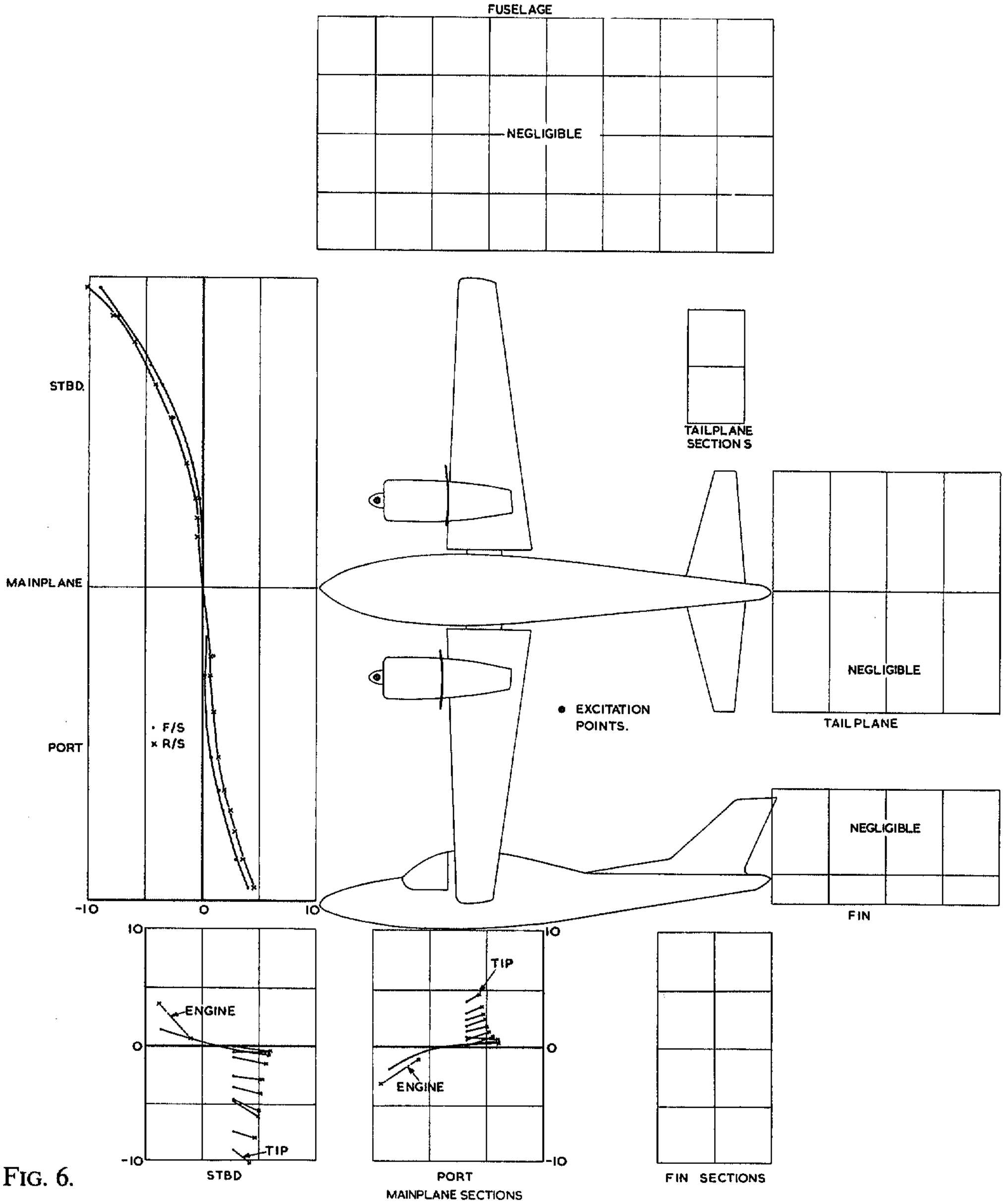

FIG. 6.

FIGS. 5 and 6. Antisymmetric wing bending, engine nodding, 6·7 *Hz*.

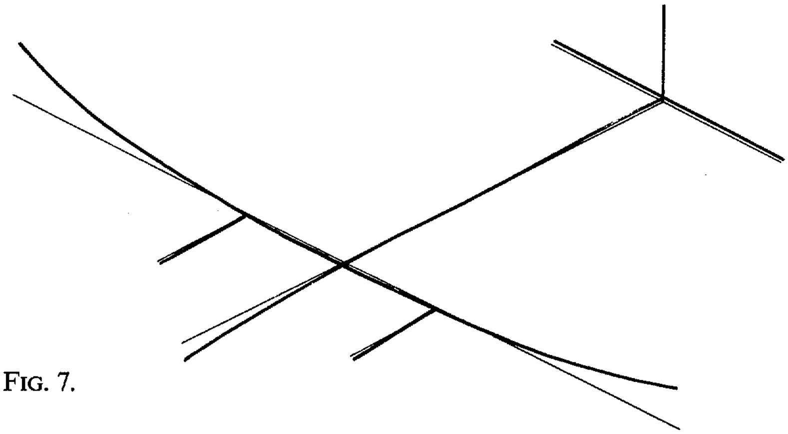

FIG. 7.

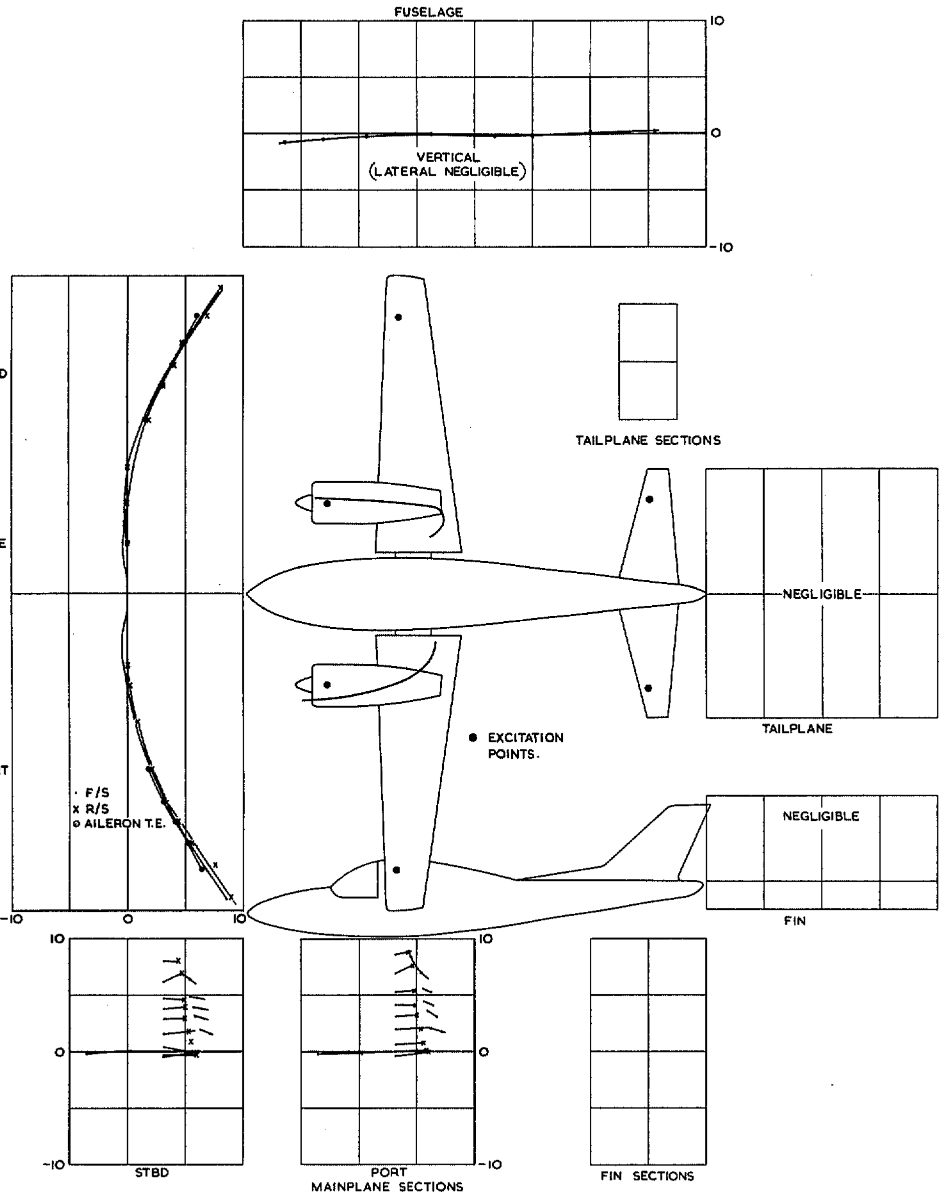

FIG. 8.

FIGS. 7 and 8. Symmetric wing bending, 6·7 *Hz*.

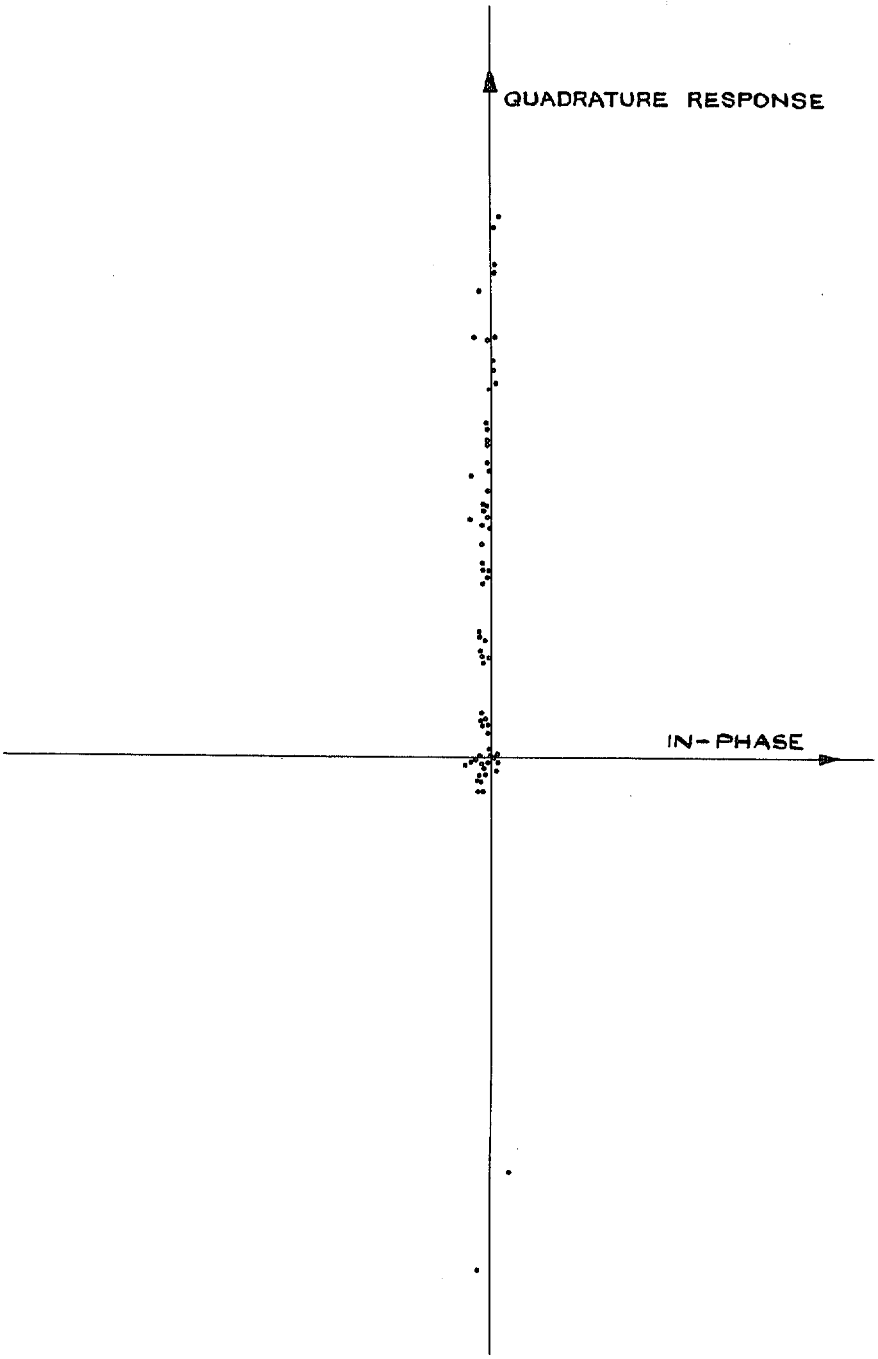

FIG. 9. Vector co-ordinates, 6·7 *Hz*.

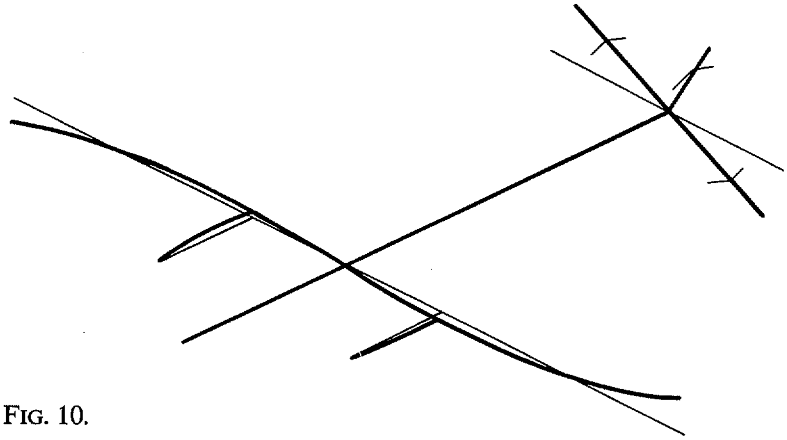

FIG. 10.

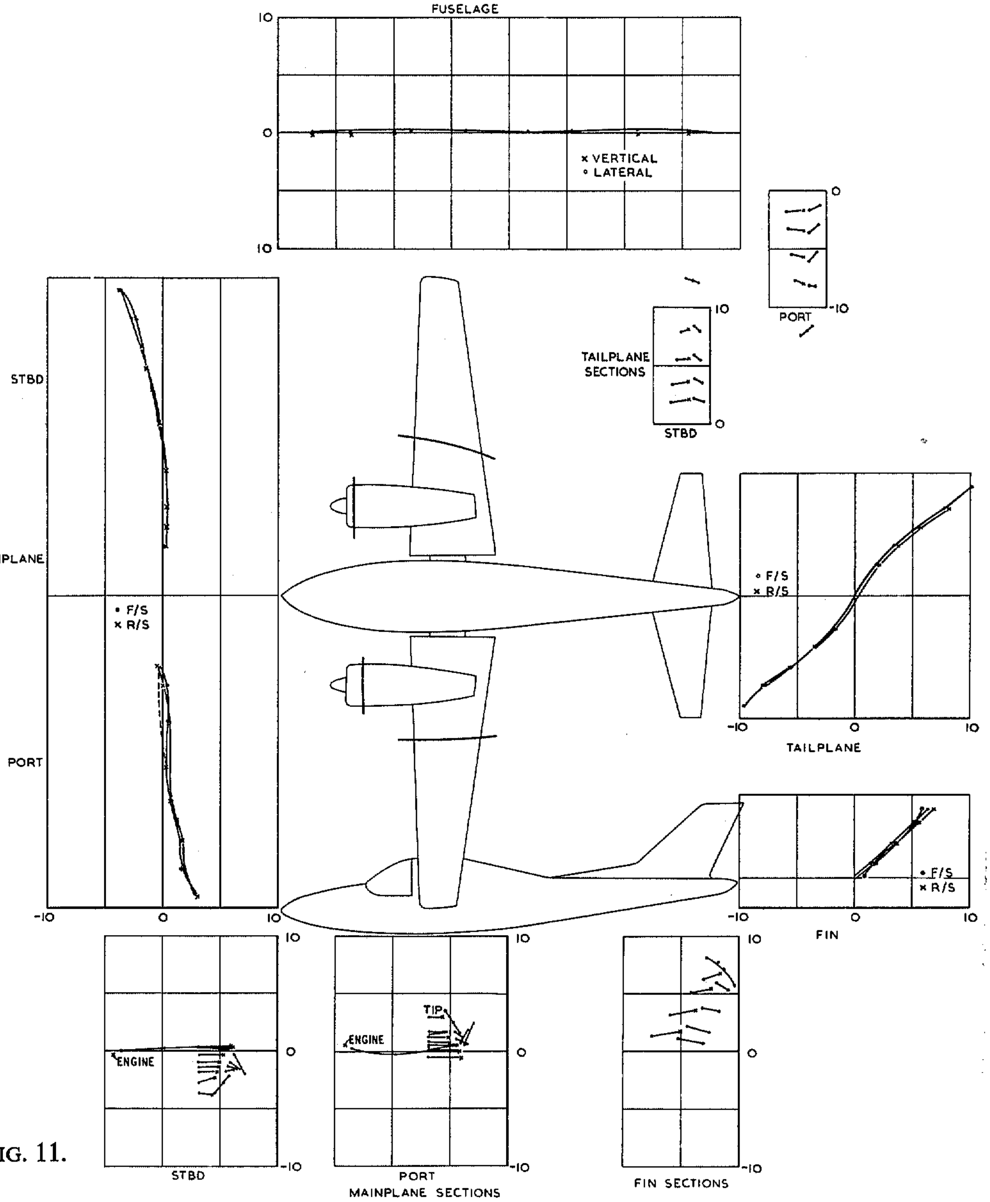

FIG. 11.

FIGS. 10 and 11. Fuselage torsion and antisymmetric wing bending, 9·1 *Hz*.

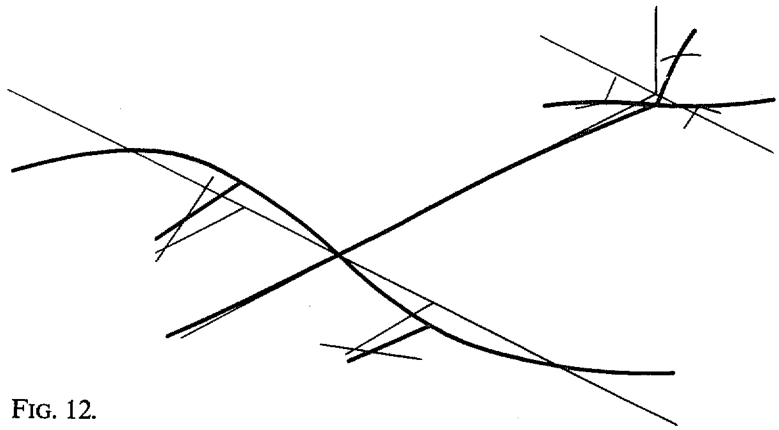

FIG. 12.

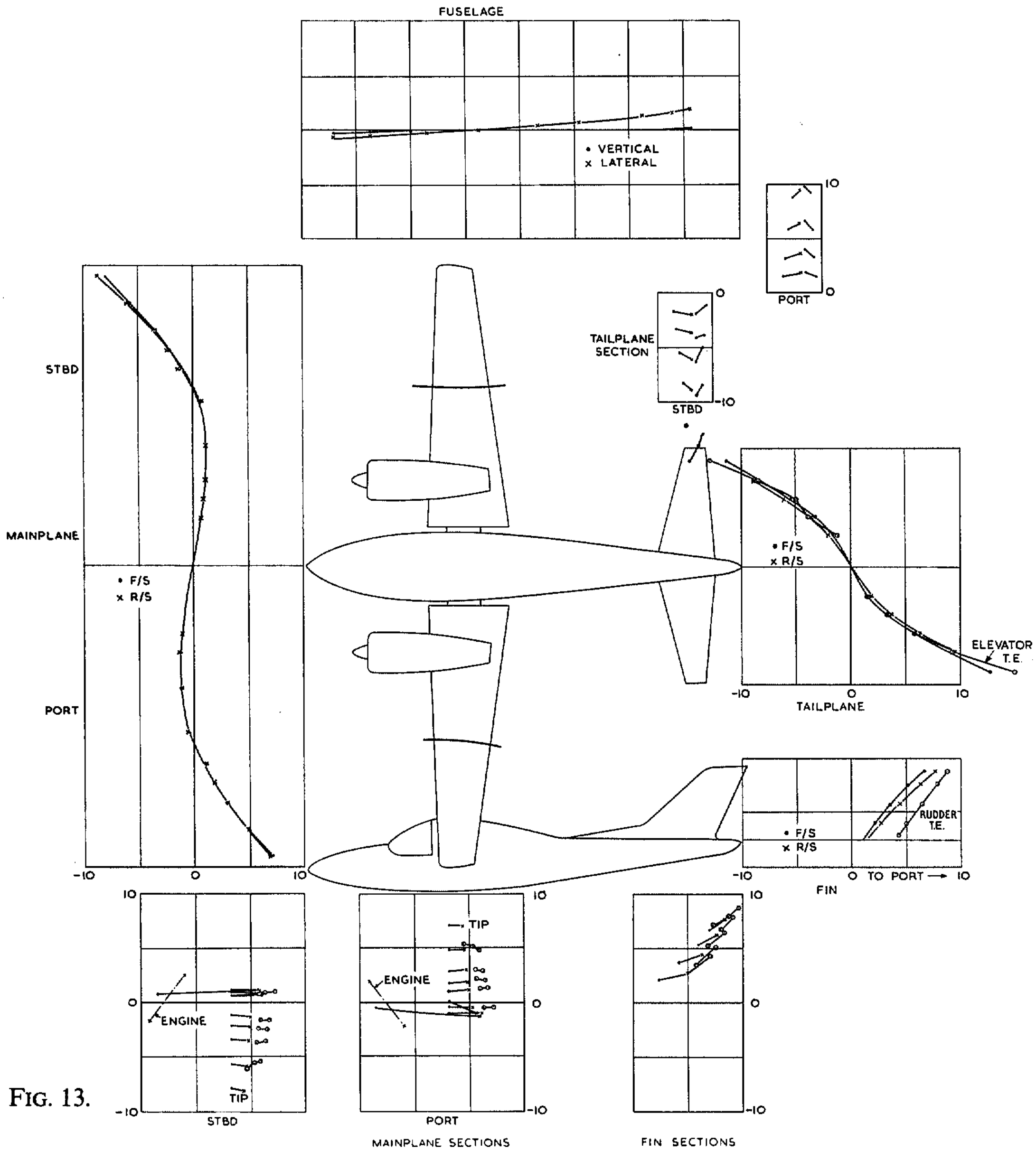

FIG. 13.

FIGS. 12 and 13. Tailplane/fin antiflexure and antisymmetric wing bending, 11·1 *Hz*.

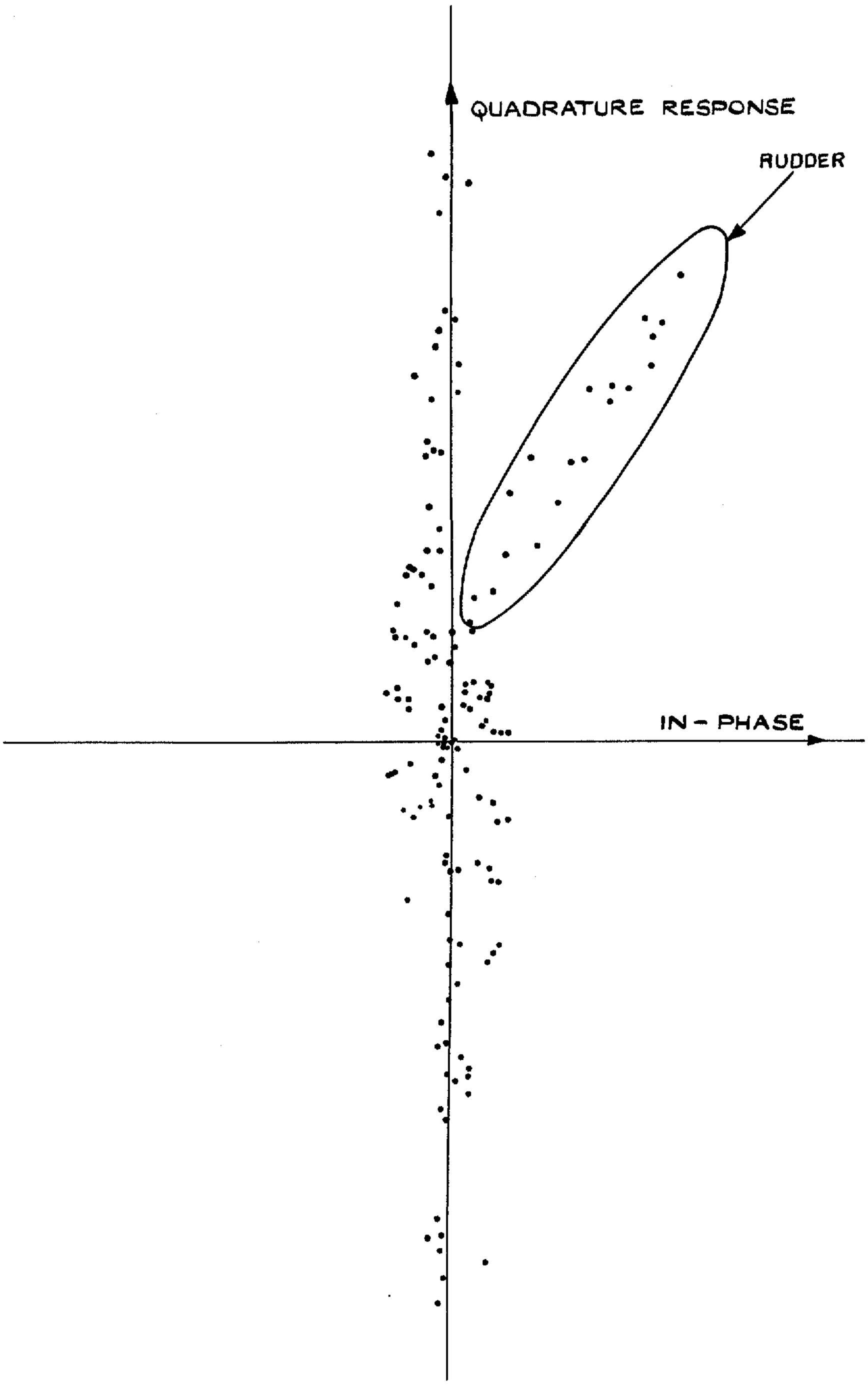

FIG. 14. Vector co-ordinates, 11·1 *Hz*.

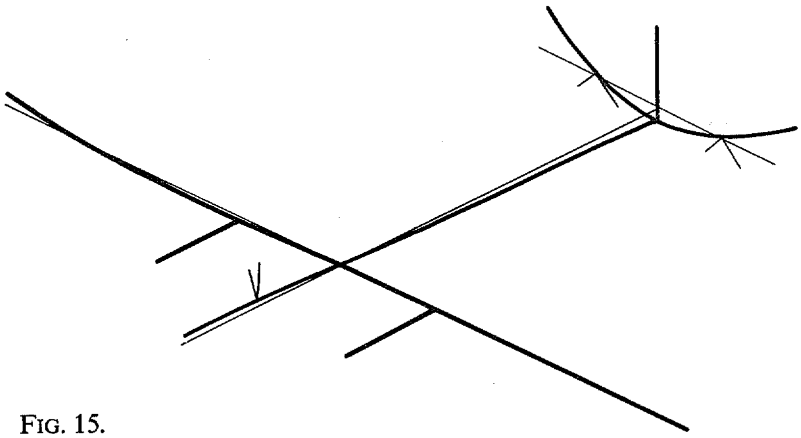

FIG. 15.

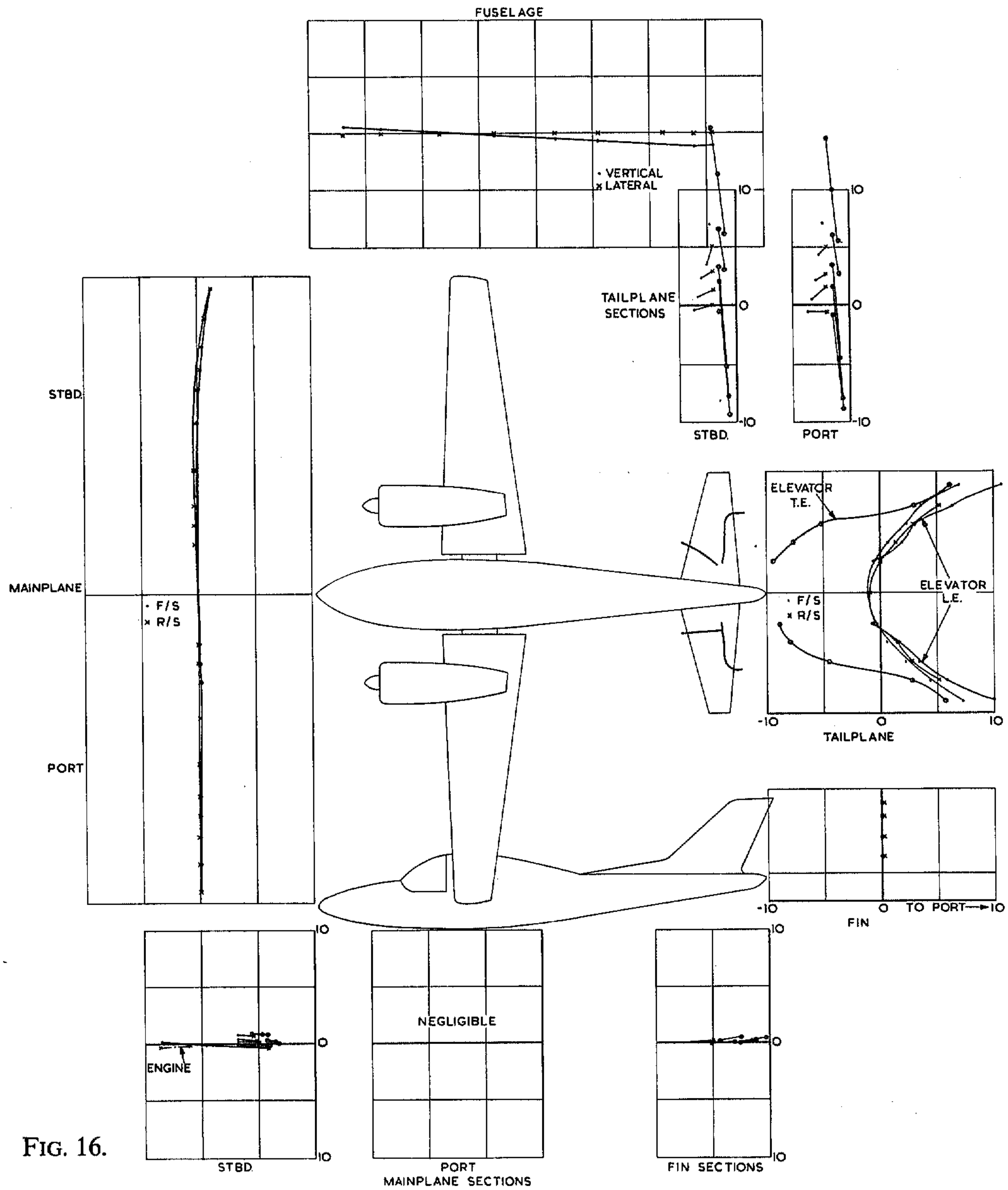

FIG. 16.

FIGS. 15 and 16. Tailplane elevator rotation and symmetric bending, 13·7 *Hz*.

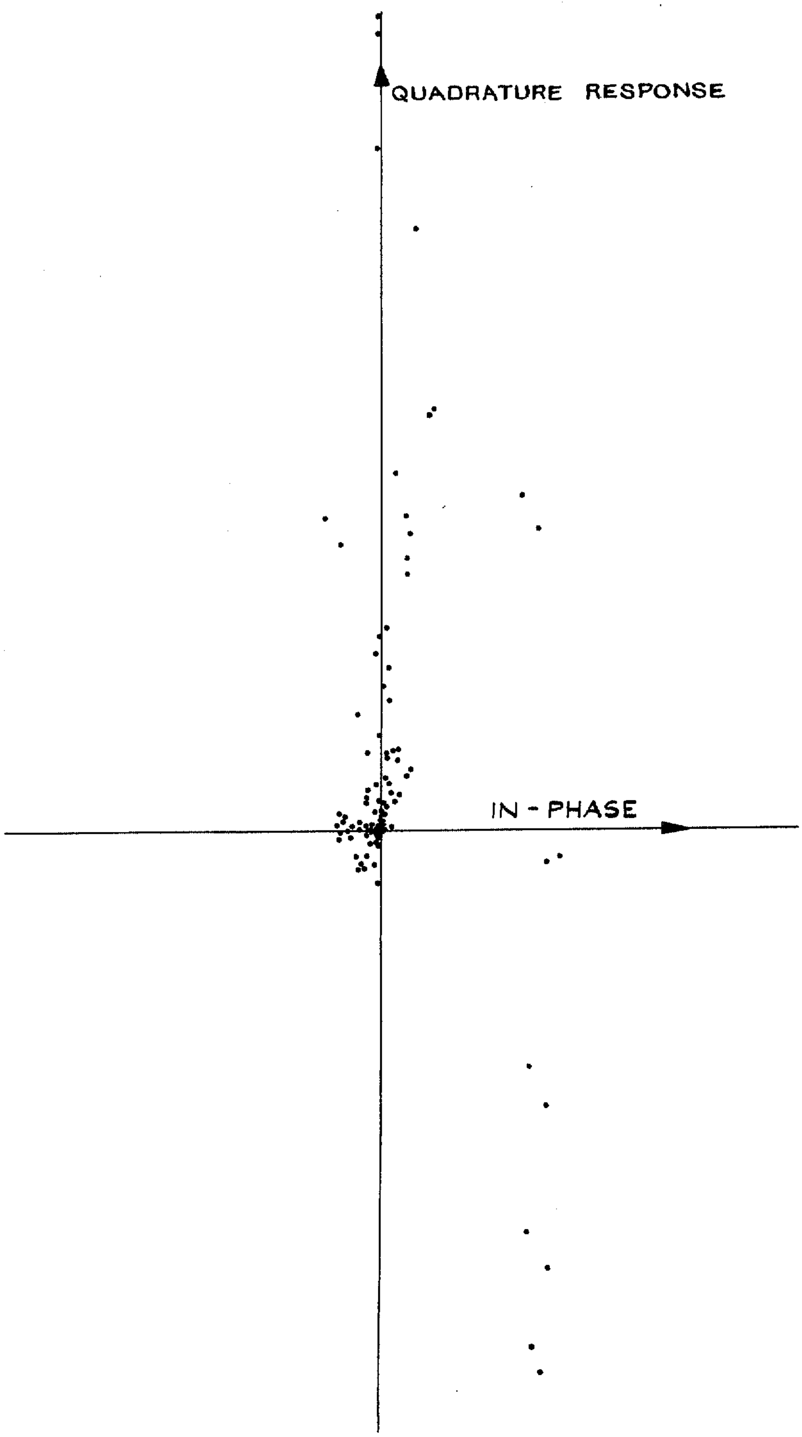

FIG. 17. Vector co-ordinates, 13·7 *Hz*.

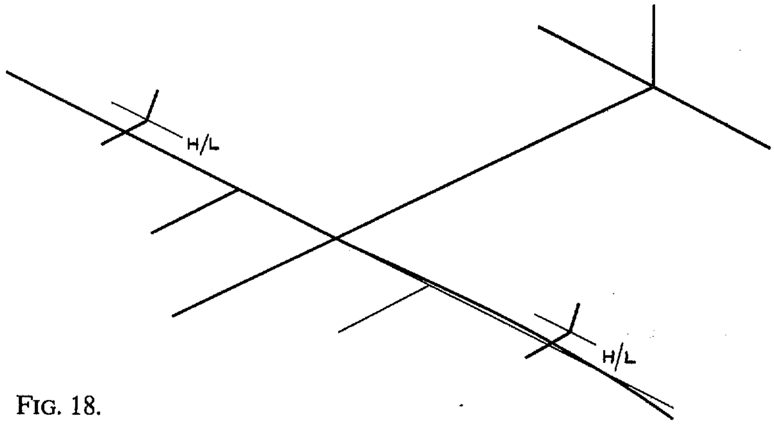

FIG. 18.

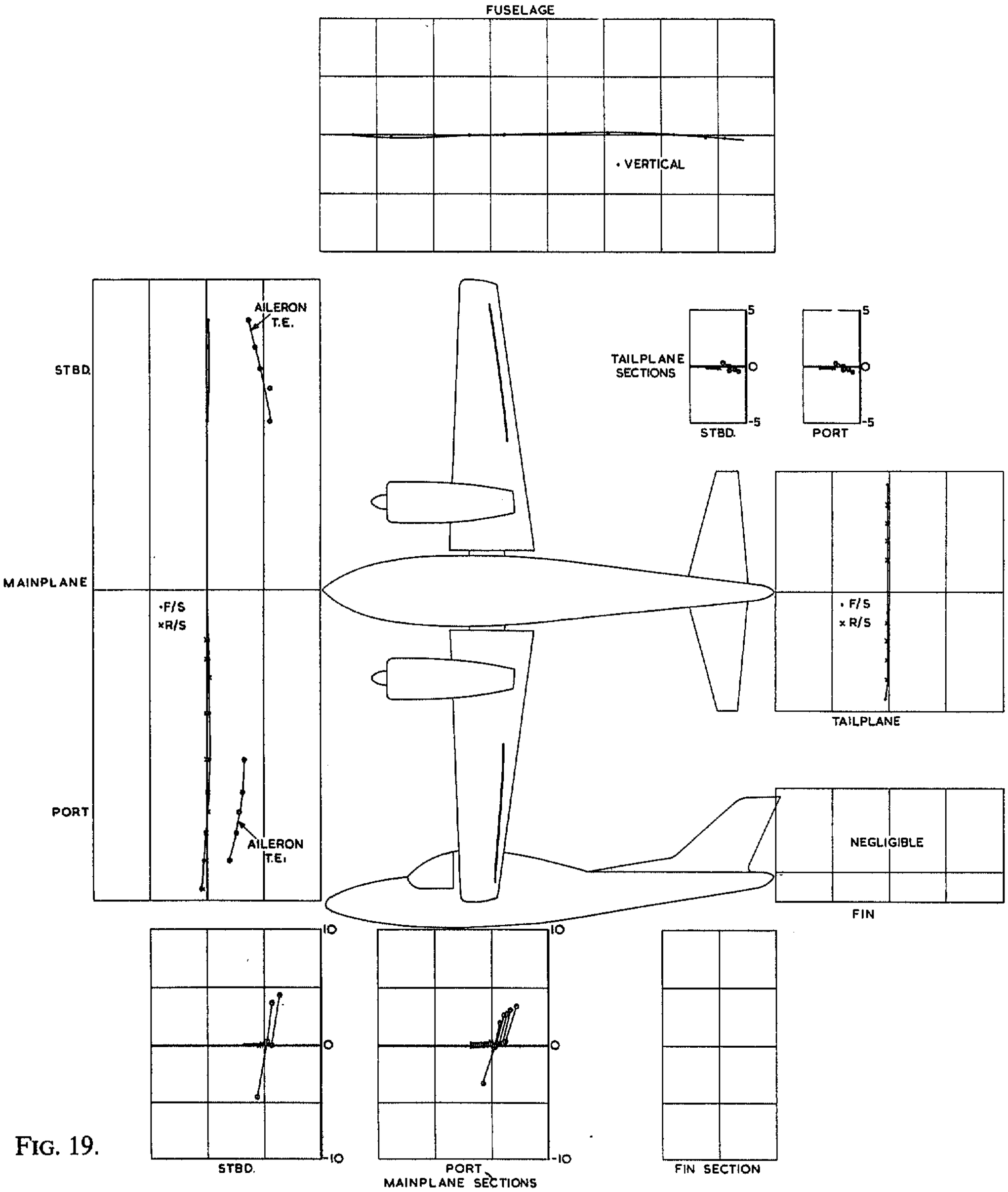

FIG. 19.

FIGS. 18 and 19. Symmetric aileron rotation, ailerons free, 15·0 *Hz*.

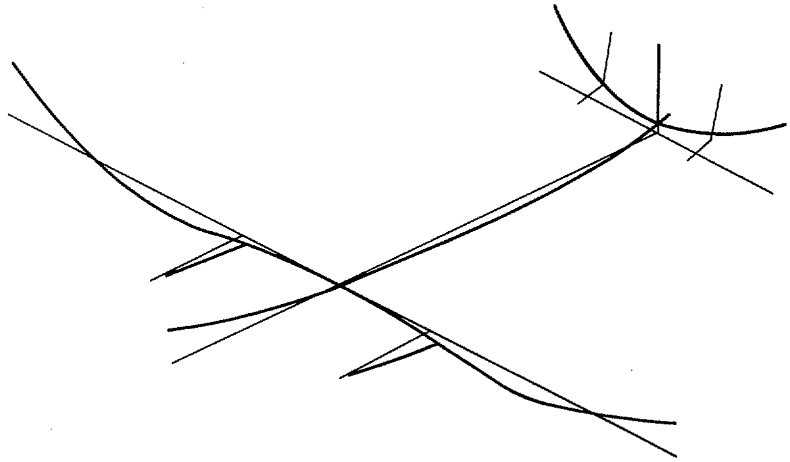

FIG. 20.

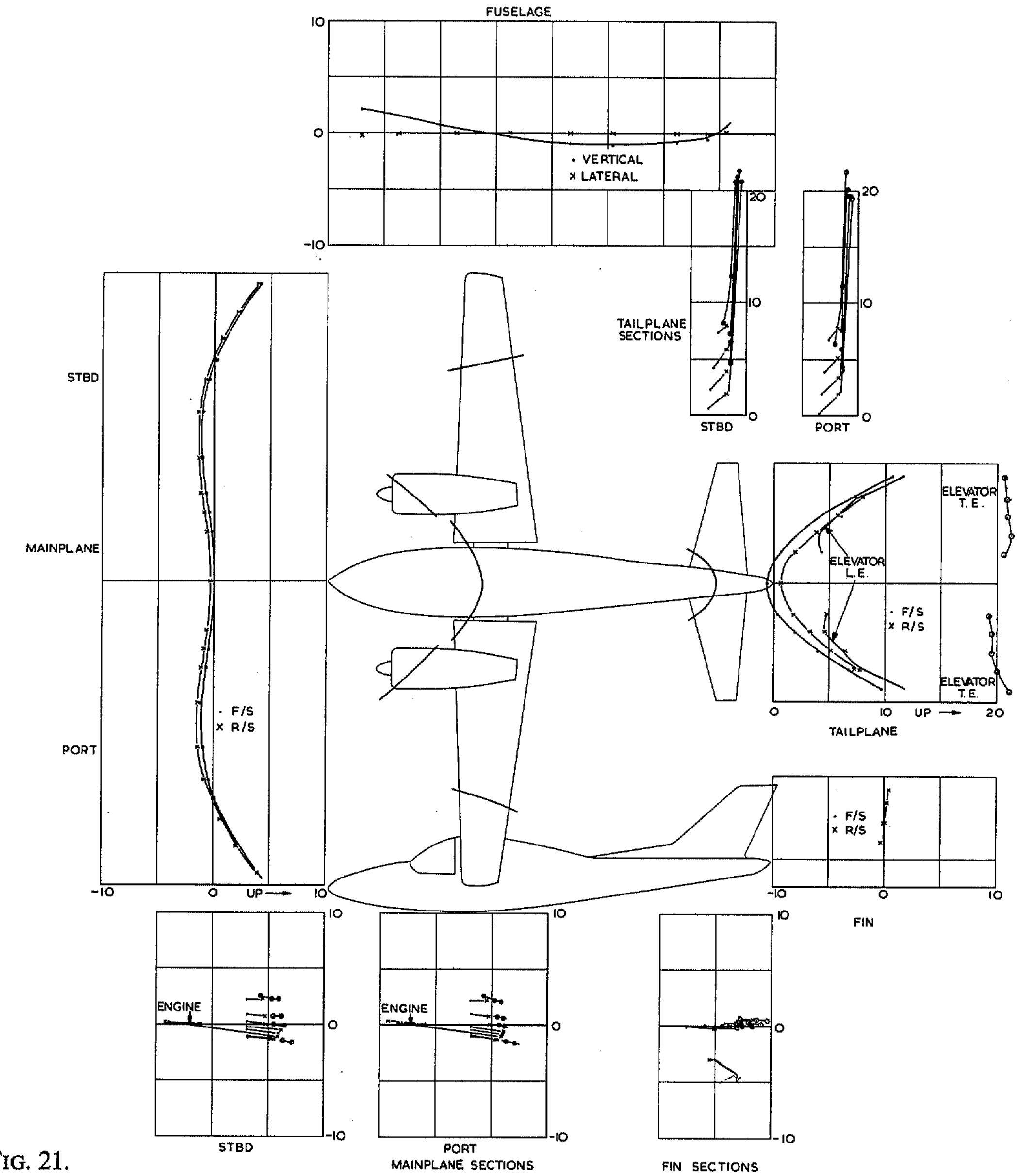

FIG. 21.

FIGS. 20 and 21. Symmetric tailplane bending, body bending, and elevator rotation, 15·8 *Hz*.

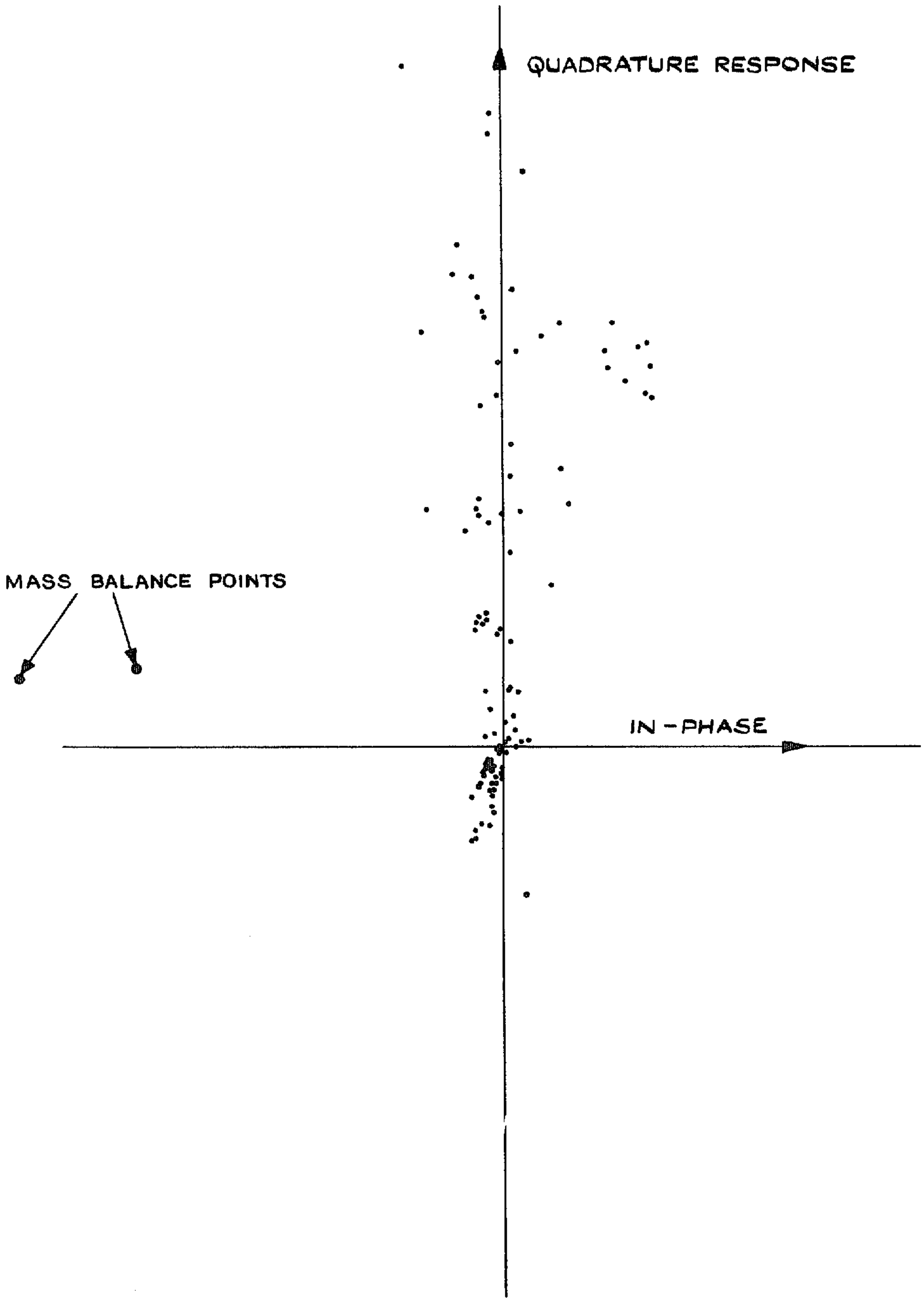

FIG. 22. Vector co-ordinates, 15·8 *Hz*.

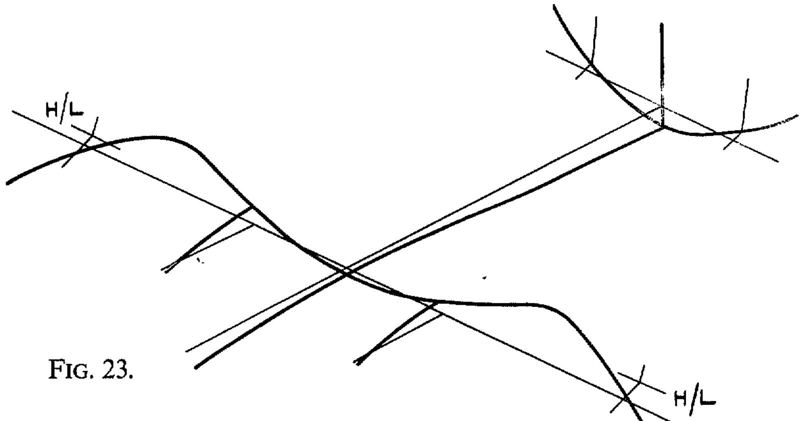

FIG. 23.

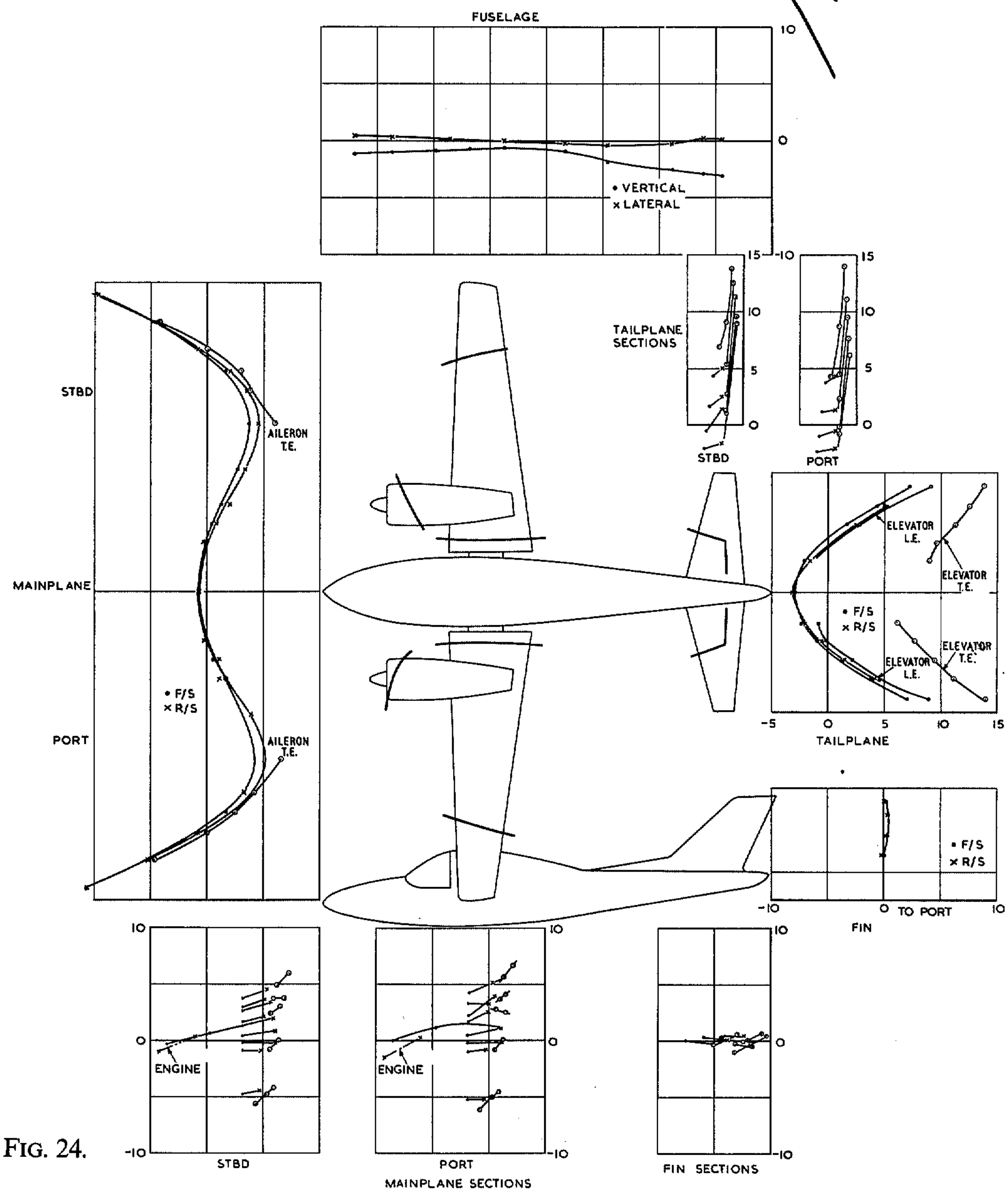

FIG. 24.

FIGS. 23 and 24. Symmetric wing overtone bending and tailplane bending, 19·5 *Hz*.

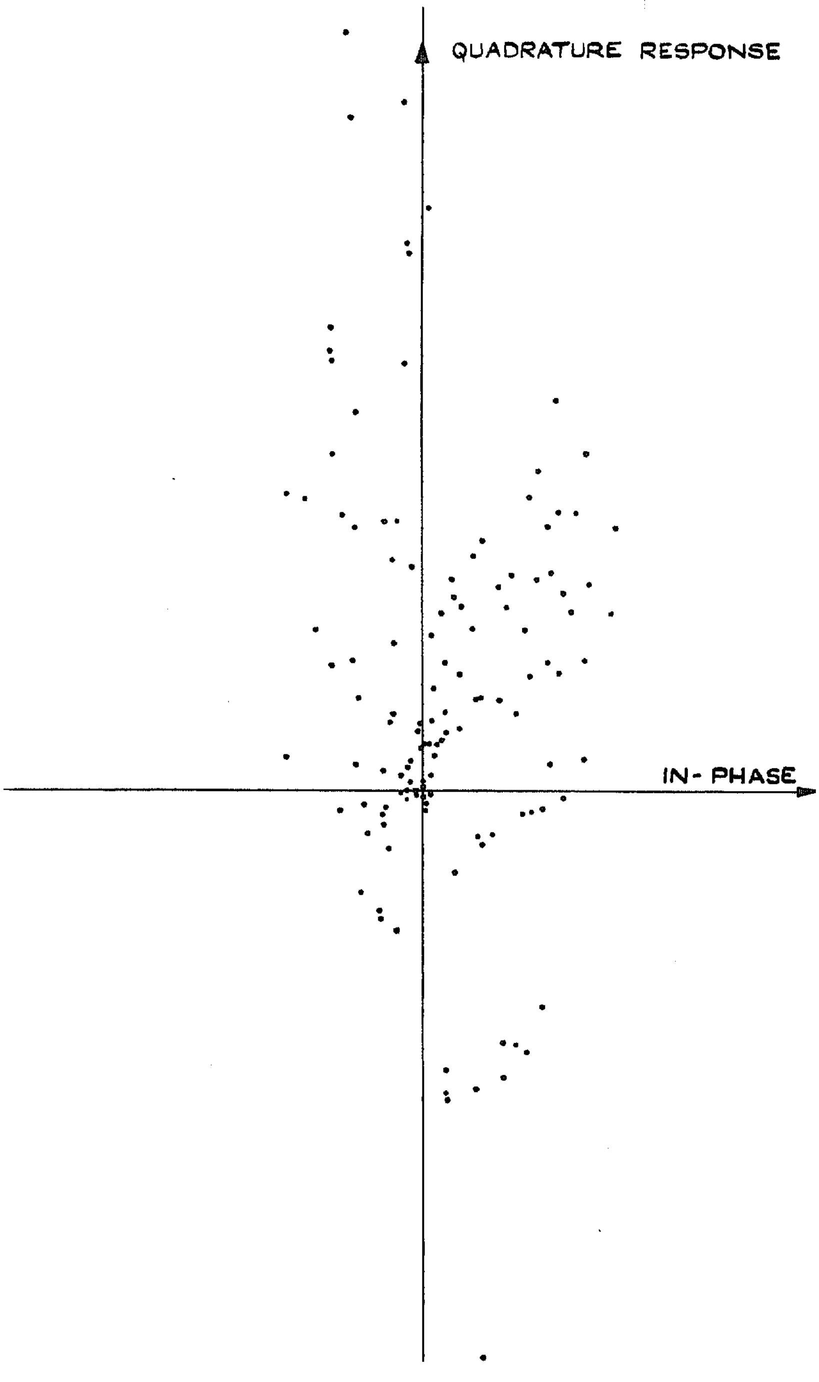

FIG. 25. Vector co-ordinates, 19·5 *Hz*.

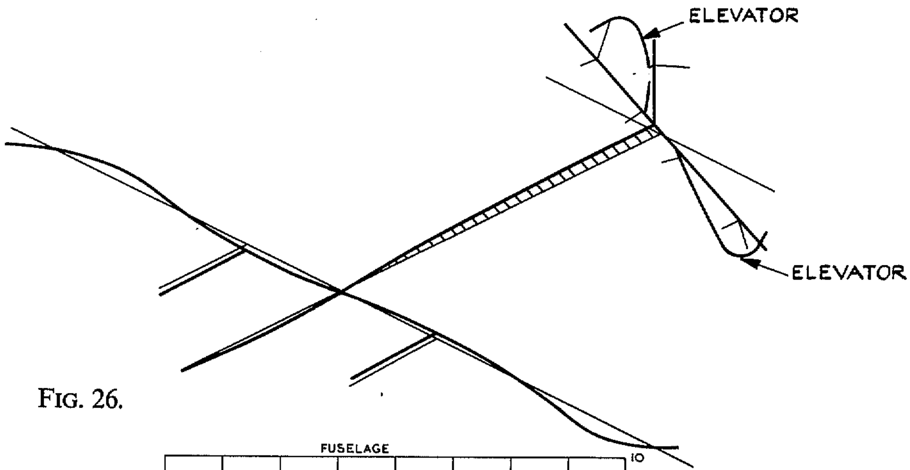

FIG. 26.

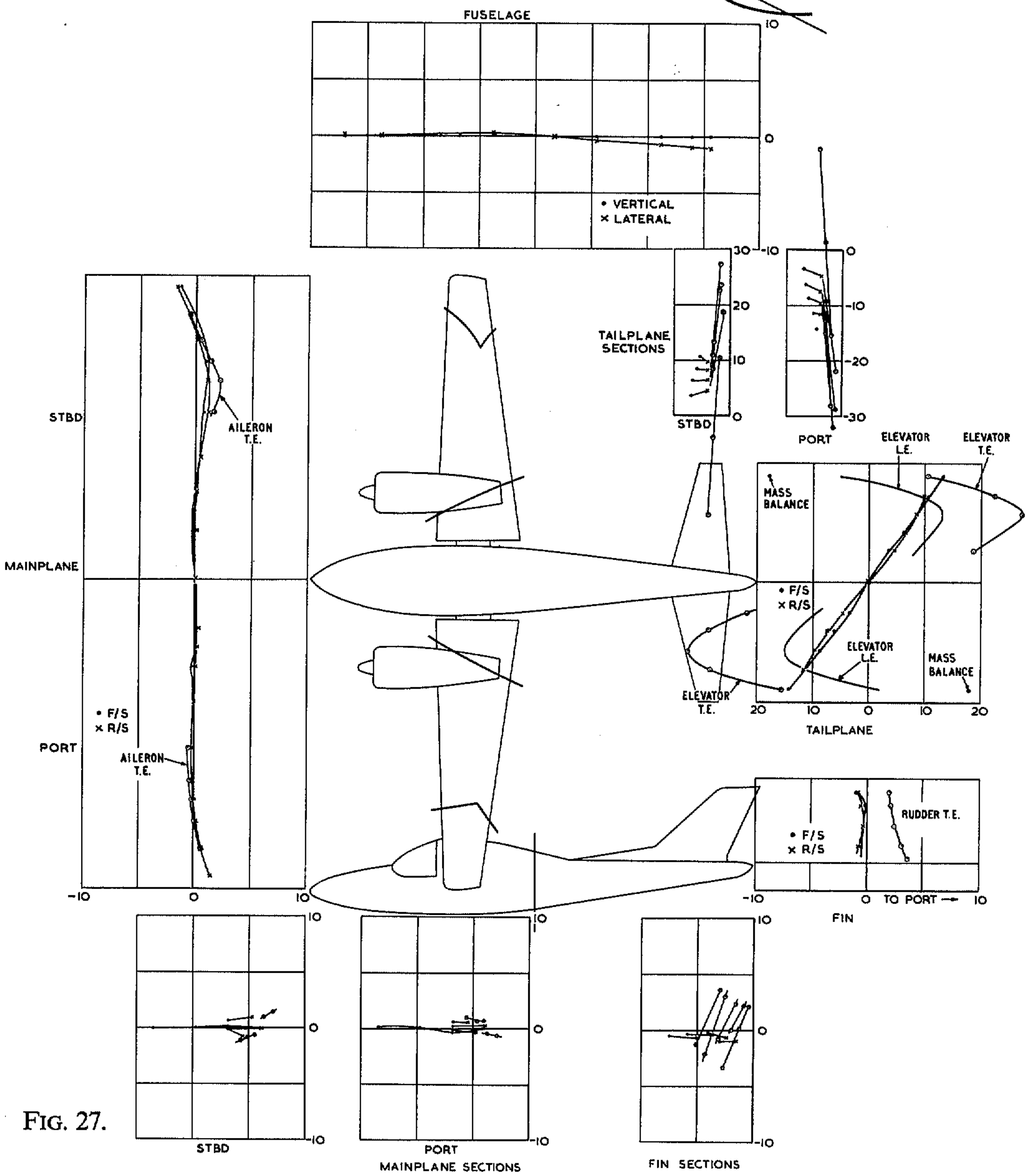

FIG. 27.

FIGS. 26 and 27. Antisymmetric elevator bending and rotation, 26·0 *Hz*.

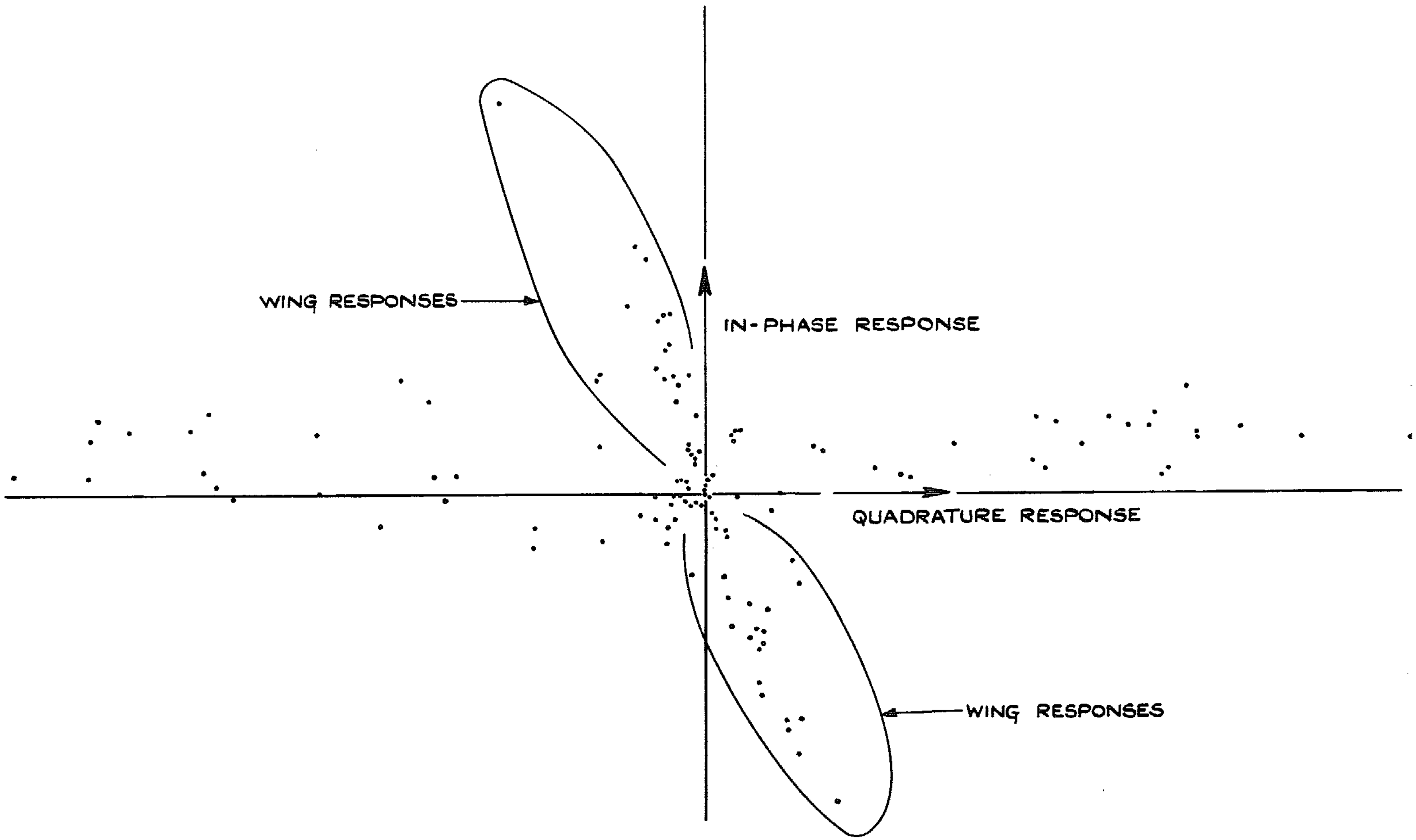

FIG. 28. Vector co-ordinates, 26 *Hz*.

FIG. 29.

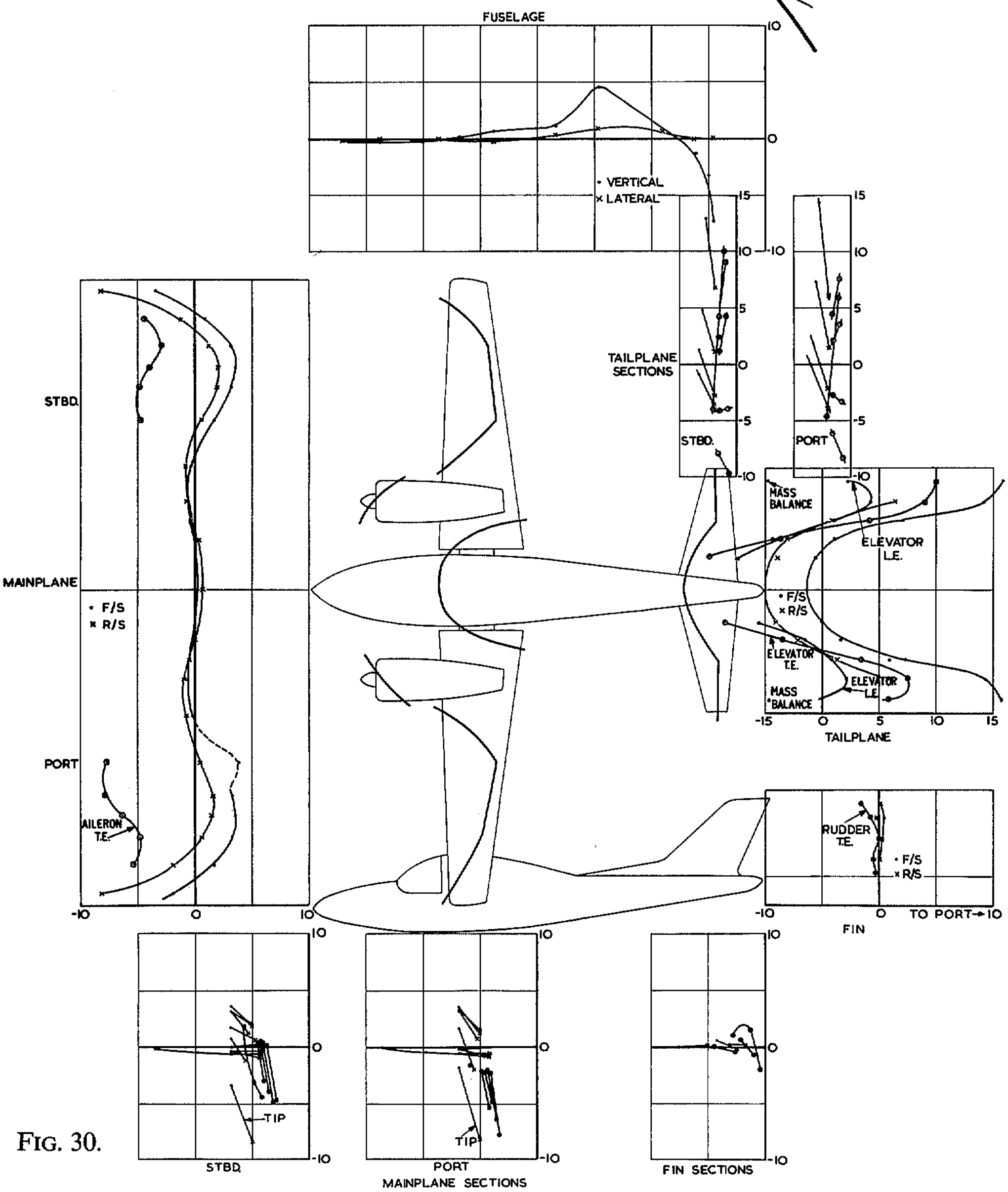

FIG. 30.

FIGS. 29 and 30. Symmetric second overtone wing bending and overtone fuselage bending, 43·6 *Hz*.

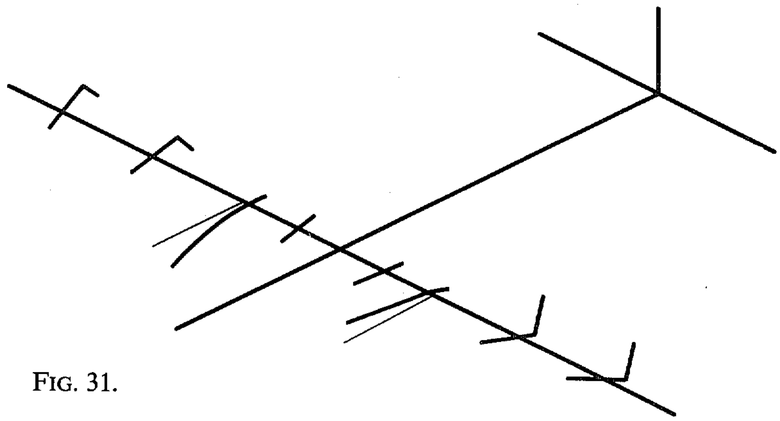

FIG. 31.

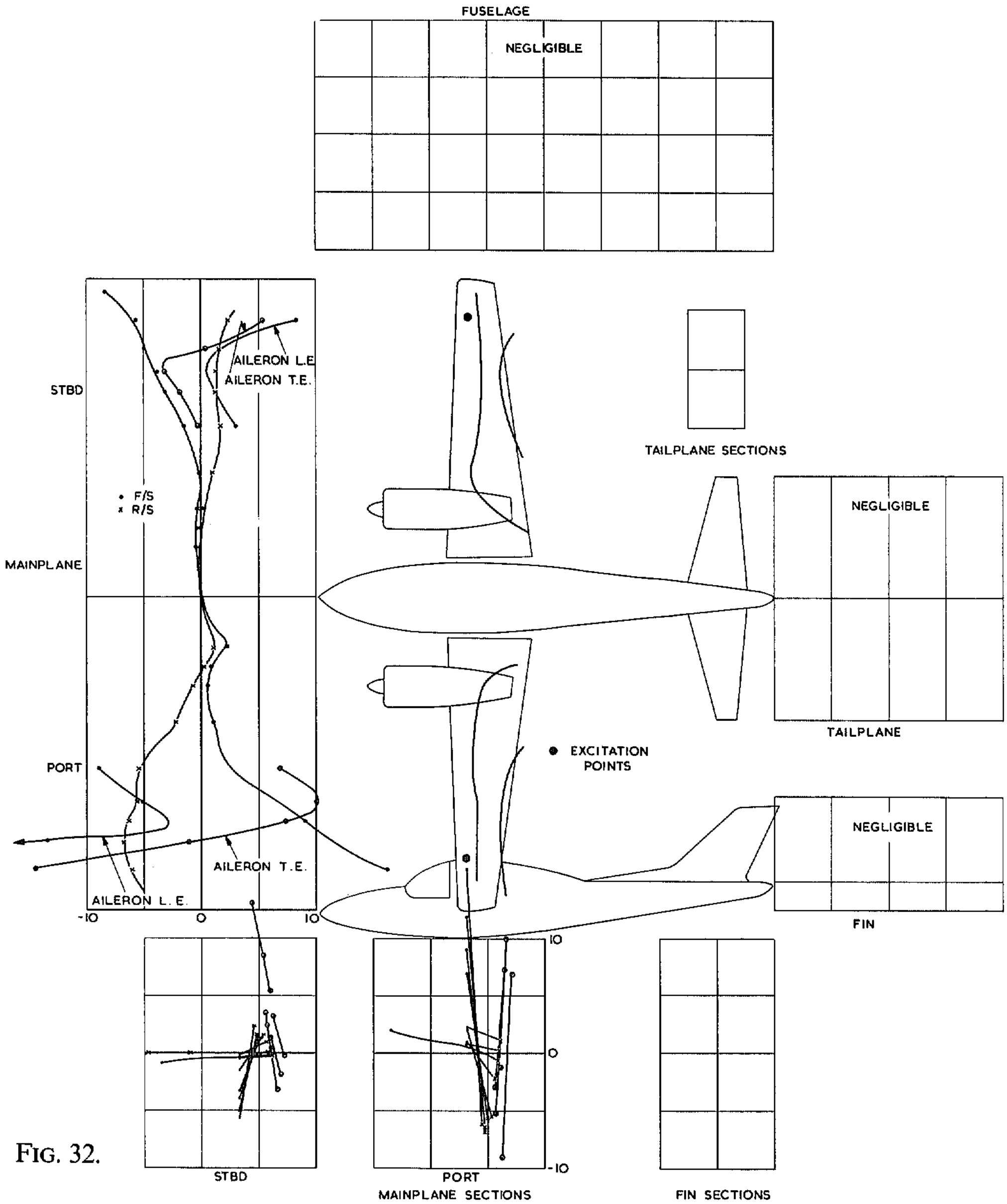

FIG. 32.

FIGS. 31 and 32. Antisymmetric wing torsion, 47·4 *Hz*.

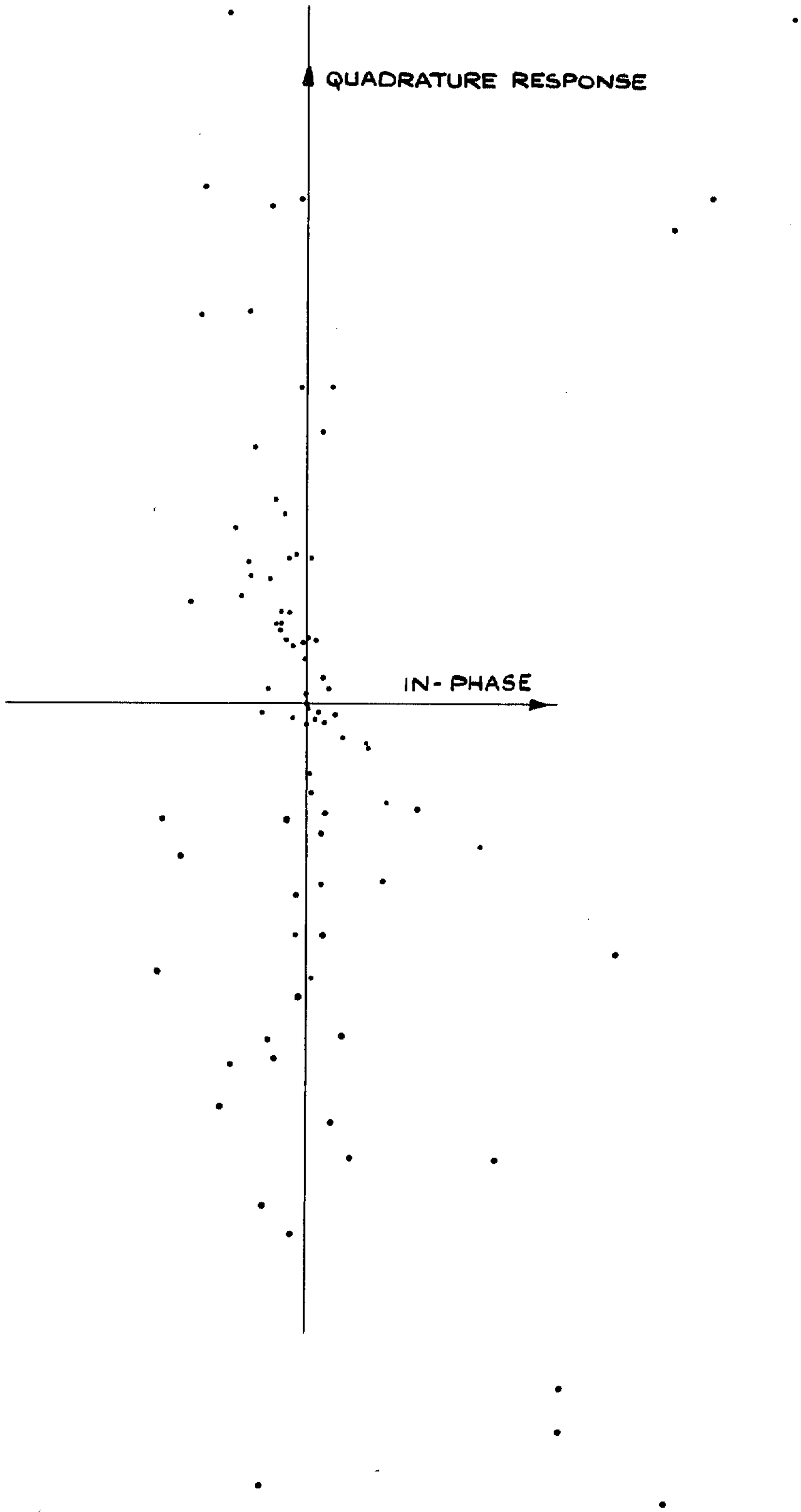

FIG. 33. Vector co-ordinates, 47·4 *Hz.*

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