**R. & M. No. 2893**
**(13,729)**
**A.R.C. Technical Report**

MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

# A Wind-Tunnel Technique for Flutter Investigations on Swept Wings with Body Freedoms

*By*

P. F. JORDAN, Dr. rer. nat. and F. SMITH, M.A.





LONDON: HER MAJESTY'S STATIONERY OFFICE
1955
PRICE 3*s* 6*d* NET

# A Wind-Tunnel Technique for Flutter Investigations on Swept Wings with Body Freedoms

*By*

P. F. JORDAN, Dr. rer. nat. and F. SMITH, M.A.

COMMUNICATED BY THE PRINCIPAL DIRECTOR OF SCIENTIFIC RESEARCH (AIR), MINISTRY OF SUPPLY

*Reports and Memoranda No.* 2893*

*September,* 1950

*Summary.*—In the past it has been usual to ignore the body freedoms of aircraft in making wing-flutter investigations. This practice is no longer justified for modern designs with swept wings, and especially for tailless aircraft. In this report a technique is described which has been developed for wind-tunnel tests on wing-flutter models with the body freedoms. A half-span wing model is used, attached to a rigid body; longitudinal stability is ensured, and the body-mass parameters are reduced to small values, by an appropriate arrangement of supporting springs. The ease of parameter variations makes the wind-tunnel rig suitable for systematic investigations.

1. *Introduction.*—Until recently it was usual to confine flutter investigations to degrees of freedom corresponding directly to structural deformation, without regard to possible overall displacements in space. In some cases the aerodynamic surface itself was allowed to have overall displacement, but only to an extent covered by elastic deformation of its supporting structure. Thus, for example, a tailplane would move bodily as appropriate to flexure and torsion of the fuselage, but the front end of the fuselage would be assumed to be fixed.

With the introduction of swept-back wings, especially on tailless aircraft, the possibility of overall motion of the complete aircraft can no longer be ignored, since such motion may appreciably alter the critical wing flutter speeds†. To the degrees of freedom of the wing itself which are normally considered for flutter investigation, therefore, there have to be added the degrees of freedom of the fuselage, or body. The type of wing flutter in which body freedoms play an important part is for convenience referred to as 'body-freedom flutter'.

With the introduction of body freedoms into flutter analysis no reduction in the number of the already assumed degrees of freedom associated with deformation is usually possible. The body freedoms which it may be necessary to introduce, therefore, are a direct addition to the degrees of freedom that have to be considered. In consequence, the theoretical investigation of body-freedom flutter is considerably more complicated and more difficult than a corresponding investigation in which body freedoms are ignored. This greatly increases the value of experimental tests, since a wide range of parameter variations can be investigated in a comparatively short time, given a suitable technique. Wind-tunnel experiments, in fact, are not only useful for checking theoretical methods but can be used directly to establish the significance of the many parameters affecting flutter.

* R.A.E. Report Structures 73 received 25th January, 1951.

† One reason is that low natural frequency of vertical translation, beneficial for straight wings, may be dangerous for swept wings; another reason is that the aerodynamic pitching moment increases greatly with sweep. Compare Jordan[1] and Broadbent[2].

One particular aspect of the technique described in this report is that the simultaneous occurrence of symmetric and anti-symmetric flutter, and the confusion which this entails, can be avoided. This appears to have considerable significance since earlier experiments carried out by Lambourne[3] with a full-span model of a flying wing were severely hampered by symmetric and anti-symmetric flutter occurring together. The method of avoiding this trouble arises directly from the use of a half-span model. The boundary conditions which have to be artificially introduced at the plane of symmetry, in any case, can without loss of realism be adapted to produce at any one time either type of flutter and to exclude the other.

2. *Principles of Half-Span Technique.*—Wind-tunnel investigations of fixed-root flutter are usually made with a half-span wing model. There are obvious advantages of using a half-span model as compared with the alternative full-span model:—

(*a*) The half-span model is simpler to build

(*b*) Its supports can be arranged outside the air stream

(*c*) The Reynolds number obtainable in a given wind tunnel can be doubled.

The displacements of the model at its plane of symmetry are described, in the case of a rigid body, by the six degrees of freedom:—

| | | |
|---|---|---|
| (i) | Pitching about a given lateral axis | Symmetric |
| (ii) | Vertical motion of the pitching axis | |
| (iii) | Fore-and-aft motion of the pitching axis | |
| (iv) | Rolling about the longitudinal axis | Anti-symmetric |
| (v) | Yawing about a given vertical axis | |
| (vi) | Lateral motion | |

Of these degrees of freedom, the anti-symmetric group has to be excluded in symmetric flutter, and *vice versa*. Furthermore the degrees of freedom (iii), (v) and (vi) above involve only motions in the horizontal plane and are generally insignificant in wing flutter*. The body freedoms to be provided must therefore correspond to pitching and vertical translation in symmetric flutter, and rolling in anti-symmetric flutter.

Considering finally the aerodynamic boundary conditions, these are fulfilled if the plane of symmetry is made a reflecting plate for symmetric flutter and a free boundary of the jet in the case of anti-symmetric flutter.

3. *Design of the Rig.*—The rig was designed for use in the Royal Aircraft Establishment 5-ft Open-Jet Wind Tunnel. Only symmetric wing flutter has so far been investigated with the present rig, and the subsequent description refers to this investigation. No tailplane was attached to the model in order to reduce the number of parameters and also to make the results applicable to 'flying wing' aircraft.

The test equipment consists of a permanent rig to which a model wing is fitted. The rig consists mainly of:—

(*a*) The model supports—three vertical struts, a drag bar and two pairs of helical springs. These supports are arranged under and fitted to a table

(*b*) The model body, a cruciform beam (Fig. 4) to which sliding weights can be attached. The model wing can be fitted to this body at various angles of sweepback

(*c*) Additional units (*see* later).

Figs. 1 to 4 show the rig in the wind tunnel. The wing is arranged vertically to avoid gravitational effects. The top plate of the table forms the reflecting plate and is slightly above the plane of symmetry which includes the model body.

* Yawing affects fin flutter but this is not under consideration here. Horizontal motions of the wing may be significant in the case of wing-aileron flutter with offset aileron mass-balance weights.

The supports are required to enforce the structural boundary conditions, to carry the weight of the model, to take the drag force and to stabilise the model in the middle of the wind tunnel. The first two requirements are fulfilled by the three vertical struts which extend from the representative body to the floor of the wind tunnel (Figs. 1, 3 and 4). There are universal cross-spring links at each end of the struts. The drag force is taken by the horizontal drag-bar.

The strut arrangement does not introduce any dry friction and very little internal damping; on the other hand the body motion which it enforces is not exactly plane but contains a vertical component for large horizontal amplitudes. It had been anticipated that the body amplitudes would be small and would be sensitive to external friction. In fact the amplitudes were, in general, large but the slight non-linearity of the arrangement seemed to have little effect.

It will be noted that the strut support is stable for small body amplitudes, owing to the stiffness of the links, and unstable for large amplitudes owing to gravity effect*; both effects are small.

The model is kept in the middle of the air stream by two pairs of helical springs (Fig. 4). The available range of effective body-mass parameters can be increased by this arrangement (see section 3.2.2).

3.1. *Support Structure*.—The table (Figs. 1 and 2) is an open-sided box with the top forming the reflecting plate. The front extension of the top plate is flexible and is screwed to the wind-tunnel nozzle thus forming a smooth contour. Parts of the top plate can be removed, giving access to the model body (Fig. 2). The only permanent opening in the top plate is a slot of 5-in. width which allows the front part of the wing root to pass through the plate to the model body beneath (*see* Fig. 3).

The struts are circular wooden tubes of artificial bamboo construction (Fig. 1). Each strut weighs $0 \cdot 12$ lb and is 2 ft long. The cross-spring links (Fig. 5) at the ends of the struts give complete pin-jointed freedom. Each strut with its links can take at least 100 lb in compression.

The drag bar can be seen in Fig. 2. It is made from light alloy and runs in two light pulleys, which are fitted to the top plate of the table. The connection between drag bar and model is formed by a ball-bearing.

3.2. *Model*.—3.2.1. *Wing*.—The model wing is interchangeable and further a given wing can be arranged at different angles of sweepback. The spar extends through the table-top and is fixed to the model body (Fig. 3). The rear part of the wing root is cut off to allow for 50 deg sweepback: the gap between the top plate and the wing at smaller angles of sweepback is filled with wedge-shaped blocks of balsa wood which are attached to the wing (Fig. 1).

The wing (Figs. 1 and 2) had been used by Molyneux[4] for tests on swept wings with fixed root conditions. The principle of the design was to obtain a well-defined flexural axis by concentrating all the stiffness of the wing in the spar. For this purpose leading and trailing edges had been stiffened with paper only and the wing skin was of fine silk doped with Vaseline. A disadvantage of the design was its lack of stiffness against loads applied in a fore-and-aft direction; in consequence appreciable fore-and-aft motions were observed in the preliminary tests. Leading edge and trailing edge were reinforced for the main tests by thin plywood inserts. Safety grabs, operating on the wing tip, were first used (Fig. 3) but were later discarded since the model developed a 'backlash' type of flutter when striking the grab pads.

The model wing, which had already been used in previous wind-tunnel flutter tests, was further weakened during the lengthy tests which were made in the process of developing the technique. Finally the wing spar broke near the wing root due to fatigue.

3.2.2. *Body and springs*.—The body (Fig. 4) is a rigid cruciform beam of Dural construction. The rear end of the body is interchangeable; its length is determined by the requirement that the c.g. (wing plus body) should lie approximately in the middle of the total body length. The total

* The arrangement can be made stable by turning it upside down. The present upright position seemed preferable for ease of access and ease of removal from the tunnel.

moment of inertia of the wing and body (without additional weights) is thus made as small as possible, in order to increase the available range of inertia values. Additional weights can be fitted to the body at various positions.

The body is described by three mass parameters; weight, c.g. position and radius of gyration with regard to pitch. The effective body-mass parameters are modified by small contributions from the vertical struts and drag bar and by the effect of the helical springs. In calculating the effective body-mass parameters the springs may be considered as negative masses of value $k/\omega^2$ where $k$ is the dynamic stiffness of the springs and $\omega$ is the circular frequency of the flutter.

The inner ends of the helical springs are attached to the body by a ball-bearing coupling (Fig. 2); their outer ends are held by clamps which slide in rails along the sides of the top plate (Fig. 1). The outer end of one of the front springs is connected to the exciter (Fig. 1). The springs should be arranged normal to the neutral position of the body (Fig. 4); the oblique arrangement of Fig. 2 is not recommended.

The dynamic stiffness $k$ of the springs is a function of the frequency $\omega$ and may be written

$$k = k_0 - m\omega^2/3$$

if $\omega$ is sufficiently small compared with the natural frequency of the springs with zero body mass; $k_0$ is the static stiffness of the springs and $m$ the mass of the springs. The static stiffness $k_0$ of the spring arrangement varies with the amplitude of the body owing to the unavoidable non-linearity of the spring characteristic, but this effect can be minimised by making the springs sufficiently long. There is a further error in the case of pitch due to the geometry of the motion (Fig. 6), which has the effect of making the stiffness proportional to $\sin \alpha/\alpha$ where $\alpha$ is the angle of pitch. The effective dynamic stiffness of the spring arrangement is best measured directly, and this is described later in section 4.1.

3.3. *Exciter.*—The exciter unit was used for exciting the model with continuously varying frequencies, either for observing the natural frequencies and the modes or for observing the approach to the critical speed ('flight resonance tests'). Excitation was applied to one of the front springs. A different exciting point is chosen for those cases where the front springs are unsuitable (*e.g.*, fixed-root case).

3.4. *Measurement of Frequency.*—The frequency of body-freedom flutter is usually of the order of the fundamental bending frequency. The frequency of the model flutter hence tends to lie in that range (3 to 10 c.p.s.) which is too low for accurate measuring by stroboscopic or resonance methods and too high for unaided counting. Since the accuracy of determining the effective body-mass parameters depends on frequency it is most important to obtain an accurate reading. The mechanism used consists of a veeder counter which is operated by a make-and-break contact connected to the model body by a very light spring. The correct working of this contact can be checked before use by a subsidiary indicator circuit. By an arrangement of relays, a stop-watch and the veeder counter can be started at the same moment, thus reducing human errors. The circuit diagram is shown in Fig. 7.

3.5. *General Stability.*—Apart from the flutter being investigated, the model should be stable in all other respects. Insufficient stability leads either to low-frequency oscillations or to divergence.

Apart from the ordinary requirements for aircraft stability, the effect of the springs must be considered. For instance, with the rig arrangement adopted (Fig. 4) a form of flutter is possible in which the effectively rigid wing oscillates in pitch and vertical translation against the action of the helical springs. This type of flutter, which if it occurred would be undesirable, can be prevented by suitable design. If the overall c.g., the aerodynamic centre, and the point at which an applied load normal to the wing produces no pitch are nearly coincident, the coupling is small and rigid-wing flutter is avoided. The arrangement shown in Fig. 4 satisfies these requirements.

A problem of greater practical concern is the effect of incipient divergence, even when actual divergence does not take place; it is necessary to trim the model during the test by adjusting the tension in the forward spring in order to avoid excessive lateral displacement. With forward c.g. positions it may furthermore be necessary to decrease the distance $s$ of the springs (Fig. 4).

4. *Test Procedure*.—4.1. *Measurement of Dynamic Spring Stiffness*.—The effective dynamic stiffness of the spring arrangement is obtained directly on the rig by measuring the natural frequency of the body (without wing) at various amplitudes with various weights. The flutter frequency will sometimes be higher than the maximum frequency which can be obtained by this method; this range, in which the equivalent spring mass is generally small compared with the mass of the model, can be covered with sufficient accuracy by arranging the pair of springs vertically between two fixed points and fixing various masses between them; again the natural frequency is measured.

4.2. *Resonance Tests*.—The natural frequencies of body pitch and fundamental wing bending were measured before each test as a matter of routine, and the modes observed. The first mode should have its nodal point at the c.g.: thus an immediate check of the arrangement of springs and the adjustable weight is obtained.

The bending and torsional frequencies under fixed-root conditions were measured at intervals during the tests to check the constancy of the wing properties.

4.3. *Flutter Tests*.—The general technique of flutter tests is the same as with other flutter tests. The particular difficulty of body-freedom tests lies in the fact that this flutter is often difficult to excite and may suddenly occur with an unforeseen mode. However, with the exciter, flight resonance tests can be made in doubtful cases. At constant speed $V$ the model was excited throughout the range of likely frequencies, and by repeating this procedure with increasing speeds $V$ the development of the flutter mode with speed could usually be observed. The exciter unit was also used for measuring the flutter frequency in a few cases of particularly violent flutter. The flutter mode was excited at a speed just below the critical speed, and its frequency was measured at this speed.

The motion can alternatively in many cases be excited by hand, but some caution is required, in particular when the model tends to diverge. The advantage of this method is that with experience the onset of flutter can be predicted in difficult cases where the mechanical oscillator would be unsatisfactory.

As regards the use of heavy springs in order to extend the range of effective mass parameters to smaller or even negative values, two difficulties arise: the large percentage contribution of the spring correction to the effective mass requires careful test procedure for accurate results; furthermore the test results, instead of forming smooth curves as in Fig. 8 (*see* below), tend to consist of several branches belonging to different types of flutter with different frequencies. The interpreting of the results thus becomes more and more complicated.

4.4. *Interpretation of Results*.—It is important to arrange the variation of parameters so that as many as possible are independent of each other. Thus the c.g. position is invariant with respect to frequency if two identical pairs of springs of equal stiffnesses are arranged symmetrically with respect to the c.g. of the positive masses. The springs are fixed at equal distances $s$, and weights $W$ are fixed at equal distances $d$ about the c.g. (Fig. 4). A first series of tests is made in which the weights $W$ are increased in steps; flutter speed and frequency are measured for each case. A second series is made with different distance $d$, and so on. Obviously the c.g. remains invariant.

Typical results obtained in this way are shown in Fig. 8 as plots of critical flutter speed and frequency against added weight for different values of the distance between the weights. In Fig. 9 the results have been 'corrected' for the negative mass effect of the springs, and are shown as plots of effective body inertia against effective body mass for different values of critical flutter speed. At any particular speed the region below the appropriate critical curve represents instability. Fixed-root flutter conditions are also shown on both Figs. 8 and 9*.

5. *Conclusion*.—A wind-tunnel technique for the investigation of wing flutter involving body freedoms has been developed, particularly for application to swept-wing aircraft. Though a complete set of final results of such an investigation cannot yet be given owing to failure of the model wing, the technique has proved successful and information has been obtained on swept-back wing flutter.

---

* It will be noticed that, for body-freedom flutter to arise, the body radius of gyration must be small.

## REFERENCES


| No. | Author | Title, etc. |
|---|---|---|
| 1 | P. F. Jordan .. .. .. | General considerations of the flutter of swept wings. R. & M. 2892. February, 1950. |
| 2 | E. G. Broadbent .. .. .. | Flutter problems of high-speed aircraft. R. & M. 2828. April, 1949. |
| 3 | N. C. Lambourne .. .. .. | An experimental investigation on the flutter characteristics of a model flying wing. R. & M. 2626. April, 1947. |
| 4 | W. G. Molyneux .. .. | The flutter of swept and unswept wings with fixed-root conditions. R. & M. 2796. January, 1950. |

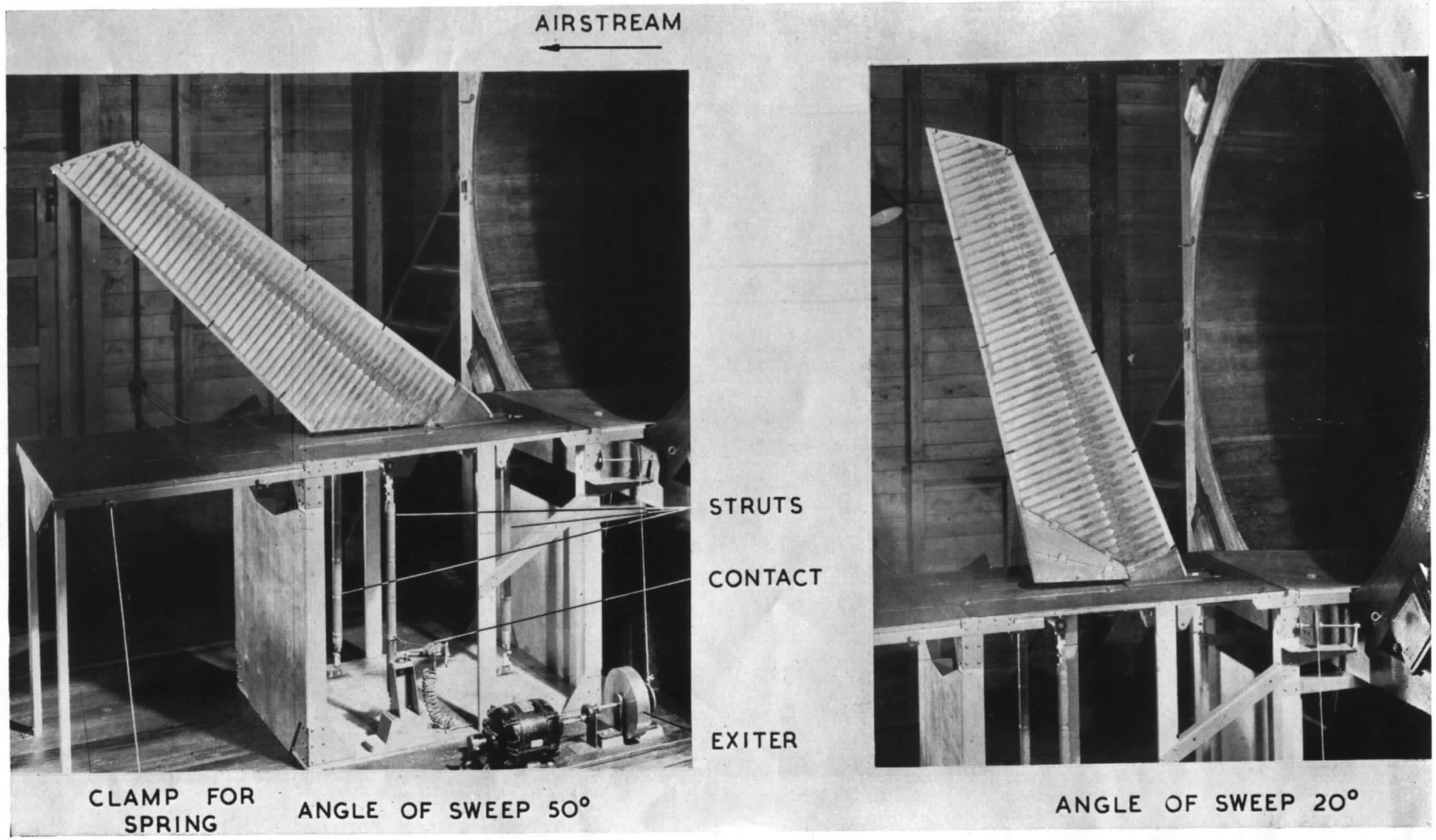


FIG. 1. Flutter Rig in Wind Tunnel.

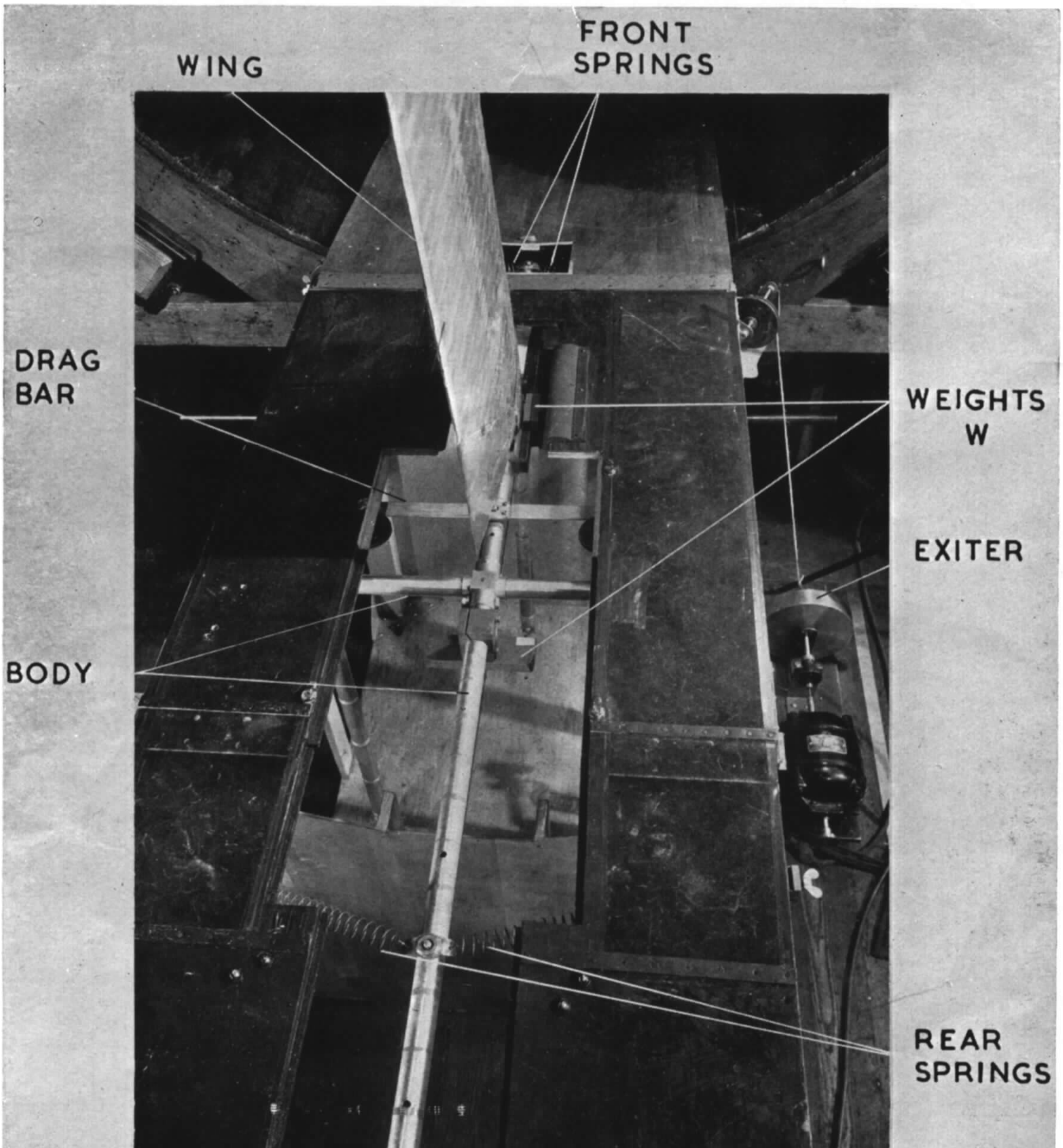


FIG. 2. Top view of flutter rig.

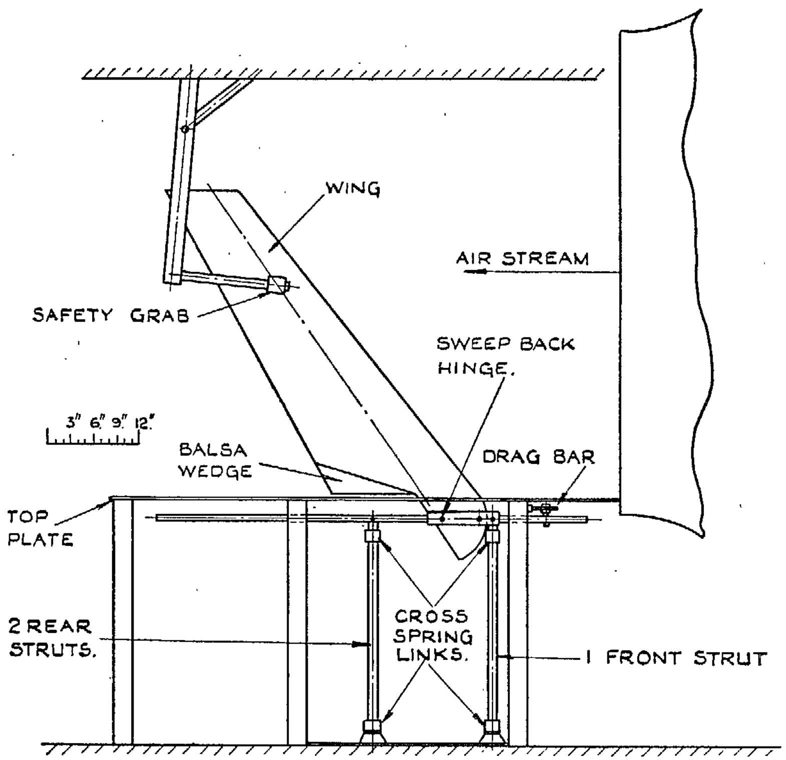


FIG. 3. General arrangement of the rig.

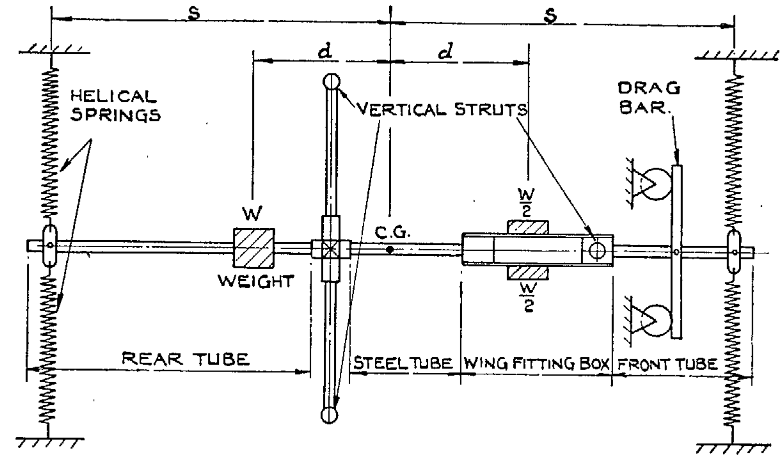


FIG. 4. Plan of body and supports—diagrammatic.

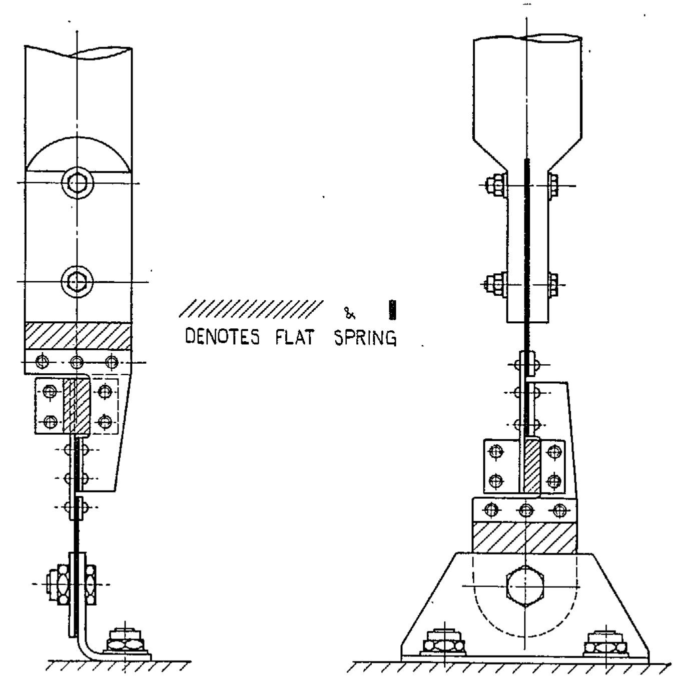


FIG. 5. Universal cross-spring link.

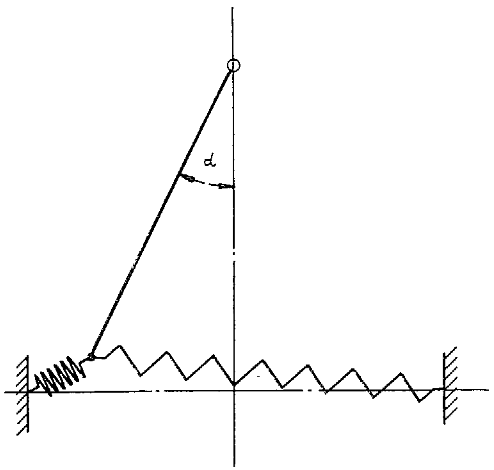


Fig. 6. Geometry of spring arrangement in pitch.

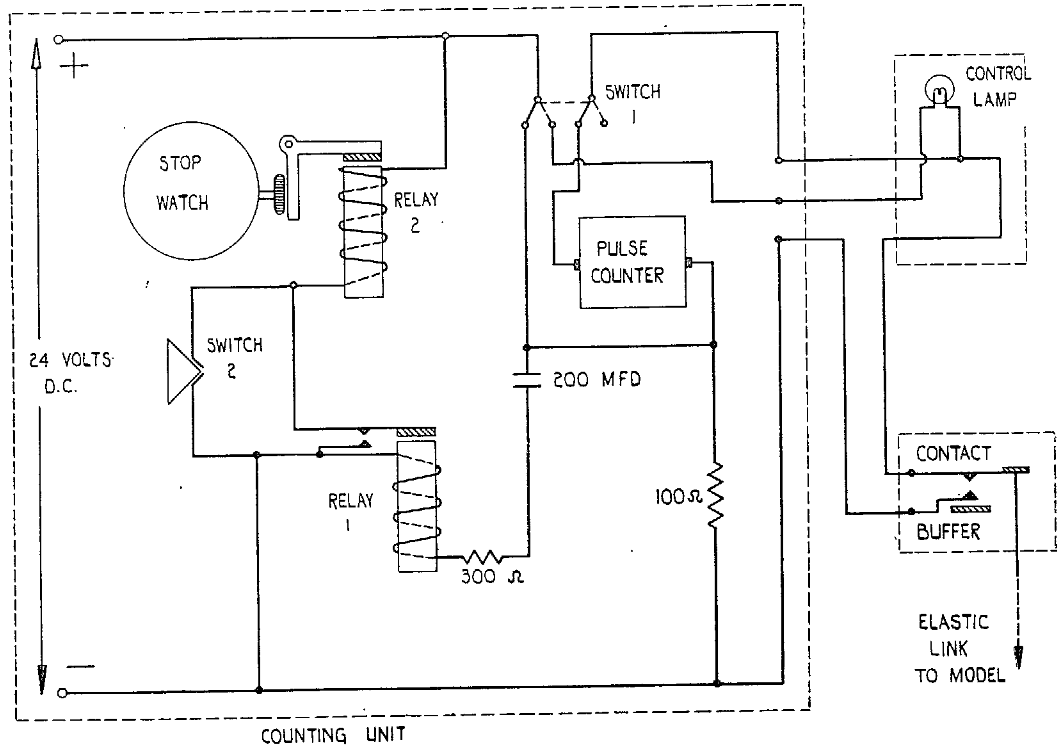


Fig. 7. Arrangement for measuring frequency.

Wt. 17/680 K.9 2/55 G.G. 34-262



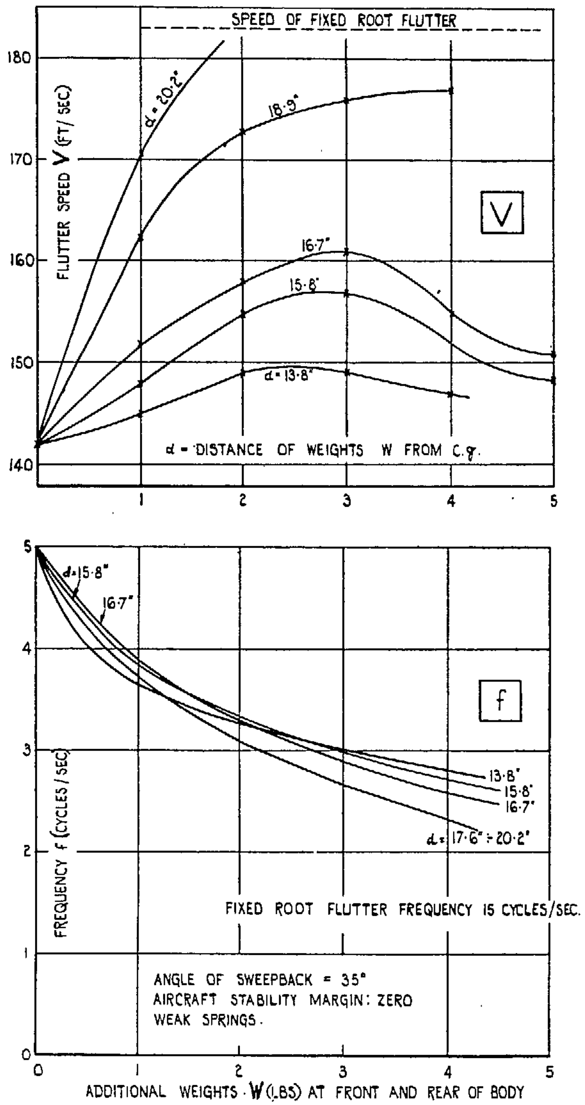


FIG. 8. Typical wind-tunnel results.

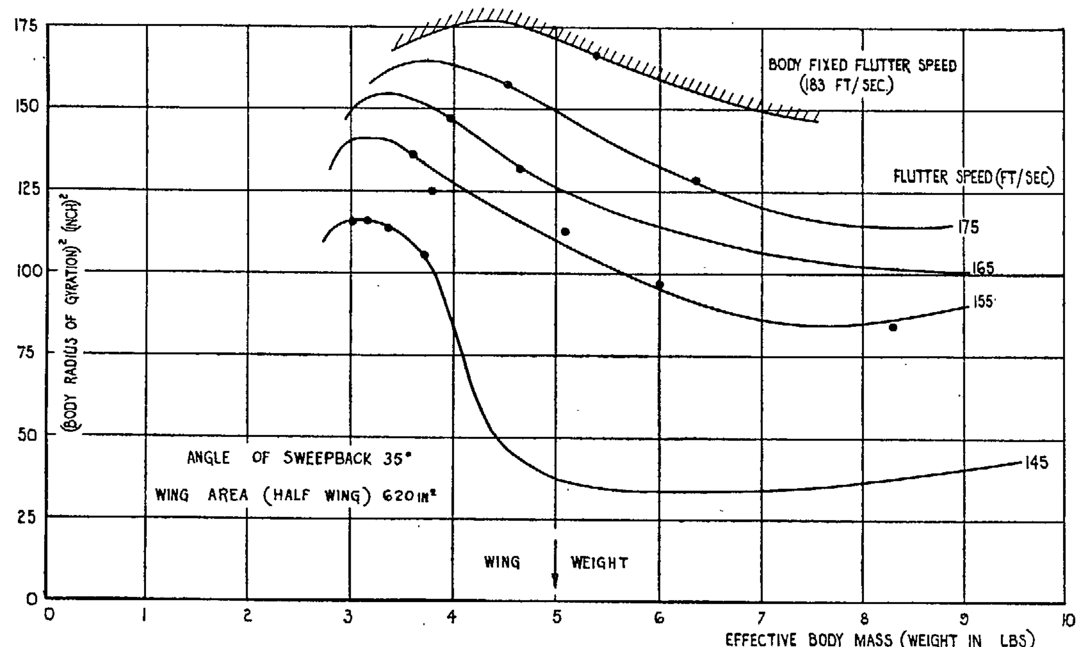


FIG. 9. Wind-tunnel results after including equivalent spring masses.

PRINTED IN GREAT BRITAIN

# Publications of the Aeronautical Research Council

## ANNUAL TECHNICAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL (BOUND VOLUMES)

1936 Vol. I. Aerodynamics General, Performance, Airscrews, Flutter and Spinning. 40*s.* (41*s.* 1*d.*)
Vol. II. Stability and Control, Structures, Seaplanes, Engines, etc. 50*s.* (51*s.* 1*d.*)

1937 Vol. I. Aerodynamics General, Performance, Airscrews, Flutter and Spinning. 40*s.* (41*s.* 1*d.*)
Vol. II. Stability and Control, Structures, Seaplanes, Engines, etc. 60*s.* (61*s.* 1*d.*)

1938 Vol. I. Aerodynamics General, Performance, Airscrews. 50*s.* (51*s.* 1*d.*)
Vol. II. Stability and Control, Flutter, Structures, Seaplanes, Wind Tunnels, Materials. 30*s.* (31*s.* 1*d.*)

1939 Vol. I. Aerodynamics General, Performance, Airscrews, Engines. 50*s.* (51*s.* 1*d.*)
Vol. II. Stability and Control, Flutter and Vibration, Instruments, Structures, Seaplanes, etc. 63*s.* (64*s.* 2*d.*)

1940 Aero and Hydrodynamics, Aerofoils, Airscrews, Engines, Flutter, Icing, Stability and Control, Structures, and a miscellaneous section. 50*s.* (51*s.* 1*d.*)

1941 Aero and Hydrodynamics, Aerofoils, Airscrews, Engines, Flutter, Stability and Control, Structures. 63*s.* (64*s.* 2*d.*)

1942 Vol. I. Aero and Hydrodynamics, Aerofoils, Airscrews, Engines. 75*s.* (76*s.* 3*d.*)
Vol. II. Noise, Parachutes, Stability and Control, Structures, Vibration, Wind Tunnels. 47*s.* 6*d.* (48*s.* 7*d.*)

1943 Vol. I. Aerodynamics, Aerofoils, Airscrews. 80*s.* (81*s.* 4*d.*)
Vol. II. Engines, Flutter, Materials, Parachutes, Performance, Stability and Control, Structures. 90*s.* (91*s.* 6*d.*)

1944 Vol. I. Aero and Hydrodynamics, Aerofoils, Aircraft, Airscrews, Controls. 84*s.* (85*s.* 8*d.*)
Vol. II. Flutter and Vibration, Materials, Miscellaneous, Navigation, Parachutes, Performance, Plates and Panels, Stability, Structures, Test Equipment, Wind Tunnels. 84*s.* (85*s.* 8*d.*)

## Annual Reports of the Aeronautical Research Council—

| | | | |
|---|---|---|---|
| 1933–34 | 1*s.* 6*d.* (1*s.* 8*d.*) | 1937 | 2*s.* (2*s.* 2*d.*) |
| 1934–35 | 1*s.* 6*d.* (1*s.* 8*d.*) | 1938 | 1*s.* 6*d.* (1*s.* 8*d.*) |
| April 1, 1935 to Dec. 31, 1936 | 4*s.* (4*s.* 4*d.*) | 1939–48 | 3*s.* (3*s.* 2*d.*) |

## Index to all Reports and Memoranda published in the Annual Technical Reports, and separately—

April, 1950 R. & M. No. 2600. 2*s.* 6*d.* (2*s.* 7½*d.*)

## Author Index to all Reports and Memoranda of the Aeronautical Research Council—

1909–1954. R. & M. No. 2570. 15*s.* (15*s.* 4*d.*)

## Indexes to the Technical Reports of the Aeronautical Research Council—

| | | |
|---|---|---|
| December 1, 1936 — June 30, 1939. | R. & M. No. 1850. | 1*s.* 3*d.* (1*s.* 4½*d.*) |
| July 1, 1939 — June 30, 1945. | R. & M. No. 1950. | 1*s.* (1*s.* 1½*d.*) |
| July 1, 1945 — June 30, 1946. | R. & M. No. 2050. | 1*s.* (1*s.* 1½*d.*) |
| July 1, 1946 — December 31, 1946. | R. & M. No. 2150. | 1*s.* 3*d.* (1*s.* 4½*d.*) |
| January 1, 1947 — June 30, 1947. | R. & M. No. 2250. | 1*s.* 3*d.* (1*s.* 4½*d.*) |
| July, 1951. | R. & M. No. 2350. | 1*s.* 9*d.* (1*s.* 10½*d.*) |
| January, 1954. | R. & M. No. 2450. | 2*s.* (2*s.* 1½*d.*) |
| July, 1954. | R. & M. No. 2550. | 2*s.* 6*d.* (2*s.* 7½*d.*) |

*Prices in brackets include postage*

Obtainable from

HER MAJESTY'S STATIONERY OFFICE

York House, Kingsway, London, W.C.2; 423 Oxford Street, London, W.1 (Post Orders: P.O. Box 569, London, S.E.1); 13a Castle Street, Edinburgh 2; 39 King Street, Manchester 2; 2 Edmund Street, Birmingham 3; 109 St. Mary Street, Cardiff; Tower Lane, Bristol 1; 80 Chichester Street, Belfast, or through any bookseller

S.O. Code No. 23-2893