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The Aerodynamic Effects of Aspect Ratio on Flutter of Unswept Wings

By

W. G. MOLYNEUX, B.Sc., and E. W. CHAPPLE

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Summary.—The report describes a method for the direct measurement of the aerodynamic effects of aspect ratio on wing flutter. The method requires the use of stiff (virtually rigid) wings flexibly mounted at the root.

Details are given of tests on untapered, unswept wings with freedoms in modes of linear flexure and uniform pitch. A comparison is made between measured values of the flutter characteristics and the values calculated using an aerodynamic theory for oscillating wings of finite aspect ratio, and reasonable agreement for flutter speeds and frequencies is obtained.

1. *Introduction.*—For typical aircraft wings change of aspect ratio affects the flutter characteristics in a number of ways. Thus two wings having different aspect ratios will normally differ in aerodynamic, inertia, and stiffness properties. For many purposes, however, it is desirable to have a good general indication of the aerodynamic effects of aspect ratio alone.

This report describes experiments made to establish these aerodynamic effects. Their segregation from the other effects, however, presents a certain amount of difficulty; and it is shown to be necessary to use arbitrary simplified wings for the experiments. These wings are virtually rigid, but are supported flexibly at the root.

For such wings the purely aerodynamic effects of aspect ratio can readily be determined by experiment. The results obtained, of course, do not necessarily apply to flexible wings, but they give a good general indication of the effects to be expected. They also provide data for comparison with aerodynamic theories for wings of finite aspect ratio, *e.g.*, those of Dingel and Küssner[3] (1943) and of Jones[4] (1943).

2. *Basis of the Technique.*—2.1. *General Considerations.*—The flutter equations of motion written in matrix form are :—

$$\left[-(a+\gamma)\omega^2 + ib\frac{V}{c_m}\omega + c\frac{V^2}{c_m^2} + e \right] q = 0 \qquad (1)$$

where a, e are matrices of structural inertia and elastic coefficients

γ, b, c matrices of aerodynamic inertia, damping and stiffness coefficients

ω is the flutter frequency

V flutter speed

c_m wing mean chord

q column matrix of generalised co-ordinates.

* R.A.E. Report Structures 135, received 5th February, 1953.

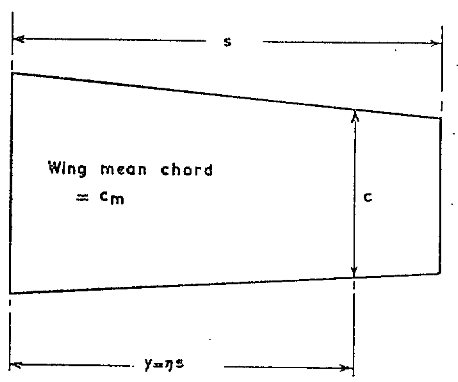
Structural damping terms are not included in the above equations, it being assumed that for a conventional structure the damping is small and the effect on flutter characteristics is negligible.

Obviously, two wings for which the ratio of corresponding coefficients is constant will have equal values of ω and V/c_m. Now suppose there are two wings of different aspect ratio for which the ratio of corresponding coefficients is constant *with the aerodynamic coefficients computed using two-dimensional aerodynamic theory**. Also, there are no other differences that might conceivably affect the flutter characteristics that are not taken account of in the flutter equations. The calculated flutter characteristics, based on two-dimensional theory, will be the same for both wings but the measured flutter characteristics will differ because of the effects of finite aspect ratio on the air forces. From tests on a series of such wings with a wide range of aspect ratios a direct measurement of the effects of aspect ratio on flutter can be obtained. The basic requirement of this technique is therefore that the ratio of corresponding coefficients of any two wings, as computed using two-dimensional aerodynamic theory, must be constant.

2.2. *Detailed Requirements.*—The implications of this basic requirement are now considered in detail. For simplicity the analysis is limited to a system with only two degrees of freedom, but the same arguments apply to other systems. The equations of motion written in full are :—

$$\left.\begin{aligned} &\left\{-(a_{11}+\gamma_{11})\omega^2 + ib_{11}\frac{V}{c_m}\omega + c_{11}\frac{V^2}{c_m^{\,2}} + e_{11}\right\}q_1 \\ &+\left\{-(a_{12}+\gamma_{12})\omega^2 + ib_{12}\frac{V}{c_m}\omega + c_{12}\frac{V^2}{c_m^{\,2}} + e_{12}\right\}q_2 = 0 \\ &\left\{-(a_{21}+\gamma_{21})\omega^2 + ib_{21}\frac{V}{c_m}\omega + c_{21}\frac{V^2}{c_m^{\,2}} + e_{21}\right\}q_1 \\ &+\left\{-(a_{22}+\gamma_{22})\omega^2 + ib_{22}\frac{V}{c_m}\omega + c_{22}\frac{V^2}{c_m^{\,2}} + e_{22}\right\}q_2 = 0 \end{aligned}\right\} \quad \ldots \quad (2)$$

Wing freedoms in modes of bending and torsion are chosen and the nodal line for the torsion mode is taken as the reference axis :



f is the bending mode of reference axis with unit value at wing tip

F ,, twisting mode about reference axis with unit value at wing tip

ω_{11} ,, frequency of bending mode

ω_{22} ,, frequency of twisting mode

ρ ,, air density.

* This implies that the aspect ratio of both wings is considered to be infinite.

The expressions for the coefficients are :

Aerodynamic

$$
\begin{aligned}
&\textit{Inertia} && \textit{Damping} && \textit{Stiffness} \\
&\gamma_{11} = \int \left(\frac{c}{c_m}\right)^2 f^2 l_{\ddot{z}}\, d\eta && b_{11} = \int \left(\frac{c}{c_m}\right) f^2 l_{\dot{z}}\, d\eta && c_{11} = \int f^2 l_z\, d\eta \\
&\gamma_{12} = \int \left(\frac{c}{c_m}\right)^3 fF l_{\ddot{\alpha}}\, d\eta && b_{12} = \int \left(\frac{c}{c_m}\right)^2 fF l_{\dot{\alpha}}\, d\eta && c_{12} = \int \left(\frac{c}{c_m}\right) fF l_\alpha\, d\eta \\
&\gamma_{21} = -\int \left(\frac{c}{c_m}\right)^3 fF m_{\ddot{z}}\, d\eta && b_{21} = -\int \left(\frac{c}{c_m}\right)^2 fF m_{\dot{z}}\, d\eta && c_{21} = -\int \left(\frac{c}{c_m}\right) fF m_z\, d\eta \\
&\gamma_{22} = -\int \left(\frac{c}{c_m}\right)^4 F^2 m_{\ddot{\alpha}}\, d\eta && b_{22} = -\int \left(\frac{c}{c_m}\right)^3 F^2 m_{\dot{\alpha}}\, d\eta && c_{22} = -\int \left(\frac{c}{c_m}\right)^2 F^2 m_\alpha\, d\eta
\end{aligned}
\quad \ldots \quad (3)
$$

$l_{\ddot{z}}$, $l_{\ddot{\alpha}}$, $m_{\ddot{z}}$, $m_{\ddot{\alpha}}$, etc., are the two-dimensional aerodynamic derivatives referred to the reference axis.

Structural

$$
\begin{aligned}
&\textit{Inertia} && \textit{Stiffness} \\
&a_{11} = \frac{1}{\rho c_m^{\,2}} \int f^2 m\, d\eta && e_{11} = a_{11}\omega_{11}^{\,2} \\
&a_{12} = a_{21} = \frac{1}{\rho c_m^{\,3}} \int fFm\bar{x}\, d\eta && e_{12} = e_{21} = 0 \\
&a_{22} = \frac{1}{\rho c_m^{\,4}} \int F^2 m K^2\, d\eta && e_{22} = a_{22}\omega_{22}^{\,2}
\end{aligned}
\quad \ldots \quad (4)
$$

m is the mass per unit span, $m\bar{x}$ is the mass moment per unit span about the reference axis, mK^2 is the mass moment of inertia per unit span about the reference axis.

The detailed requirements are derived as follows :

(*a*) When the basic requirement of section 2.1 is satisfied, the calculated values of ω and V/c_m based on two-dimensional theory will be the same for all wings. Now the aspect ratio of a given wing plan form (defined as $2s/c_m$) can be increased either by a reduction of the wing mean chord or an increase in the wing span. However, since the calculated V/c_m will be the same for all the wings the calculated flutter speeds of the different wings will vary directly as the mean chords. Different flutter speeds involve different conditions of Reynolds number and compressibility*, and in order to exclude all but aspect ratio effects it is essential that the wings should have the same calculated flutter speeds. Therefore all wings must have the same value of wing mean chord.

(*b*) If the wings have different taper ratios the spanwise distribution of local frequency parameter, $\omega c/V$ will vary from wing to wing. This may introduce an effect not allowed for in the equations based on two-dimensional theory, and by the general requirements of the technique (*see* section 2.1) any such possible effect must be avoided. This can be done by giving all the wings the same taper ratio, *i.e.*, the value of c/c_m at a section η from the wing root must be the same for all the wings.

* This fact might be used to investigate compressibility effects on flutter.

(*c*) In the same way, to avoid any effects on flutter due to different modes, corresponding modes must be identical for all the wings.

(*d*) The local values of the aerodynamic derivatives for two-dimensional incompressible flow depend only on the local frequency parameter and the reference-axis position relative to the wing leading edge. Since the wing modes and the spanwise distribution of frequency parameter are the same for all wings the values of corresponding derivatives will be equal for equal wing chords. Referring to the expressions for the aerodynamic coefficients, it is apparent that with the above requirements satisfied the ratio of corresponding aerodynamic coefficients for the different wings is unity.

(*e*) Since the ratio of corresponding coefficients must be constant throughout, the ratio of corresponding structural coefficients must also be unity. To satisfy this condition for the inertia coefficients, all the wings must have the same local values of wing mass, mass moment and mass moment of inertia per unit span. The ratio of corresponding stiffness coefficients is then unity when the frequencies of corresponding modes are equal.

To summarise, the detailed requirements are :

(i) The wings must have the same taper ratio and the same mean chord, aspect ratio being varied by varying the span.

(ii) The mass, mass moment and mass moment of inertia per unit span at a wing section η from the root must be the same for all the wings.

(iii) Corresponding modes must be identical.

(iv) The frequencies of corresponding modes must be equal.

With these requirements satisfied the ratio of corresponding coefficients for the different wings is unity and all the wings have the same calculated flutter characteristics ; in particular the calculated flutter speeds will be equal.

2.3. *Interpretation of the Requirements.*—The first of the above requirements specifies that aspect ratio must be varied by varying the span, but it is apparent that this can be achieved by varying wing dimensions in a direction either normal to the root or along an inclined axis. In Fig. 1 three sets of wings which satisfy the requirements are shown. Figs. 1a and 1b show sets of untapered-unswept and tapered-unswept wings for which dimensions normal to the root have been varied, and Fig. 1c shows a set of swept wings for which dimensions along the axis of sweepback have been varied. It should be noted that for wings 1b the sweep angles of the wing leading and trailing edges vary with aspect ratio. This may have an effect on flutter additional to the effects of aspect ratio, but for these wings any such effect is likely to be small by comparison with the aspect ratio effects. For wings 1a there are no sweepback effects and for wings 1c the sweepback effects are constant.

The second requirement may be interpreted that the wing structure must be homogeneous, with the spanwise dimensions of all components of the structure varying as the wing span. This would be difficult to satisfy for a conventional stressed skin structure since rib thickness, etc., would have to vary as the span. The requirement is most easily satisfied by a solid wing structure, *e.g.*, a solid wood or metal wing.

The third requirement, affecting modes, might possibly be satisfied for flexible wings with plan forms shown in Fig. 1, but would be very difficult to satisfy for plan forms such as a delta, where wings of different aspect ratio have a different distribution of stress at the wing root. It might be possible to satisfy the requirement by building the wing with a segmented structure, but undoubtedly the requirement is most easily satisfied by using rigid wings with prescribed flexibilities provided at the root.

The fourth requirement is impossible to satisfy for flexible wings if the preceding requirements are also to be satisfied, as the modal frequencies for wings of homogeneous construction using similar materials decrease as the wing span increases. It would be very difficult to satisfy for a segmented wing because of the intricate adjustment of stiffness that would be required, but it is readily satisfied using rigid wings as the stiffnesses at the root are easily adjusted to provide the required modal frequencies.

Therefore, in practice, the proposed technique is mainly applicable to rigid wings with prescribed root flexibilities. The results obtained are of limited value in their application to flexible wings, but they provide useful data for comparisons with aerodynamic theories for wings of finite aspect ratio.

It is to be noted that the inertia coefficients for rigid wings with root flexibilities reduce to the moments of inertia of the wings in the prescribed modes divided by air density and appropriate powers of the span and chord. For instance, a rigid wing with roll and pitch freedoms has the following coefficients :

$$a_{11} = \frac{I_R}{\rho c_m{}^2 s^3}$$

$$a_{12} = a_{21} = \frac{I_{RP}}{\rho c_m{}^3 s^2}$$

$$a_{22} = \frac{I_P}{\rho c_m{}^4 s}$$

where I_R is the moment of inertia about the roll axis, I_{RP} is the product of inertia about the roll and pitch axes and I_P is the moment of inertia about the pitch axis.

3. *Flutter Tests on Untapered, Unswept Rigid Wings with Roll and Pitch Freedoms.*—To illustrate the method, details are given of flutter tests, in the Royal Aircraft Establishment 5-ft diameter Open-Jet Wind Tunnel, on a series of vertically mounted half-span wings with freedoms in modes of linear flexure (*i.e.*, roll of the half-wing with a reflector plate to simulate the symmetric air flow conditions) and uniform pitch. The wing aspect ratios ranged from two to six, aspect ratio being defined as $2s/c$, where c is the wing chord.

3.1. *Description of Rig.*—The layout of the rig is shown diagrammatically in Fig. 2. The wing root was $0 \cdot 075s$ above the roll axis, and the pitch axis was $0 \cdot 35c$ aft of the leading edge. Torsion bars of adjustable length on these axes provided the required stiffnesses, and sliding weights enabled adjustment of the roll and pitch inertias. The wing mounting was designed so that its total product of inertia about the roll and pitch axes was zero, and the wings were of solid construction designed so that their inertia characteristics varied in the required manner. Since the mounting contributed to the direct inertias a means of adjusting these inertias was required, but a means of adjusting product of inertia was not provided. Cross-spring bearings were used on the roll and pitch axes so that friction damping was reduced to a minimum.

3.2. *Test Procedure.*—3.2.1. *Adjustment of the structural coefficients.*—The inertias of the rig (wing and mounting) about the axes of roll and pitch were determined from laboratory tests, and were adjusted, using the sliding weights, to vary as $(s)^3$ and (s) respectively. The uncoupled frequencies of the rig in roll and pitch were measured by disturbing the rig in one freedom, with the other locked, and counting the cycles of the decaying oscillation by an electrical recorder over a time interval of about one hundred cycles of oscillation. The fact that such a large number of cycles could be counted indicates the low structural damping present in the rig. The torsion bars were adjusted so that the frequencies of corresponding modes were the same for all wings.

Six different sets of wings having different natural frequencies were investigated, and the corresponding values of the inertias are given in Table 1.

3.2.2. *Wind-tunnel measurements.*—A pitot traverse was made above the reflecting plate on which the rig was mounted, and showed the flow to be reasonably uniform at the wing position (*see* Fig. 3). The flutter speed and frequency of each wing were measured, and photographs of the motion of the wing tip during flutter were taken using a ciné-camera mounted vertically above the wing. This record provided a means of obtaining the amplitudes and phase relationships of the roll and pitch modes. For these tests the camera was used for only one set (roll frequency 4·0 c.p.s., pitch frequency 14·2 c.p.s.). It was found that the photographs of the wing tip were blurred due to the exposure time of the camera being too large, and phase angles could not be determined to an accuracy greater than about $\pm$ 4 deg.

3.3. *Discussion of Results.*—The results of the tests are plotted in Figs. 4 and 5. It can be seen that as the aspect ratio decreases the flutter speed increases, the flutter frequency remaining approximately constant. For the particular set investigated, the ratio (angle of roll) : (angle of pitch) and the phase angle between roll and pitch both increase as aspect ratio decreases. The rate of change of flutter speed with aspect ratio appears to be independent of the wing modal frequencies, for the range investigated, and is given approximately by :

$$V = V_0\left(1 + \frac{0 \cdot 78}{A}\right) \qquad \ldots \qquad (5)$$

where V is the flutter speed

V_0 ,, calculated flutter speed for infinite aspect ratio wing

A ,, aspect ratio.

It might be possible to use this expression in the flutter speed criterion proposed by Collar, Broadbent and Puttick[2] (1946) for flexible wings. The rate of increase of flutter speed with decrease of aspect ratio should be less for a rigid wing fluttering in modes of linear flexure and uniform pitch than for a flexible wing of the same aspect ratio fluttering primarily in modes of fundamental bending and torsion, and the expression (5) should therefore give a conservative value for the flutter speed of a flexible wing.

It should be noted that expression (5) for the variation of flutter speed with aspect ratio also includes a contribution due to effects of the change of frequency parameter on flutter. Obviously, since the flutter speed changes with aspect ratio, whereas the flutter frequency does not, there is a change of flutter-frequency parameter, and this may have an effect on flutter characteristics which is distinct from the aspect ratio effects. However, for these wings the frequency parameter changes by about 25 per cent for the range of aspect ratio considered and the effect is likely to be small when compared with the aspect ratio effects.

4. *Theoretical Investigation.*—The aerodynamic coefficients for the wings were evaluated using the theory proposed by Dingel and Küssner[3] (1943) for oscillating wings of finite aspect ratio. The theory is based on lifting-line theory, as distinct from the lifting-surface theory adopted by Jones[4] (1943), and is intended to apply to aerofoils of 'large' aspect ratio. However, a limiting aspect ratio is not specified and it was thought that these tests would provide a convenient means of assessing the range of aspect ratio over which the theory could be applied.

The solutions of the flutter equations were obtained using an electronic simulator (*see* Smith and Hicks[5] (1950)), and an accurate balance of the frequency parameter initially assumed and that obtained from the solution was achieved in every case. The results are shown, together with the measured results, in Figs. 4 and 5. The measured and calculated flutter speeds are in reasonable agreement over the complete range of aspect ratio investigated. They agree very closely for the wings of largest aspect ratio but the agreement becomes less close as the aspect ratio decreases. The theoretical curves of flutter speed are linear with the reciprocal of aspect ratio and are given very closely by :

$$V = V_0\left(1 + \frac{0 \cdot 67}{A}\right). \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (6)$$

The calculated flutter frequency is lower than the measured frequency and ranges from about 90 per cent of the measured value for the wing of aspect ratio 6 to 80 per cent for the wing of aspect ratio 2.

The greatest discrepancies occur between measured and calculated amplitude ratios and phase angles (*see* Fig. 5). The curves of amplitude ratios show the same general trends with change of aspect ratio, but the calculated values are about 65 per cent greater than those measured. The curves of phase angles show that the measured phase angle increases as the aspect ratio decreases, whereas the calculated phase angle falls slightly. There is no obvious explanation for these discrepancies but they could be explained by large differences in the theoretical and experimental values of particular aerodynamic derivatives. For instance, further calculations in which the theoretical values of the leading-edge derivative $l_{\dot{\alpha}}$ (lift due to rate of change of incidence) were increased by 50 per cent gave amplitude ratios which were in good agreement with experiment, and improved the agreement of flutter frequencies and phase angles. However, the calculated flutter speeds were about 5 per cent lower than their original values.

The comparison does not indicate any definite limiting aspect ratio beyond which the theory of Dingel and Küssner is inapplicable. However, this does not necessarily imply that the theory would give equally good results for flexible wings of such small aspect ratio as are considered here.

5. *Conclusions.*—A direct measurement of the aerodynamic effects of aspect ratio on the flutter of rigid wings with root flexibilities can be obtained by the method described.

Tests on untapered, unswept wings with freedoms in roll and pitch show that their flutter speeds are given quite closely by :

$$V = V_0\left(1 + \frac{0 \cdot 78}{A}\right) .$$

where V is the flutter speed

V_0 ,, calculated flutter speed for wing of infinite aspect ratio

A ,, aspect ratio.

A comparison of the measured results with those calculated using the Dingel and Küssner aerodynamic theory for wings of finite aspect ratio shows reasonable agreement for flutter speeds and frequencies. The agreement for amplitude ratios and phase angles is poor.

Acknowledgment.—Acknowledgments are due to Dr. P. F. Jordan, R.A.E., for the determination of the aerodynamic coefficients for these wings from the Dingel and Küssner theory.

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TABLE 1

Structural Details

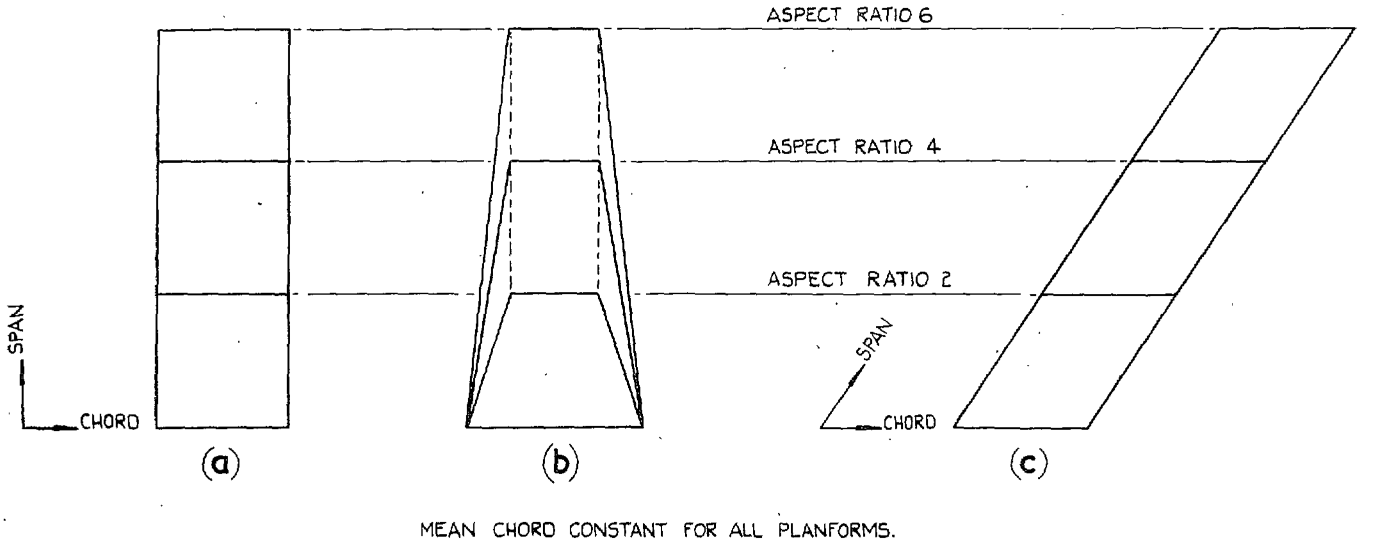
Wing chord = 0·5 ft

Wing thickness/chord = 0·10

Wing section = RAE 101

Wing No.	Wing span s (in.)	Inertias Wing + mounting (lb in.^{2})		
		Roll inertia	Roll-pitch cross inertia	Pitch inertia
1	6	3·6	0·175	0·40
2	7	5·8	0·240	0·47
3	8	8·3	0·315	0·53
4	9	11·7	0·395	0·60
5	10	16·6	0·490	0·67
6	12	27·8	0·705	0·79
7	15	55·1	1·100	1·00
8	18	93·6	1·590	1·20

Wing frequencies { Roll 4·0, 5·5 cycles/second; Pitch 11·0, 12·5, 14·2 cycles/second



FIGS. 1a, 1b and 1c. Wing geometry for various plan forms.

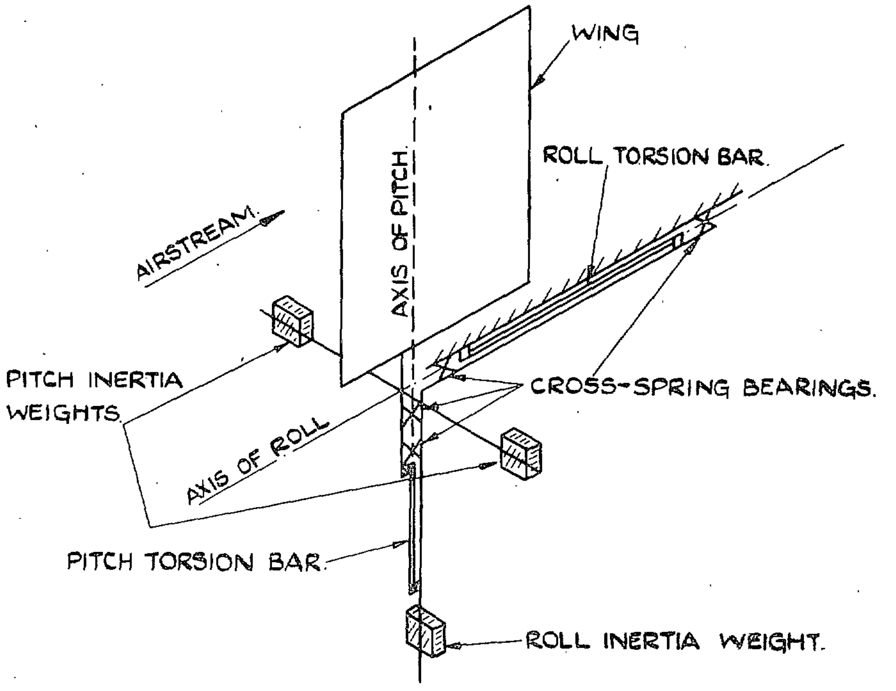


FIG. 2. Layout of rig for wing freedoms in roll and pitch.

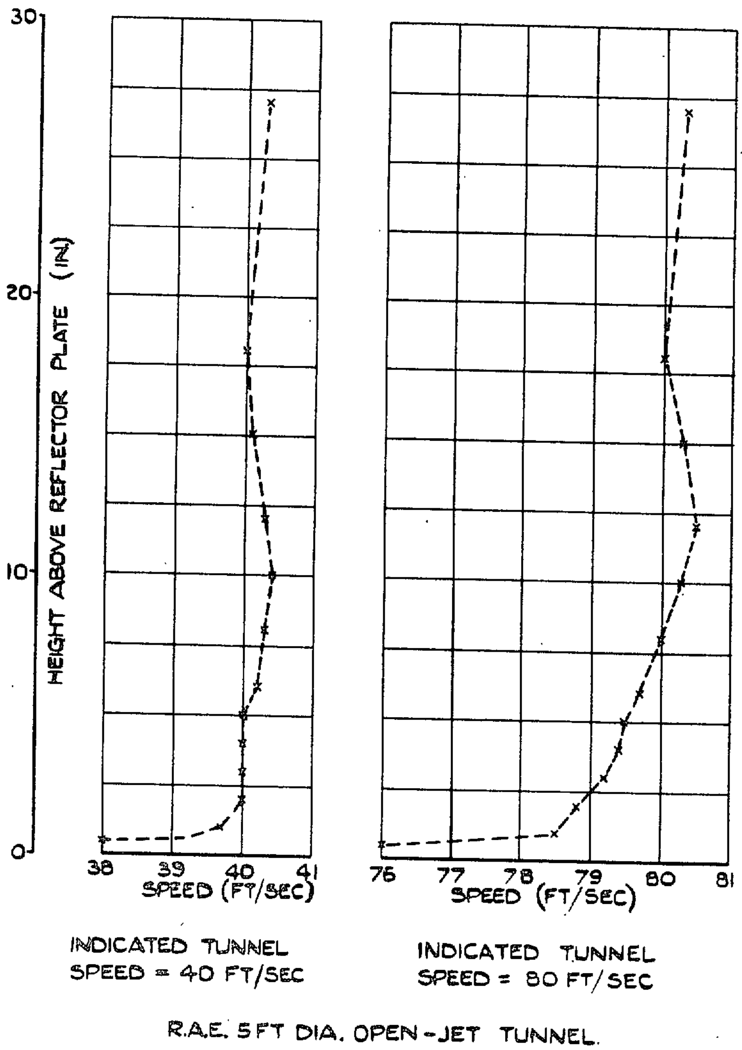


FIG. 3. Velocity distribution at wing position.

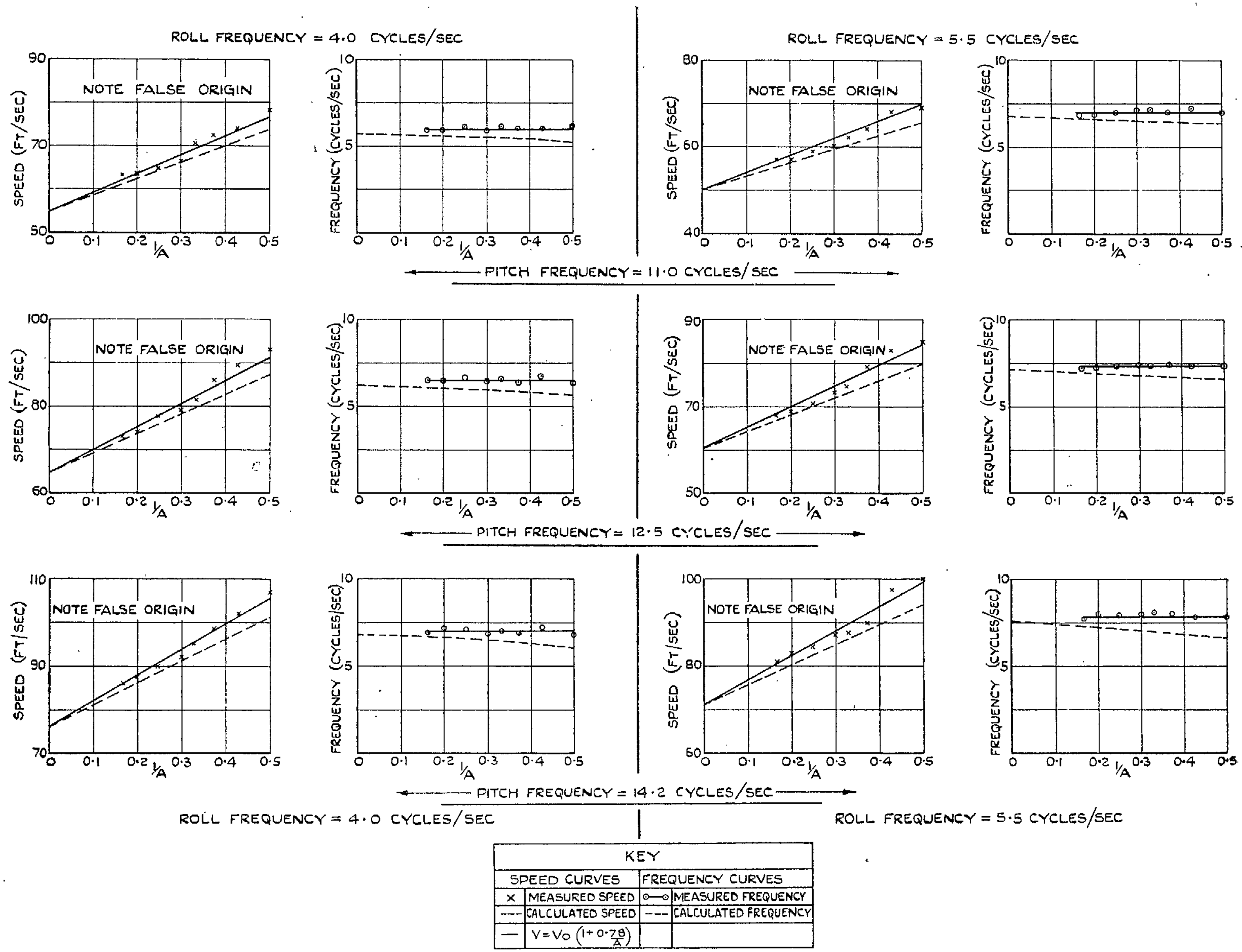


FIG. 4. The effect of aspect ratio on flutter speed and frequency.

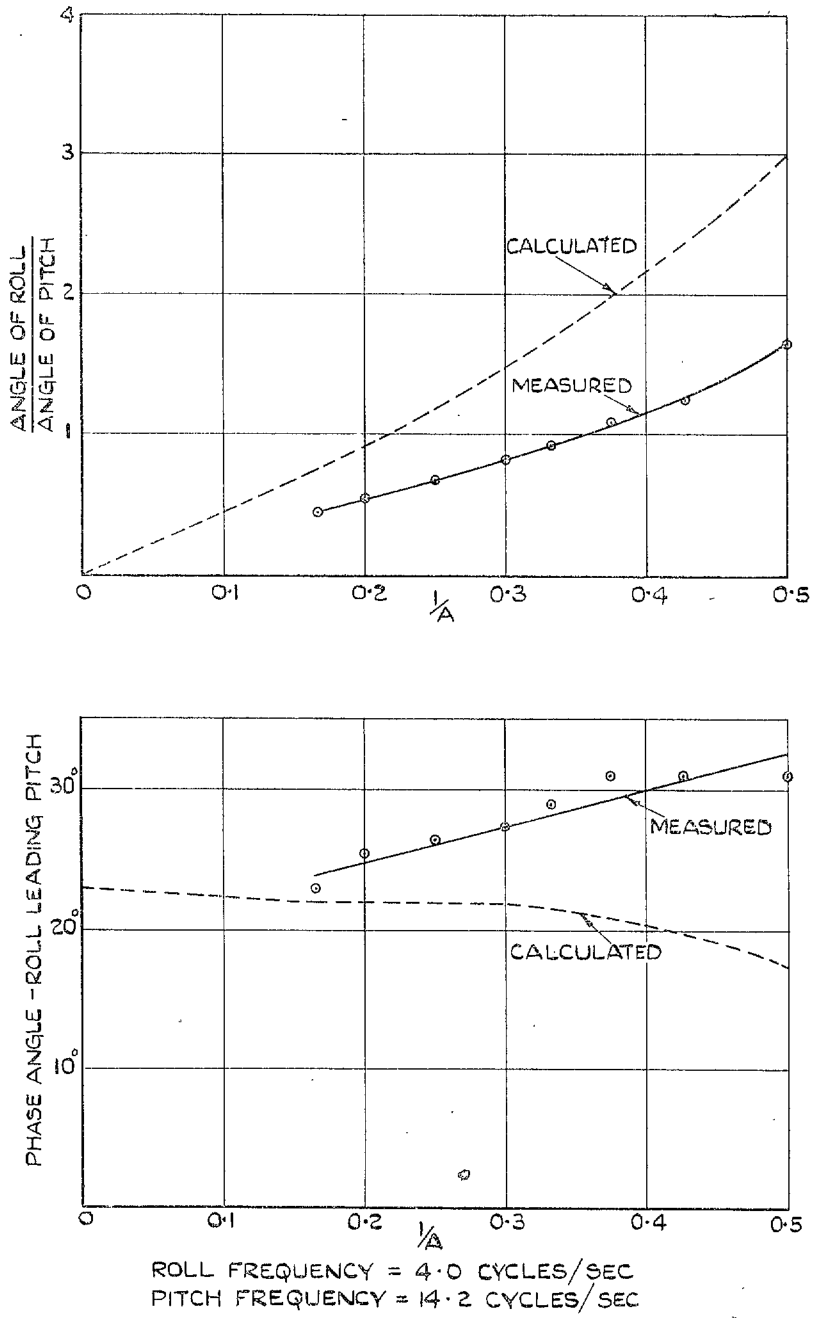


FIG. 5. The effect of aspect ratio on amplitude ratio and phase angle.

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