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# Body Freedom Flutter of Ground-Launched Rocket Models at Supersonic and High Subsonic Speeds

*By*

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# Body Freedom Flutter of Ground-Launched Rocket Models at Supersonic and High Subsonic Speeds

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COMMUNICATED BY THE DIRECTOR-GENERAL OF SCIENTIFIC RESEARCH (AIR)
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*Summary.*—A theoretical investigation of symmetric body freedom flutter of a rocket model is described. The results confirm that structural failures of models were caused by this type of flutter, and an extension of the investigation indicates the parameters that are of importance. A high ratio of body to wing mass and a well forward position of the overall centre of gravity are conditions under which flutter may occur. Increase of body pitching radius of gyration and tailplane volume are beneficial.

It is concluded that this type of flutter may be significant in some aircraft designs, and that the canard has no advantage in this respect over the conventional lay-out of wing and tailplane.

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1. *Introduction.*—Evidence from various sources has indicated that symmetric body freedom flutter may be critical for wing-body-tailplane configurations in which the mass and pitching moment of inertia of the body are large in relation to the wing values. Wind-tunnel tests have shown[1] that an increase in the value of the ratio of body to wing pitching moment of inertia tends to eliminate body freedom flutter, but these tests did not cover sufficiently high values to be applicable to the configurations considered here.

The present report gives the results of a limited theoretical investigation of the subject. Several Royal Aircraft Establishment ground-launched rocket flutter models have failed in flight following low-frequency divergent oscillations, and a typical model is the subject of the investigation. The calculations confirm that symmetric body freedom flutter was the probable cause of failure, and the investigation was extended to include variations in the more important parameters. Since the aim of the calculations was primarily to indicate a remedy for a particular case of body freedom flutter certain aerodynamic effects (mentioned in Section 3) were ignored. Clearly in any comprehensive investigation allowance should be made for these effects.

The conclusions reached are that this type of flutter is of practical importance in designs where the fuselage inertia properties are large in relation to those of the wings. The foreplane arrangement has no advantage over the tailplane in this respect, but for either arrangement aft movement of the overall centre of gravity is beneficial.

2. *Basis of Investigation.*—The analysis of telemetry records from the testing of five ground-launched rocket flutter models showed that four of the models had failed in flight at speeds between 1400 and 1800 ft/sec as a result of low-frequency divergent oscillations. The models

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* R.A.E. Report Structures 227, received 6th March, 1958.

were under test to provide information on the flutter of wings with ailerons, and the frequencies of the oscillations leading to failure were too low to be explainable on the basis of wing-aileron flutter. The possibility of symmetric body freedom flutter having occurred appeared to be unlikely, in view of the very large pitching moment of inertia of the rocket body compared to that of the wing[1], but at about this time a flutter analysis made on the *Jindivik* radio-controlled target aircraft in Australia[2, 3] showed that body freedom flutter was likely to be critical for body parameters outside the range investigated in Ref. 1. More recently, two free-flight drag models, tested by the R.A.E., failed under conditions suggestive of body freedom flutter. One of these models was of canard lay-out. A much earlier experimental and theoretical investigation of body freedom flutter of a rocket propelled vehicle has been made by Cunningham and Lundstrom (1950)[4]. They obtained symmetric body freedom flutter on two vehicles and confirmed the results theoretically.

A common feature of these cases was the large ratio of fuselage to wing pitching moment of inertia. Low-speed wind-tunnel tests[1] have shown that relatively large values of this ratio can suppress body freedom flutter. The wind-tunnel tests, however, were confined to ratios appropriate to aircraft which were either flying or in the design stage at the time the tests were made in 1951. The very much higher ratios occurring now in aircraft, and those of some rocket test vehicles were not included in the tests. For instance, the maximum value of the ratio of the pitching moments of inertia of the body to the wing in the wind-tunnel tests of Ref. 1 was 12 : 1, whereas in the ground-launched rocket flutter models mentioned above the ratio was nearly 30 : 1. Similarly the ratio of body mass to wing mass in the models was much greater than had been covered by wind-tunnel tests.

In the *Jindivik* analysis[2] and that of Cunningham and Lundstrom[4] one of the parameters investigated was the position of the aircraft centre of gravity; this was found to be of considerable significance in its effect on the body freedom type of flutter. It is, moreover, a parameter that is initially variable over a wide range in rocket flutter tests. In view of this a theoretical investigation was made at the R.A.E.; a typical rocket flutter test vehicle was chosen for the calculations and, in the first instance, the effect of variation of the centre-of-gravity position was investigated. As the results agreed broadly with the experimental evidence available, and also with the trends shown in Refs. 2 and 4, the investigation was extended to include variation of tailplane volume coefficient and variation of tailplane plan-form. The canard lay-out was also investigated.

3. *Details of Calculations.*—The lay-out of the rocket flutter test vehicle on which the calculations were based is shown in Fig. 1. The vehicle consists of a 5-in. boost motor to which the wings are clamped. A telemetry transmitter is carried at the nose of the boost and standard four-fin tail units are attached to the venturi such that two of the fins are in the wing plane. The telemetry transmitter and tail fins are fixed relative to the boost motor, but in assembly the wings may be clamped anywhere on the motor. The actual fore and aft positioning of the wings is governed by two considerations; firstly, that an adequate margin of static stability shall be provided, and secondly, that the wings shall be spaced sufficiently far from the tail fins to avoid excessive aerodynmaic interaction. In practice, it is usual for the wings to be attached so that the overall centre of gravity lies forward of the wing leading edge. In the past, no particular importance has been attached to the degree of static stability, and there has been a tendency to have a large static margin in order to ensure an undisturbed flight path in the test.

The model wings (Fig. 1) have a semi-span (measured from the side of the boost motor to the tip) of 2 ft. The plan-form is rectangular with a chord of 1 ft. Two standard four-fin tail assemblies are available both having a fin semi-span of 6 in. The smaller has a fin chord of 6 in. and the larger of 18 in. In both cases the trailing edges of the fins coincide with the rear end of the venturi.

The all-up-weight of such a vehicle before test is of the order of 110 lb. Of this, the wings weigh 10 lb and about 40 lb of propellent is carried. Thus when the boost motor is fully burnt the weight has dropped to approximately 70 lb. Burning of the propellant also causes a shift in centre-of-gravity position. The centre of gravity moves forward as the charge is burnt, and the movement may be as much as 4 to 5 in., thus increasing the static margin considerably. The pitch radius of gyration of the body about the overall centre of gravity is just over twice the wing mean chord and tends to increase by about $0 \cdot 1$ of the chord as the propellant is burnt (it should be noted, however, that the pitching moment of inertia of the whole vehicle decreases as the propellent burns).

In the calculations no attempt has been made to represent the changing inertia characteristics of the body due to the burning of the propellent. The body mass was assumed to be 90 lb (representing a partially burnt boost) and the body pitching radius of gyration was taken as $2 \cdot 0$ ft.

Supersonic aerodynamic derivatives[5] ($M = 1 \cdot 4$) were used in the initial calculations with a correction for aspect ratio. These calculations were then repeated using two-dimensional derivatives[6] for a Mach number of $0 \cdot 7$, no aspect-ratio correction being applied. The assumed frequency parameter for the wing was $0 \cdot 08$, necessitating considerable extrapolation in obtaining the supersonic derivatives from Ref. 5. No allowance was made for the aerodynamic force acting on the body, for wing-body interference, or for loss of tailplane effectiveness due to downwash.

In the general parameter variations not directly relating to the rocket flutter models, the subsonic derivatives[6] were used.

Three modes were considered: (i) fixed-root wing flexure, (ii) pitch of the whole vehicle about the reference axis and (iii) normal translation of the whole vehicle. The reference axis was taken at the wing quarter-chord for the tailplane cases, and three-quarter wing chords forward of the wing leading edge for the foreplane cases. The displacements in mode 1 (wing flexure) were assumed to be those for a uniform beam, and the frequency of the mode was taken to be 30 c.p.s. which is a mean figure for the type of model. The equations of motion were solved for flutter speed and frequency on the R.A.E. flutter simulator. Some difficulty was encountered in balancing the problem on the simulator because of the zero structural stiffness terms in the body freedom modes. This was overcome in the usual way by introducing a direct structural stiffness term $K$ in each degree of body freedom and increasing the direct inertia terms by $K/\omega^2$ so that the added inertia exactly compensated the added stiffness at the flutter frequency $\omega$.

4. *Results.*—The first case considered was with a tailplane of 6-in. chord and 6-in. semi-span. Although no accurate data exist for the wing and tailplane relative positions in the rocket models that failed in flight (Table 1), the tailplane arm was approximately $28 \cdot 5$ in., giving a tailplane volume coefficient of $0 \cdot 297$. For this condition, and with a body pitching radius of gyration of $2 \cdot 0$ ft, the overall centre of gravity was varied from the leading edge to a point 12 in. forward. The variation of flutter speed with centre-of-gravity position is shown in Fig. 2, using both subsonic and supersonic derivatives. The flutter speed falls as the centre of gravity is moved forward, although there is a considerable difference between the two curves both in respect of speed, and in the centre-of-gravity position for which flutter is just prevented. Comparison of these results with the measured flutter speeds of Table 1 shows that the calculations give speeds that are higher than those measured, assuming the centre of gravity for the models to have been no more than $0 \cdot 5$ ft forward of the wing leading edge. However, the aerodynamic forces on the body are probably of some significance and the loss of tailplane effectiveness due to wing downwash will also have an effect; the omission of both these effects from the calculations might explain the discrepancy. The calculated frequencies are higher than those measured, particularly using supersonic derivatives, but are well below the natural frequency of the fundamental flexure mode of the wing.

The effect of pitching radius of gyration of the whole vehicle is shown in Fig. 3 (This and the parameter variations that follow were all made with the subsonic derivatives). The pitching radius of gyration was varied from $1 \cdot 5$ to 3 ft for two positions of the overall centre of gravity. Fig. 3 shows that a rapid change of flutter speed can occur if the centre-of-gravity position is marginal with respect to this type of flutter.

The effect of varying the tailplane volume coefficient was investigated. This may be achieved on a standard rocket flutter model by using a tailplane having a chord of 18 in. and a semi-span of 6 in. This triples the tailplane area but since the trailing edge of the tail fins remains in line with the boost venturi, the tailplane arm is decreased, and the tailplane volume coefficient is only increased from 0·297 to 0·609. The flutter-speed curve for change in centre-of-gravity position is shown in Fig. 4. On the same Figure is shown the corresponding curve for the 6-in.-chord tailplane. There is little increase in flutter speed obtained by fitting the larger tailplane, although a slightly more forward centre-of-gravity position can be tolerated than with the small surface. If, however, the tailplane area could be increased simply by increasing the span of the small tailplane whilst maintaining tailplane rigidity, a considerable improvement in flutter characteristics could be obtained for the same value of tailplane volume coefficient (Fig. 4). The effect of step-by-step increases in tailplane volume coefficient by increasing the tailplane span with a constant chord of 6 in. is shown in Fig. 5. The curves relate to two values of tailplane arm, distinguished by full and broken lines in the Figure; it will be seen that the shorter tailplane arm yields the higher flutter speeds.

It may be noted that in oscillatory flow the aerodynamic pitching moments due to the tailplane are dependent on both tailplane arm and tailplane span, and not simply on the product of these as is the case in steady flow.

In order to discover the effect of body inertia on the flutter, the body mass was varied for two positions of the overall centre of gravity. For this investigation the 6-in. chord, 6-in. semi-span, tailplane was assumed, with a tailplane volume coefficient of 0·297. Fig. 6 shows that there is little change in flutter speed until the mass is reduced to approximately twice the wing mass. In this region the flutter speed rises sharply with further decrease of body mass and the curve has a clearly defined minimum value of body mass below which flutter does not occur. It is apparent from this curve that the limited range of body mass covered by the tests of Ref. 1 probably explains why body freedom flutter did not occur in those tests. However, no attempt was made in the present calculations to cover small body-mass conditions similar to those of the wind-tunnel tests, so that the curves of Fig. 6 show the flutter characteristics only above values of the body mass equal to the wing mass.

Owing to interest in the canard lay-out a comparison was made of the flutter characteristics of tailplane and foreplane arrangements in which tailplane volume coefficient and tailplane arm were the same. The results are given in Fig. 7. From this, it seems that the canard has less favourable flutter properties than the conventional lay-out for the type of flutter considered. The effect of centre-of-gravity variation, however, is the same for both arrangements, with an aft position being beneficial.

5. *Discussion and Conclusions.*—The results published here show that symmetric body freedom flutter may be of some significance for certain classes of aircraft and missiles. The structural failure of some R.A.E. rocket-propelled flutter models can almost certainly be explained on the basis of these results. In the case of the models, the overall centre-of-gravity position was further forward than would be the case in an aircraft, but it is significant that similar calculations on the *Jindivik* pilotless target predicted body freedom flutter at a speed and frequency close to those at which flutter subsequently occurred. In both the *Jindivik* analysis and that of Cunningham and Lundstrom four modes were used; wing bending, wing torsion and the two body freedoms of pitch and normal translation. Cunningham and Lundstrom concluded that a torsion mode was necessary, since, by omitting it the calculated flutter speed was raised by 16 per cent. The omission of the torsion mode in the present analysis may therefore partly account for the calculated flutter speeds being too high. It has been suggested in Section 4 that the omission of aerodynamic forces on the body is also a probable explanation, as is the loss of tailplane effectiveness due to wing downwash.

An aft movement of the overall centre of gravity gives a decrease in the static stability margin and raises the flutter speed. A reduction in tailplane volume also decreases the static margin, but reduces the flutter speed. The reason is that moving the centre of gravity aft decreases the coupling between the modes, whereas reducing the tailplane volume decreases the aerodynamic damping contribution of the tail. The degree of static stability is not of itself a reliable indication of the susceptibility of a design to body freedom flutter.

The main conditions under which this type of flutter may occur are:

(i) Body mass large in relation to wing mass
(ii) Small value of tailplane volume coefficient
(iii) Overall centre-of-gravity position well forward.

The first condition exists in many rocket test vehicles but it should be noted that the value of the body pitching radius of gyration is also important, and an increase in this parameter is beneficial. The foreplane arrangement has no advantage over the conventional lay-out for this type of flutter, and centre-of-gravity position is again important.

In practice, the low frequency of flutter of this type (of the order of half the natural frequency of the fundamental bending mode of the wing) may lead to confusion between flutter and rigid body stability oscillations. It is suggested, where a design embodies at least the first of the above conditions, that consideration should be given to the possibility of symmetric body freedom flutter being critical.

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## TABLE 1

*Details of Flight Test Failures of Flutter Models*

| Model number | Speed at start of oscillation (ft/sec) | Frequency of oscillation c.p.s. | Natural frequencies | | Remarks |
|---|---|---|---|---|---|
| | | | Fundamental flexure mode c.p.s. | Fundamental torsion mode c.p.s. | |
| 1 | 1840 | 13·6 | 33 | 70 | Failure after 3 cycles |
| 2 | 1480 | 12·0 | 29 | 70 | Failure after $2\frac{1}{2}$ cycles |
| 3 | 1830 | 12·7 | 27 | 72 | Failure after 7 cycles |
| 4 | 1604 | 12·5 | 27 | 73 | Failure after $3\frac{1}{2}$ cycles |

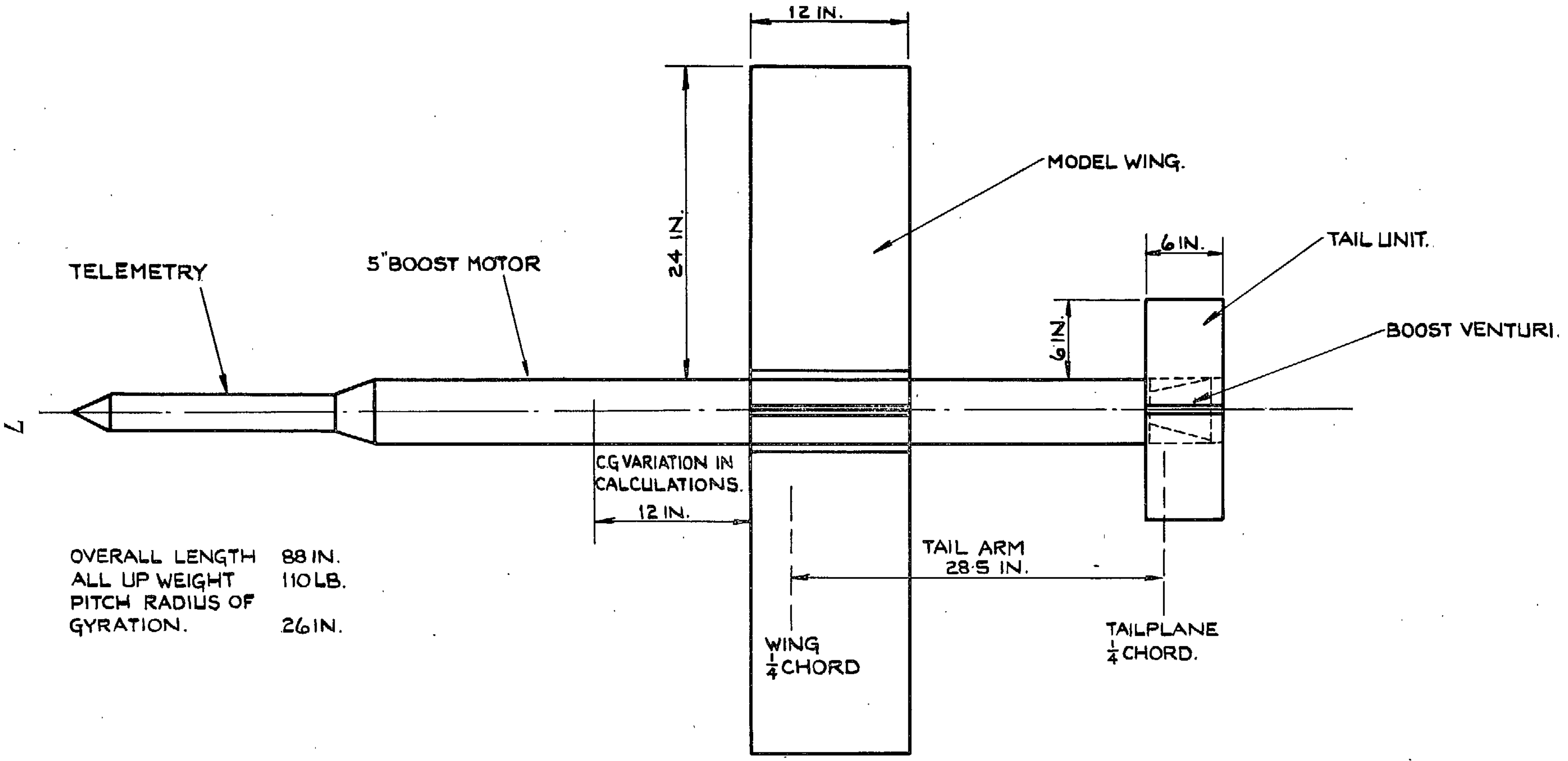

FIG. 1. Lay-out of flutter rocket model.

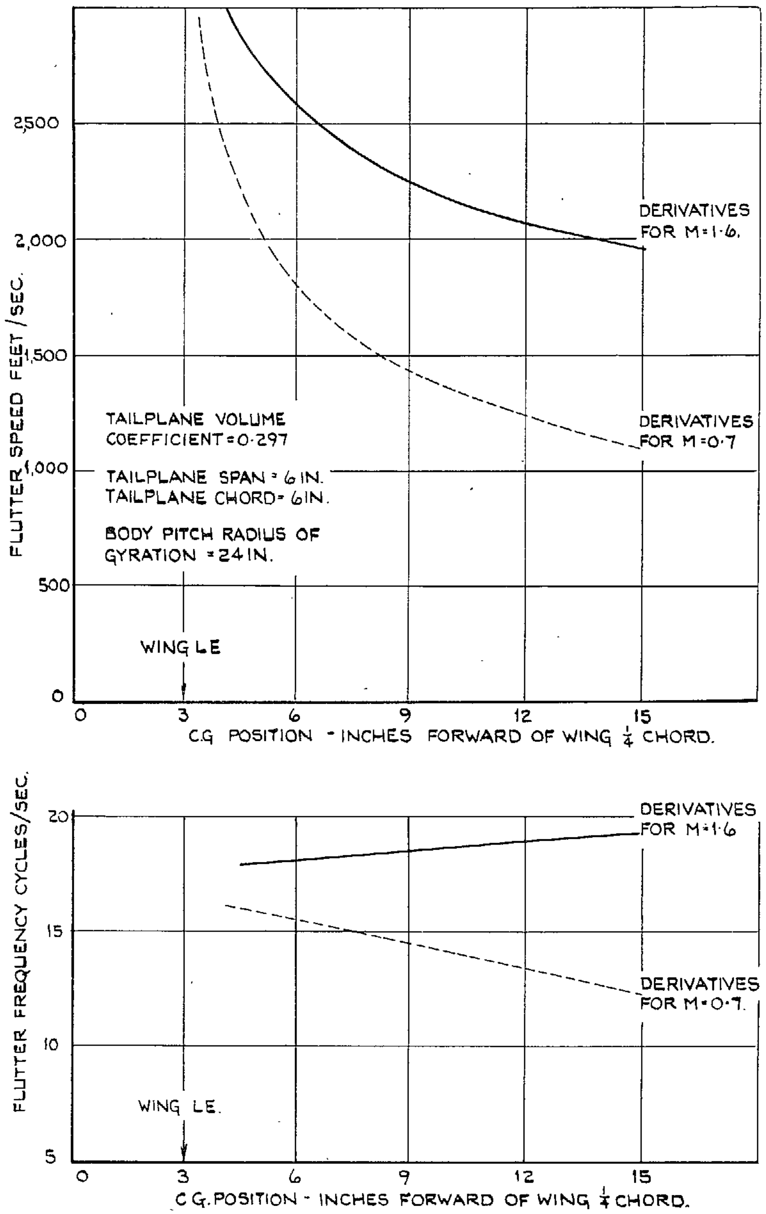

FIG. 2. The effect of c.g. position on flutter.

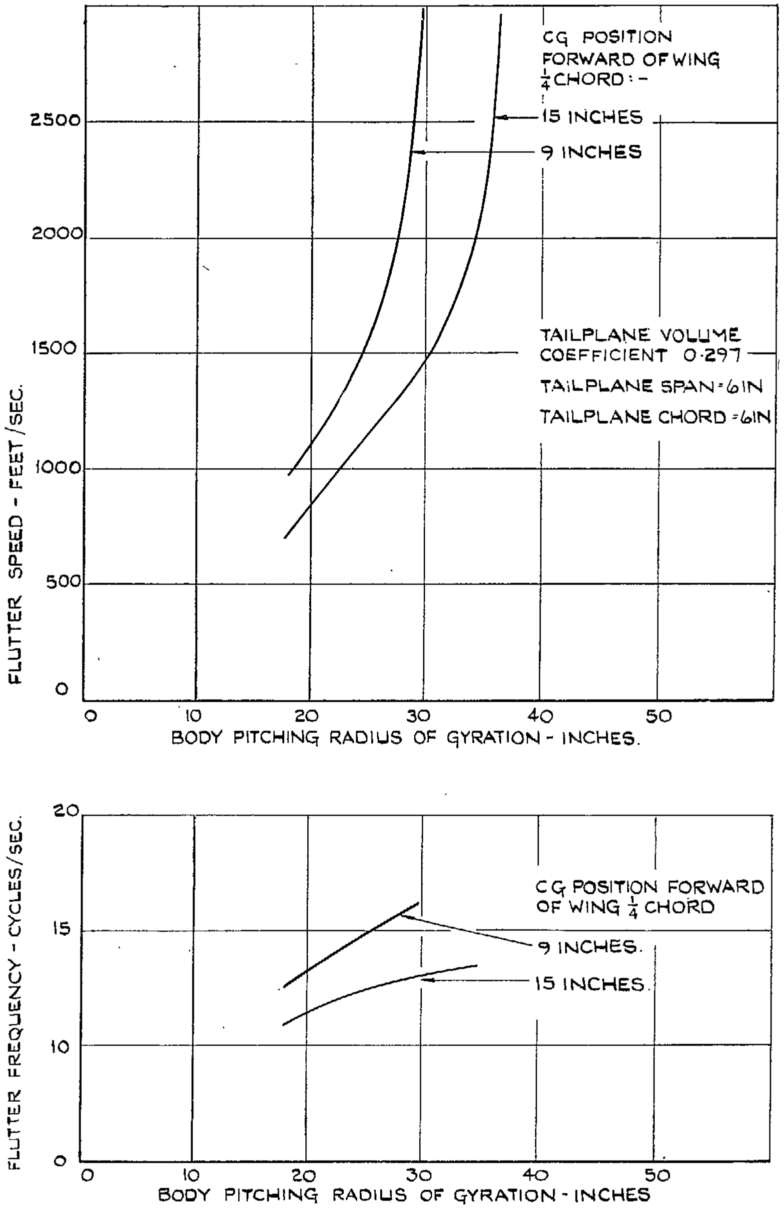

FIG. 3. The effect of pitching radius of gyration on flutter.

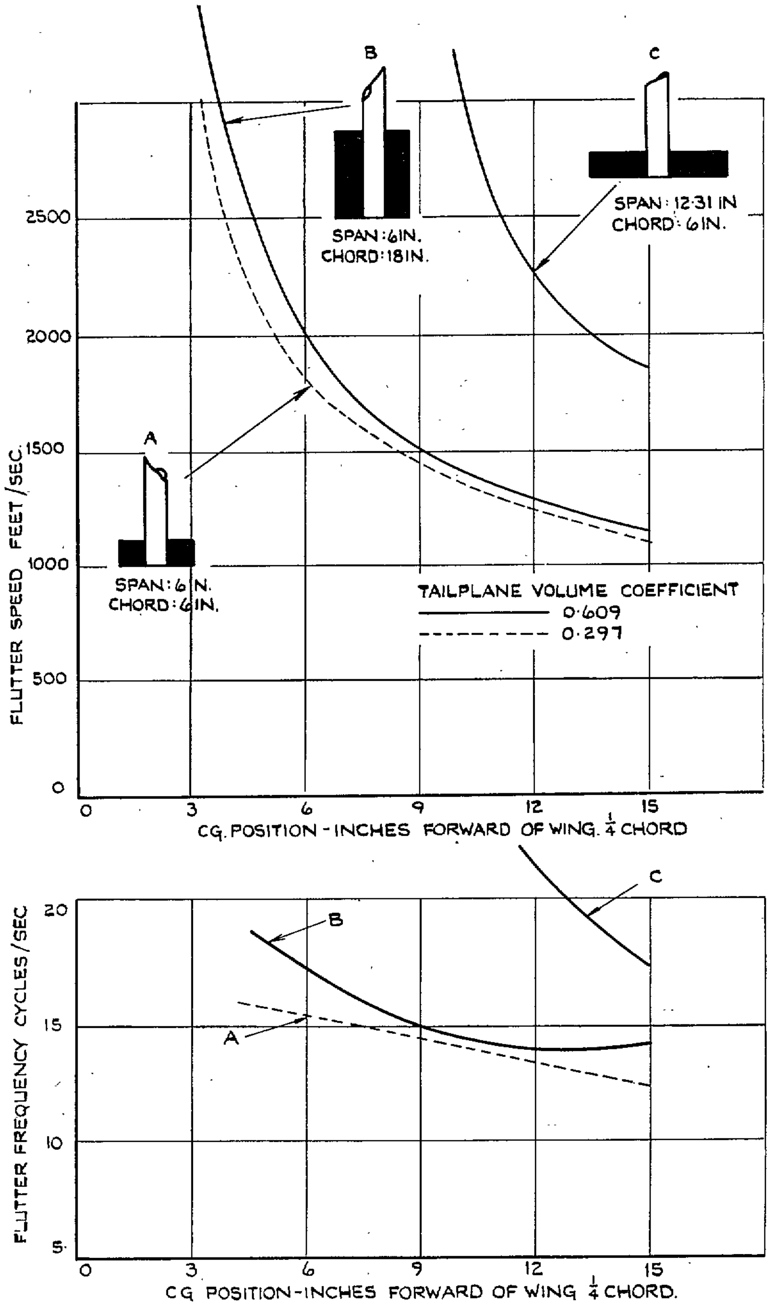

FIG. 4. The effect of tail shape on flutter.

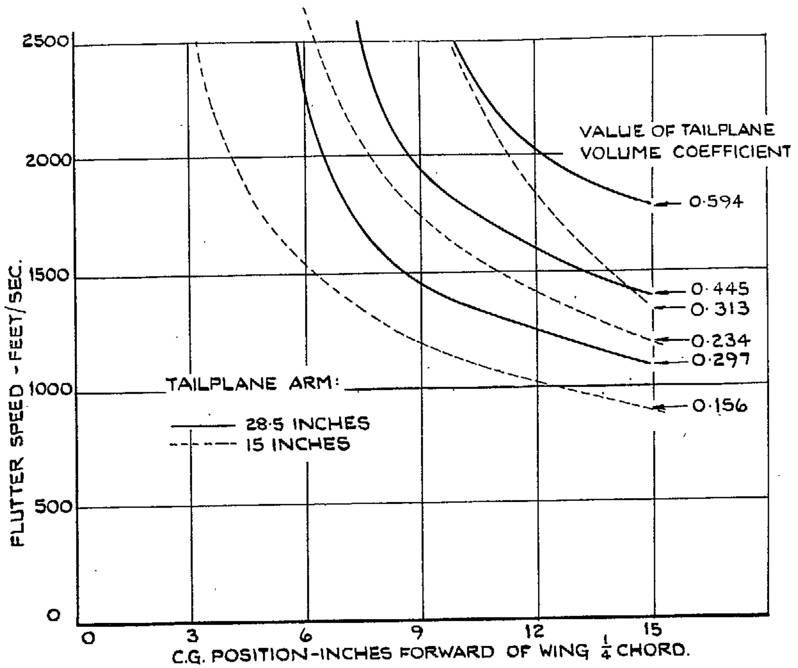

FIG. 5. The effect of tailplane volume coefficient on flutter.

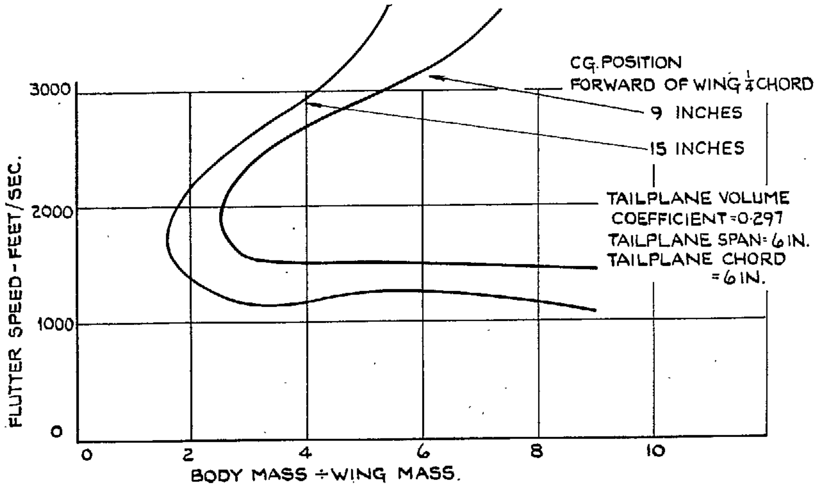

FIG. 6. The effect of body mass on flutter.

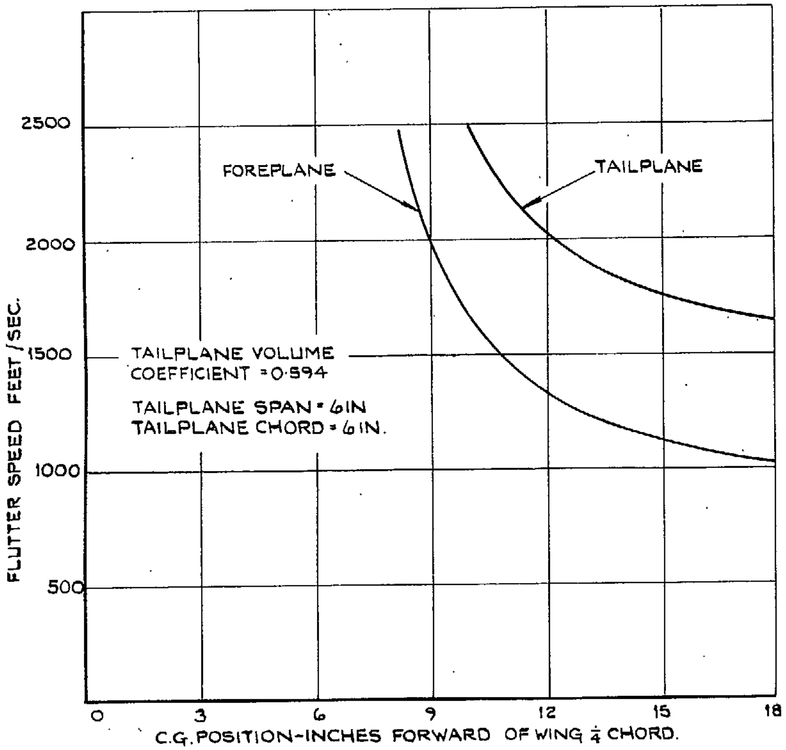

FIG. 7. Comparison of tailplane and foreplane lay-out.

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