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A Geared Flywheel Balance Arrangement for the Prevention of Control Surface Flutter

By

W. G. Molyneux

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A geared flywheel balance arrangement for the prevention of control surface flutter

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SUMMARY

Some geared massbalance systems are described that are effective in eliminating inertial couplings between modes of the main surface and the control surface. These arrangements are shown to have an advantage over the conventional arrangement for preventing flutter involving main surface torsion and control rotation, particularly where there is a near frequency coincidence between the modes.

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1 Introduction

The conventional method of providing massbalance for control surfaces is by the direct attachment of masses to the control surface forward of the hinge. It is generally possible, by this means, to reduce to zero the inertia coupling for a selected type of binary motion (e.g. wing flexure-aileron rotation, wing torsion-aileron rotation), but zero coupling cannot be achieved when flexural and torsional modes of the main surface have to be considered simultaneously.

To avoid this difficulty Frazer[1] has suggested an alternative balance arrangement consisting of a rearward facing massbalance arm, pivoted about the hinge axis of the control surface and geared to the surface so as to rotate in the opposite sense to the surface rotation. With this system dynamic balance of the surface can be obtained for any mode of wing distortion provided the control surface can be treated as rigid. Unfortunately, with the present trend towards very thin wing sections, the assumption of control surface rigidity cannot be justified.

To allow for control surface flexibility a further form of geared balance is considered, consisting of a combination of a statically balanced control surface (balanced in the conventional manner) and a system of flywheels geared to the control to rotate in the opposite sense to the control surface rotation. With this arrangement the inertial couplings between wing and control surface motions can be reduced to zero for any mode of distortion of the wing or control surface.

However the elimination of inertial couplings does not necessarily imply that the system will benefit over the conventional system as a flutter preventive. Accordingly a flutter investigation has been made to compare the relative effectiveness in preventing flutter of the two geared systems and the conventional system. This shows that both geared balance arm and flywheel balance arrangements have a marked advantage over conventional direct balance in preventing flutter of the main surface rotation - control surface rotation type, particularly where there is a near frequency coincidence between the modes. This type of flutter has proved troublesome on some recent aircraft designs.

2 The arrangements considered

2.1 Rearward facing geared balance arm

The system is as shown in Fig.1. Let z_a and z_b denote arbitrary vertical displacements of the wing at the hinge attachments distance a and b respectively from the wing root, let α_c denote the angular displacement of the wing at the section c for control operation and β_c the rotation of the aileron relative to the wing at this section. Then the vertical linear displacement of a point P(x,y) on the control is

$$z_a \frac{(y - b) + z_b(a - y)}{a - b} + x(\alpha_c + \beta_c) .$$

If δm denotes the mass at P then the total kinetic energy in a general motion is

$$2T = \sum_{\text{aileron}} \delta m \left[\frac{\dot{z}_a(y - b) + \dot{z}_b(a - y)}{a - b} + x(\dot{\alpha}_c + \dot{\beta}_c)\right]^2 . \qquad (1)$$

The wing aileron inertial couplings in this expression are those terms involving products of β_c with z_a, z_b and α_c, i.e.

$$\text{Coefficient of } \dot{\beta}_c \, \dot{z}_a \qquad \frac{2}{a-b} \left(\Sigma \delta mxy - b\Sigma \delta mx\right) \tag{2a}$$

$$\text{"} \quad \text{"} \quad \dot{\beta}_c \, \dot{z}_b \qquad \frac{2}{a-b} \left(a\Sigma \delta mx - \Sigma \delta mxy\right) \tag{2b}$$

$$\text{"} \quad \text{"} \quad \dot{\beta}_c \, \dot{\alpha}_c \qquad 2\Sigma \delta mx^2 \tag{2c}$$

and inertial coupling is eliminated when all these coefficients are zero.

If massbalance is to be achieved by the direct attachment of a distributed or concentrated mass forward of the aileron hinge then it is apparent that all the expressions (2) cannot be zero. Expression 2(c) for example will always have a real, positive value, indicating that direct balance cannot provide zero inertia coupling in a pitch mode involving rotation of the main surface about the control surface hinge.

However, suppose that massbalance is to be achieved by a concentrated mass M_b on a rearward facing arm x_b at section c, pivoted about the hinge axis of the control surface, and geared to the surface so as to rotate in the opposite sense to the surface rotation. Let the gear ratio massbalance arm rotation : control surface rotation be q. For this system the kinetic energy in a general motion is

$$2T = \sum_{\text{aileron}} \delta m \left[\frac{\dot{z}_a(y-b) + \dot{z}_b(a-y)}{a-b} + x(\dot{\alpha}_c + \dot{\beta}_c) \right]^2$$

$$+ M_b \left[\frac{\dot{z}_a(c-b) + \dot{z}_b(a-c)}{a-b} + x_b(\dot{\alpha}_c - q\,\dot{\beta}_c) \right]^2 \tag{3}$$

and the inertial coupling coefficients are

$$\text{Coefficient of } \dot{\beta}_c \, \dot{z}_a \qquad \frac{2}{a-b} \left(\Sigma \delta mxy - b\Sigma \delta mx - qM_b x_b c + bqM_b x_b\right) \tag{4a}$$

$$\text{"} \quad \text{"} \quad \dot{\beta}_c \, \dot{z}_b \qquad \frac{2}{a-b} \left(a\Sigma \delta mx - \Sigma \delta mxy - aqM_b x_b + qM_b x_b c\right) \tag{4b}$$

$$\text{"} \quad \text{"} \quad \dot{\beta}_c \, \dot{\alpha}_c \qquad 2(\Sigma \delta mx^2 - qM_b x_b^{\,2}) \tag{4c}$$

All expressions (4) will be zero when the following conditions are satisfied.

$$c = \frac{\Sigma \delta mxy}{\Sigma \delta mx} \tag{5}$$

$$x_b = \frac{\Sigma \delta mx^2}{\Sigma \delta mx} \tag{6}$$

$$qM_b = \frac{(\Sigma \delta mx)^2}{\Sigma \delta mx^2} \tag{7}$$

Equation (5) determined the section for massbalance attachment and control operation, (6) defines the length of the (weightless) massbalance arm and (7) determines the balance mass.

It is apparent that by using this massbalance arrangement the inertial couplings can be reduced to zero. However, the system has the disadvantages that the control surface must be slotted to allow movement of the balance arm, leading to aerodynamic interference and structural difficulties, and flexibility of the control surface can reduce the massbalance effectiveness. Furthermore, it is not practicable to use a high gear ratio q, thus reducing the mass required for massbalance, because if the gear ratio differs greatly from unity the massbalance effectiveness will vary considerably over the range of control surface travel. It may be noted that the effective moment of inertia of the control surface is given by

$$I = (1 + q)\, Ia$$

where Ia is the moment of inertia of the unbalanced control.

2.2 Statically balanced control with geared flywheels*

When there is significant flexibility of the control surface within the frequency range for flutter it is potentially dangerous to attempt to massbalance with a single concentrated mass, such as is required with the above arrangement. In an unfavourable mode of distortion it is possible for an arrangement of this sort to act in the anti-balance sense. For the flexible control surface an alternative arrangement is therefore required.

Now consider the system shown in Fig.2 in which there is a shaft within the wing that carries a series of discrete flywheels, geared to the control surface with gear ratio q to rotate in the opposite sense to the control surface rotation..

The total kinetic energy in a general motion is

$$2T = \sum_{\text{aileron}} \delta m \;[\dot{z} + x(\dot{\alpha} + \dot{\beta})]^2 + \Sigma\, I(\dot{\alpha} - q\dot{\beta})^2 \tag{8}$$

where I is the local flywheel moment of inertia and z, α, and β are all functions of the spanwise coordinate.

To satisfy the condition of zero inertial coupling for any mode of distortion of the control surface the inertial coupling terms must be zero at every local section. At a local section we have:-

$$\left.\begin{array}{lll} \text{Coefficient of} & \ddot{\beta}\ddot{z} & 2\Sigma\,\delta m x \\ \quad\text{"} \qquad \text{"} & \ddot{\beta}\ddot{\alpha} & 2(\Sigma\,\delta m x^2 - q\, I) \end{array}\right\} \tag{9}$$

These expressions will be zero provided every local section is massbalanced so that its c.g. is on the hinge line, and provided the local value of qI for the flywheels is equal to the local moment of inertia of the control surface. In this condition the control will be statically balanced and its total effective moment of inertia I will be

$$I = (1 + q) I_b \tag{10}$$

where I_b is the moment of inertia of the statically balanced control surface.

*Patent Application 34009/56.

With this arrangement the whole balance system can be housed within the wing contour thus avoiding aerodynamic interference. Furthermore, high gear ratios can be used thus reducing flywheel mass, though it should be noted that the effective control inertia will increase with gear ratio.

In practice it is rarely convenient to utilise an ideally distributed balance system, the usual practice being to concentrate the balance at three or four sections along the span of the control. For the present system this would require a directly mounted mass to balance a particular portion of the control surface and a geared flywheel to balance the moment of inertia of this same portion.

3 Flutter investigation

Reducing inertial couplings to zero does not necessarily avoid flutter entirely, since aerodynamic and elastic couplings will generally still be present.

In what follows a limited theoretical investigation is therefore made to compare the effectiveness of the conventional balance system with that of the geared balance arm and geared flywheel balance systems. A rigid wing section is considered with freedoms in vertical translation, pitch about the quarter chord and aileron rotation. The main details of the wing are given in Fig.3 and Table I. Two dimensional incompressible flow derivatives are used for a fixed frequency parameter of 1.4, and flutter properties are investigated for different massbalance conditions over a range of control circuit stiffness that ensures a coincidence between the frequencies of the wing and control surface modes.

3.1 Comparison of direct balance with geared balance arm system

Referring to equation (6) and using the data from Table I, the length of the arm for the geared balance system is

$$x_b = \frac{(0.25)^2}{0.095} = 0.65 \text{ ft} .$$

For simplicity it is assumed that this same length of arm is used for the direct balance system, so that static balance of the control is obtained for both systems with a mass of about 0.031 slugs at the end of the arm.

Flutter curves for different values of the balance mass and for a range of control circuit stiffness are shown in Fig.4. The gear ratio for the geared balance is assumed to be unity throughout.

For a balance mass of zero it can be seen that two distinct types of flutter occur. When the circuit stiffness is low the flutter is of type (A) which involves modes of vertical translation and control rotation, pitch of the main surface having an insignificant effect. As the circuit stiffness is increased there is an abrupt change to type (B) flutter which involves wing pitch and control rotation. The type (A) flutter region is the same for both geared and direct balance systems, and disappears entirely for a balance mass of 0.025 slugs/ft, but the type (B) flutter regions differ considerably for the two systems. Whereas for the geared balance the low flutter speeds associated with type (B) flutter are avoided with a balance mass of 0.031 slugs/ft (i.e. static balance), a comparable condition is not achieved with the direct balance system until the balance mass is increased to 0.05 slugs/ft. With direct balance a balance mass some 50% in excess of that required for static balance of the control is therefore necessary to avoid the low flutter speed region for the pitch-aileron rotation type of flutter. These low flutter speeds result from a near coincidence of the wing pitch and control rotation frequencies, in association with unfavourable inertial couplings between wing and control motions. With the geared balance system the unfavourable inertial couplings are eliminated when the static balance condition obtains.

3.2 Direct balance in association with flywheel balance

The case considered is that of statically balanced control with a mass of 0.031 slugs/ft on a balance arm 0.65 ft long (as in section 3.1) to which a flywheel is geared. The effects of variation in flywheel inertia are investigated for two values of the gear ratio

$$q \left(= \frac{\text{flywheel rotation}}{\text{control rotation}} \right).$$

The results are shown in Fig.5.

The flutter obtained is of the torsion-aileron type throughout, static balance having eliminated the translation-aileron type flutter. It can be seen that for corresponding values of qI the minimum flutter speed is about the same for both values of q, but the flutter region extends over a greater range of circuit stiffness when $q = 3$ than when $q = 1$. As qI is increased the minimum flutter speed increases rapidly, and when $qI = 0.026$ slugs ft^2/ft (i.e. inertial coupling zero) the speed is everywhere greater than 900 ft/sec (as compared with 180 ft/sec when $qI = 0$). A further increase in qI leads to a further increase in the minimum flutter speed for $q = 1$, and a slight decrease for $q = 3$. The minimum flutter speeds when inertial coupling is zero ($qI = 0.026$) are almost identical with that for the corresponding condition with the geared balance arm ($M = 0.031$), indicating that both systems are equally effective in raising the minimum speed.

3.3 Flywheel balance alone

It is of interest to investigate the effect of using flywheel balance alone on the flutter of an unmassbalanced control surface. Obviously, since the flywheel presents an opposing moment of inertia against control surface rotation it cannot eliminate the mass-moment inertia coupling that results from translation of the main surface. In consequence flywheel balance alone would not be expected to eliminate flutter of the flexure-aileron type, though it should be effective for torsion-aileron type flutter. This is borne out by the results shown in Fig.6, in which the effect on flutter of flywheel balance alone has been investigated for gear ratios q of 0.5 and 1.0. It is apparent that the area of torsion-aileron flutter (B) is markedly reduced as the flywheel inertia is increased, but the area of flexure-aileron flutter (A) is increased because of the resultant increase in the effective moment of inertia of the control surface. The effective control surface moment of inertia is given by -

$$I = (I_a + q^2 I_f)$$

where I_a is the moment of inertia of the unbalanced control surface

I_f is the flywheel inertia

from which it is apparent that a low gear ratio is required to avoid an excessively large value of I.

The local value of I_f required to eliminate torsion-aileron coupling if given by -

$$q\, i_f = i_a + m_a \bar{x}_a \ell$$

where i_a is the local moment of inertia of the unbalanced control surface

m_a is the local mass of the unbalanced control surface

$\bar{x}_a$ is the distance of the c.g. of the local section aft of the hinge

ℓ is the distance between the torsional nodal line and the aileron hinge,

which indicates that the value of I_f required reduces as the nodal line approaches the aileron hinge and is a minimum when these two axes coincide. With a direct balance arrangement the mass required to eliminate this form of coupling increases as the nodal line approaches the hinge, tending to infinity when it coincides with the point of installation of the balance mass.

Flywheel balance alone may therefore have an advantage over direct balance in any circumstance where the nodal line for torsion-aileron flutter is close to the hinge, provided the flexure-aileron flutter branch can be avoided (e.g. by providing an adequate circuit stiffness).

4 Discussion

It may be noted that the penalty for the elimination of inertial couplings is a marked increase in the effective moment of inertia of the control surface as compared with that for conventional massbalance. In consequence a greater initial force is required to achieve the same rate of control application, and furthermore, it becomes increasingly difficult to achieve a high natural frequency for the control on its circuit. Though the latter feature may no longer be important so far as coupled flutter is concerned it may well be important in the low supersonic speed regime where single degree of freedom flutter can occur due to negative aerodynamic damping for the control surface. If the frequency of the control on its circuit can be made high enough this region of negative damping can be avoided[2]. However, even with a conventional massbalance system the required frequency often cannot be achieved, and the alternative in such cases is to eliminate the flutter by the introduction of damping. With a flywheel massbalance system it seems likely that damping units could be housed within the flywheels themselves.

The "flywheels" need not of course be in the form of circular discs but might equally well consist of linkage arms pivoted at their centres; they could be incorporated as part of the circuit through which the control is operated.

The system is open to the usual objections regarding any geared massbalance system, namely, there must be no undue flexibility in the linkage and backlash must be kept to a minimum. Furthermore, the danger of jamming the mechanism due to icing or due to differential expansion arising from kinetic heating must also be borne in mind, but the system is unlikely to be worse off on any of these counts than say a power operated control using screw jacks or hydraulic actuators.

5 Conclusions

The conventional control surface massbalance arrangement, whereby a balance mass is attached direct to the control on a forward facing arm, does not enable the simultaneous elimination of inertial couplings for vertical displacement and pitch modes of the main surface to be achieved. Massbalance for main surface pitch is impracticable for a mode whose nodal line lies close to the control surface hinge.

A theoretical investigation of two alternative arrangements of geared massbalance show that they are more effective than the conventional arrangement in eliminating inertial couplings, and they benefit greatly over the conventional system in preventing flutter of the torsion-aileron type where there is a near coincidence of frequencies. However, the arrangement consisting of a rearward facing balance arm geared to rotate about the control surface hinge in the opposite sense to the control surface rotation presents an installation problem since it would normally project into the airstream. Furthermore, the massbalance effectiveness will be influenced by flexibility of the control surface or of the balance arm.

The alternative arrangement of flywheels geared to a statically balanced control overcomes these difficulties. The flywheels can be housed within the wing itself and are effective even for a flexible control surface. The arrangement is, of course, open to the usual objections regarding geared massbalance; namely, there must be no undue flexibility in the linkage and backlash must be kept to a minimum. However, the flywheel balance system is worth consideration in any circumstance where the flutter is of a pitch-control rotation type with a near frequency coincidence between the modes, and where the more usual method of flutter prevention by increasing the control circuit stiffness is impracticable.

REFERENCES

No.	Author	Title, etc.
1	Frazer, R. A.	Note on a 'scissors-type' of dynamic balance for control surfaces. R & M 2369 July, 1941.
2	Broadbent, E. G.	Aero-elastic problems in connection with high speed flight. Journal of the Royal Aeronautical Society, July, 1956.

TABLE I

Wing details

Wing mass = 1.0 slugs/ft span (including aileron)

Wing chord = 5.0 ft (including aileron)

Wing c.g. = 1.25 ft aft of leading edge

Wing radius of gyration = 1.25 ft about quarter chord

Wing vertical translation frequency = 100 rads/sec

Wing pitch frequency = 200 rads/sec

Aileron c.g. = 0.096 ft aft of hinge line

Aileron mass = 0.21 slugs/ft

Aileron radius of gyration = 0.25 ft about hinge line

$$\frac{\text{Aileron chord}}{\text{Wing chord}} = 0.2$$

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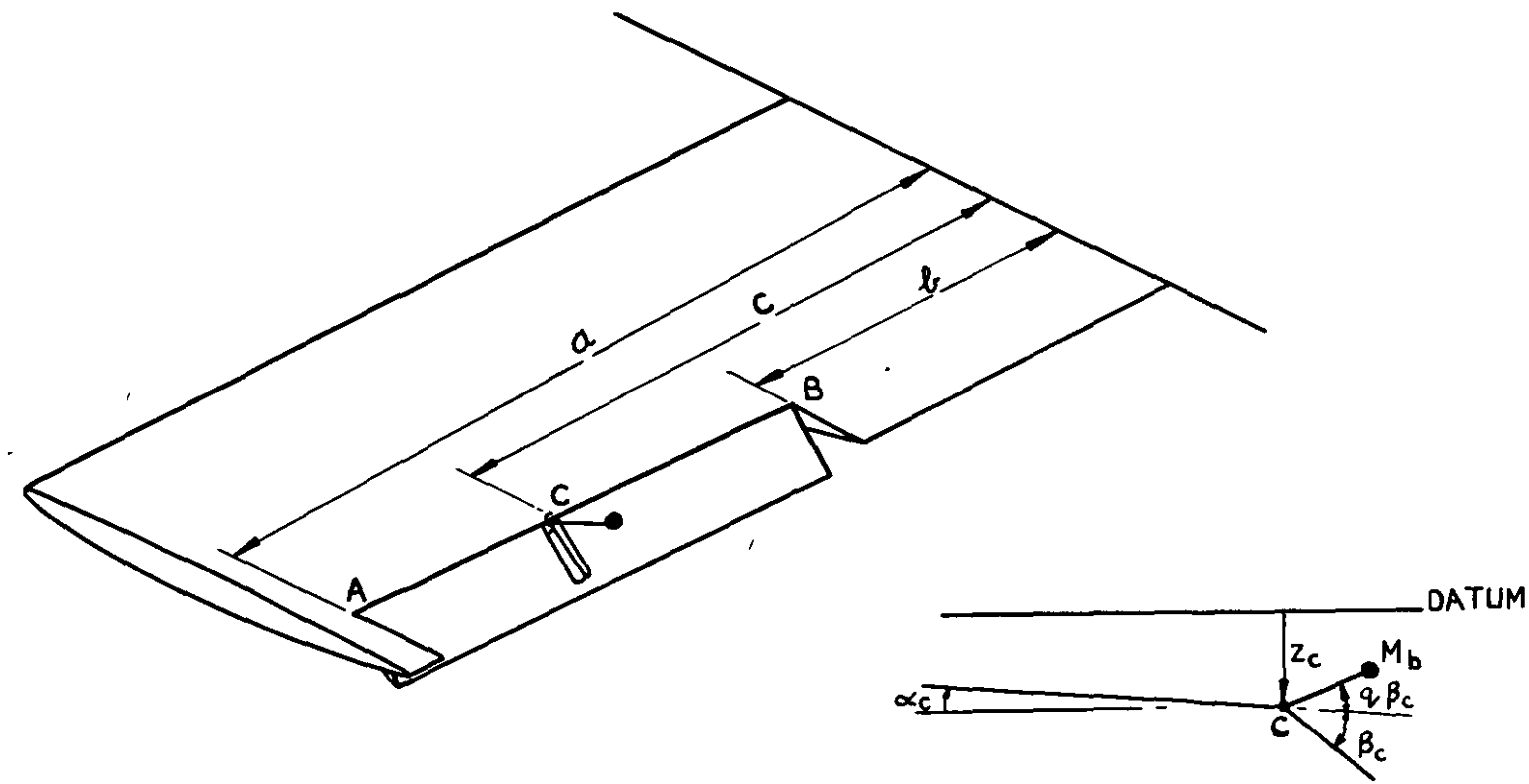


FIG.1. REARWARD FACING, GEARED BALANCE ARM SYSTEM.

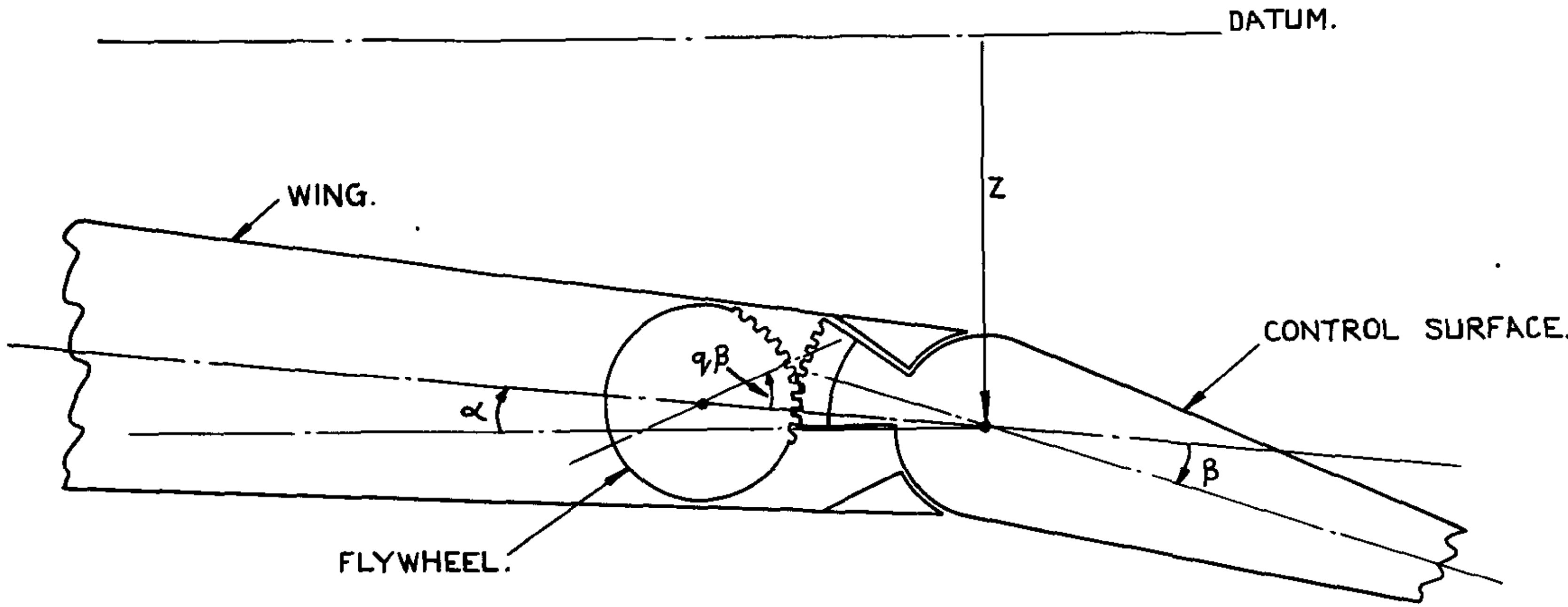
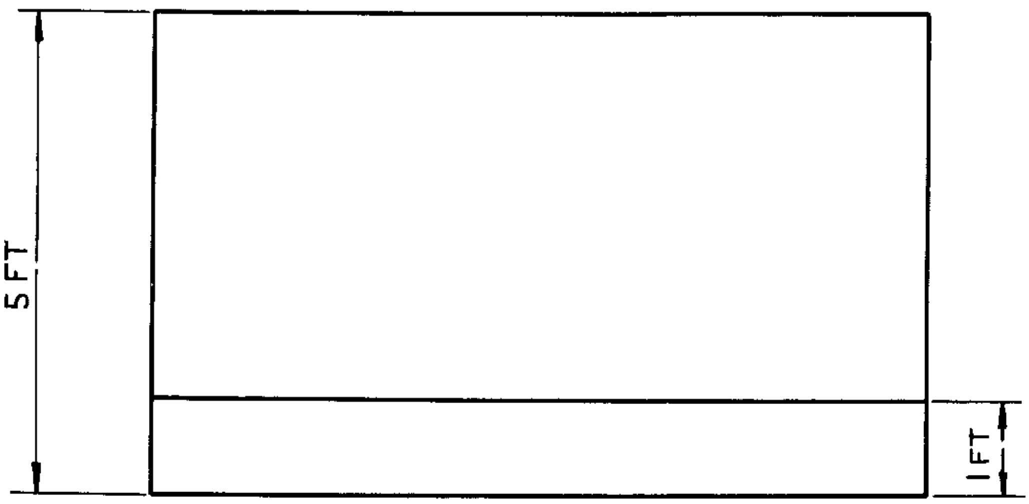
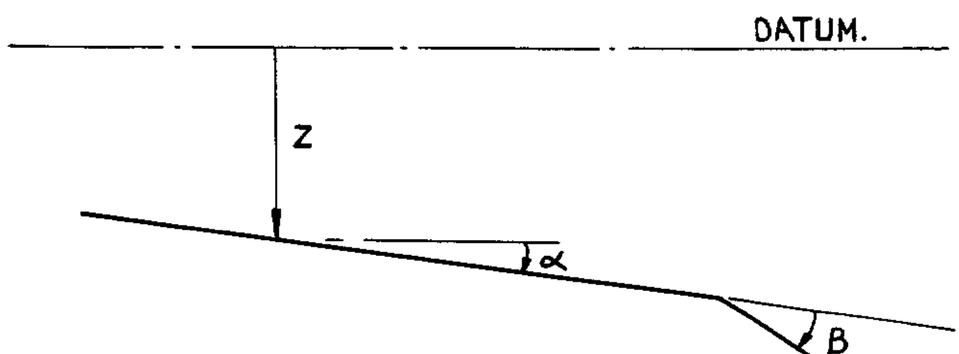


FIG. 2. STATICALLY BALANCED CONTROL WITH GEARED FLYWHEEL.

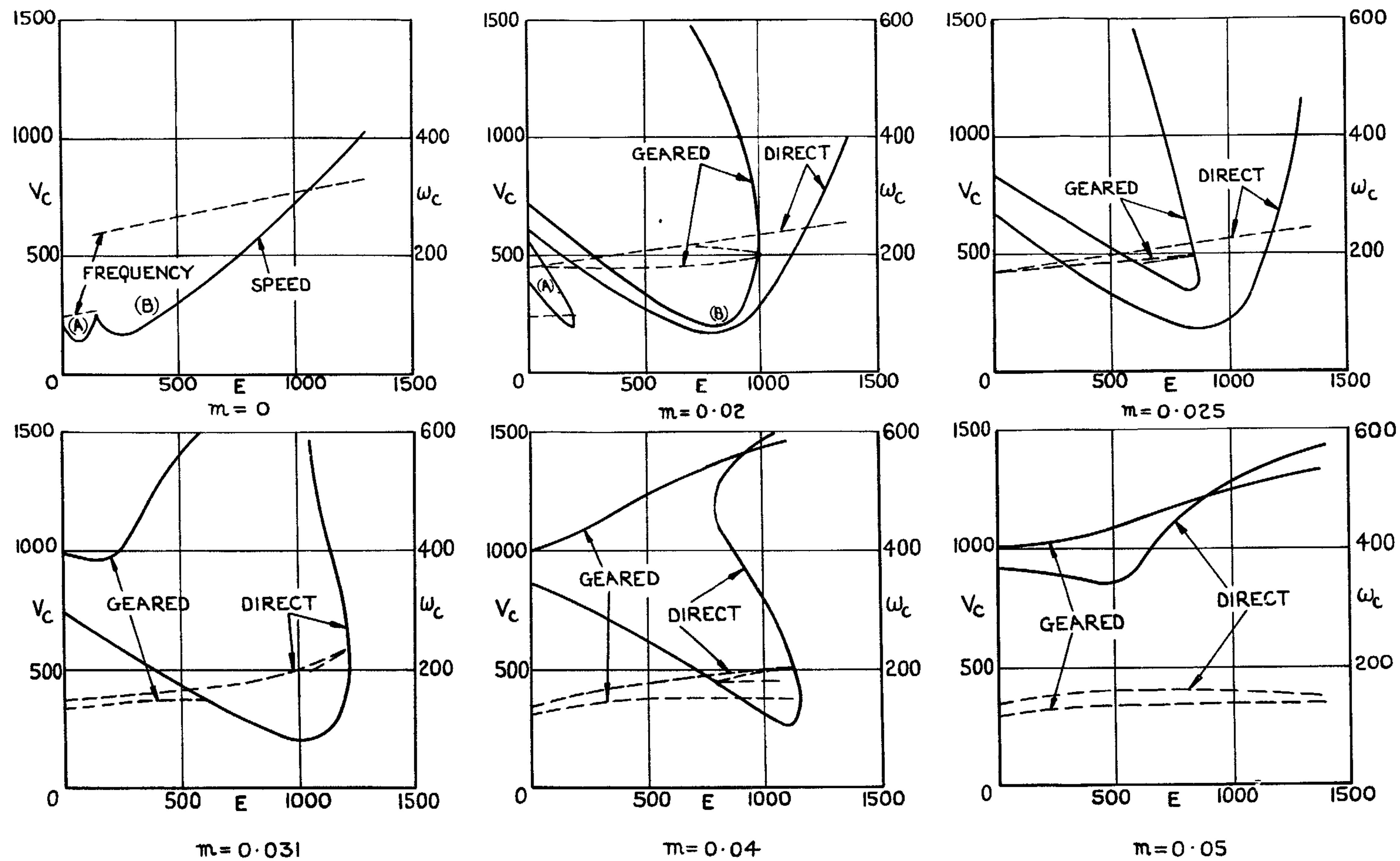


WING PLANFORM.



DEGREES OF FREEDOM.

FIG.3. THE SYSTEM CONSIDERED.



V_c = FLUTTER SPEED — FT/SEC.
ω_c = FLUTTER FREQUENCY — RADS/SEC.
E = CIRCUIT STIFFNESS — LB FT/RAD.
m = BALANCE MASS — SLUGS/FT.

FIG. 4. COMPARISON OF DIRECT & GEARED BALANCE ARM SYSTEMS.

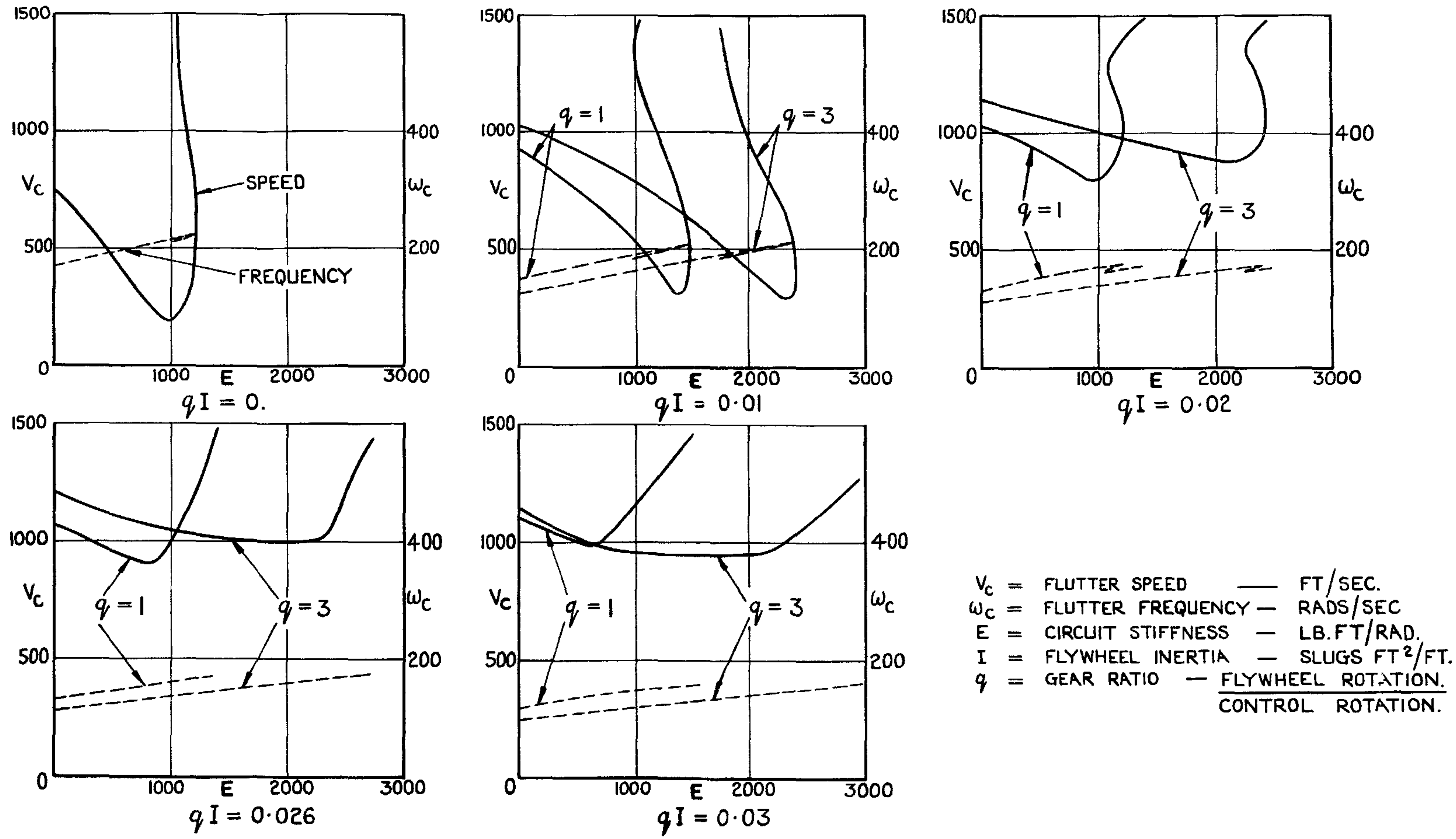


FIG.5. EFFECT OF GEARED FLYWHEEL — STATICALLY BALANCED CONTROL.

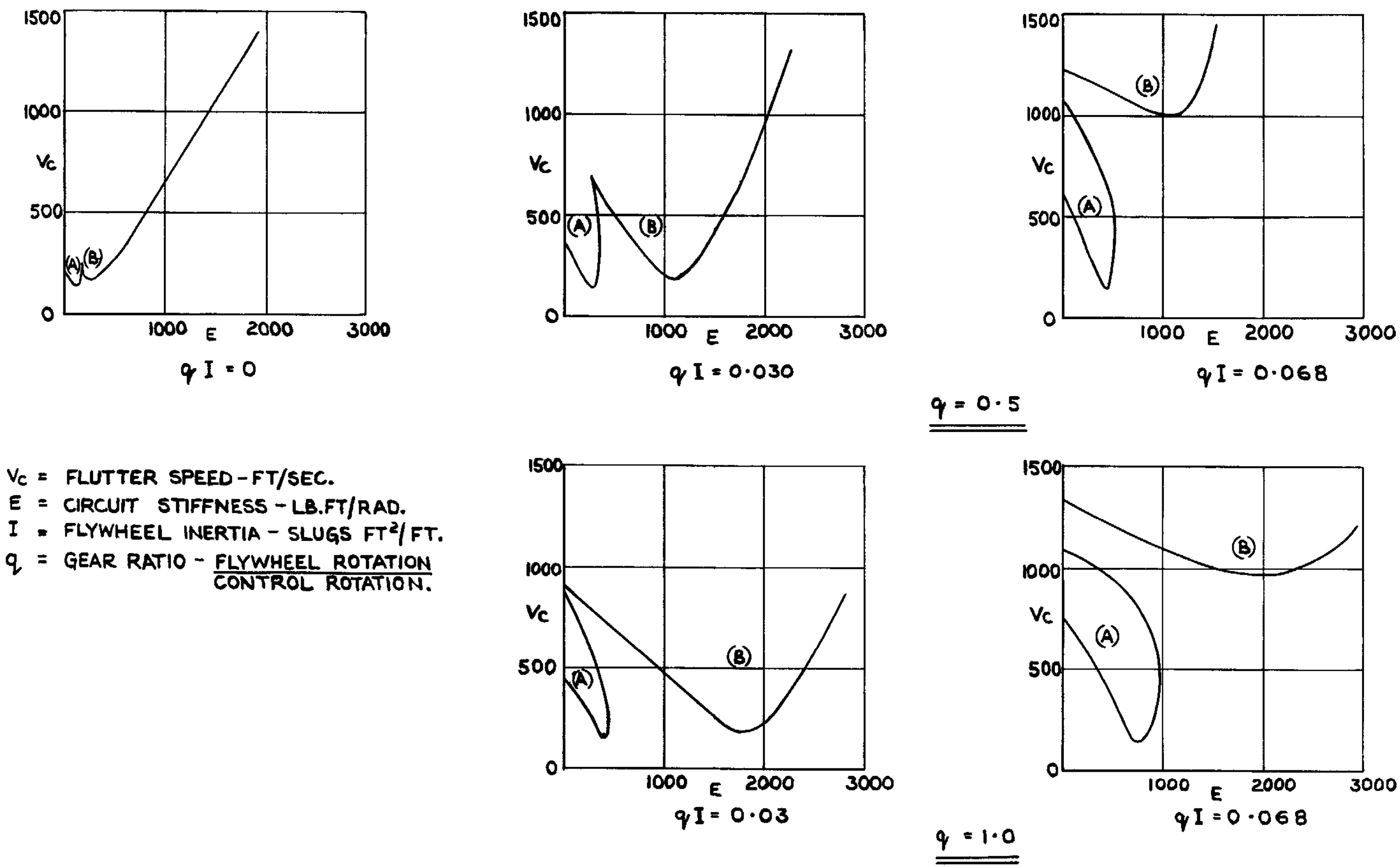


FIG. 6. EFFECT OF GEARED FLYWHEEL-UNBALANCED CONTROL.

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