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ANALYSIS OF THE LONGITUDINAL STABILITY OF HOMING GLIDE-BOMBS WITH APPLICATIONS TO NAVY SWOD MARK 7 AND MARK 9

By
Harold K. Skramstad
National Bureau of Standards

A Report to Division 5
from the
National Bureau of Standards

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ANALYSIS OF THE LONGITUDINAL STABILITY OF HOMING GLIDE-BOMBS WITH APPLICATIONS TO NAVY SWOD MARK 7 AND MARK 9

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A report from the National Bureau of Standards
to
Division 5, National Defense Research Committee
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Approved for National Bureau of Standards by
Lyman J. Briggs, Director.

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Preface

The work described in this report is pertinent to the projects designated by the War Department Liaison Officer as AC-1, AC-36, and AC-[illegible] and to the projects designated by the Navy Department Liaison Officer as NO-115, NO-174, and NO-235. This work was carried out and reported by National Bureau of Standards under a transfer of funds from OSRD with the cooperation of the Washington Radar Group of the Massachusetts Institute of Technology and Section Re4g of the Bureau of Ordnance, Navy Department.

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ANALYSIS OF THE LONGITUDINAL STABILITY OF HOMING GLIDE-BOMBS
WITH APPLICATIONS TO NAVY SWOD MARK 7 AND MARK 9

1. General Considerations

The stability characteristics of a glider are those qualities which determine its motion after a small deviation from an initial condition of equilibrium. The motion may be periodic, with a certain rate of increase or decrease in amplitude of the oscillations, or it may be aperiodic, with a certain rate of deviation toward or away from equilibrium.

There are two kinds of forces to be considered; first, aerodynamic forces and moments caused by the action of the air on various parts of the glider, and second, forces and moments due to gravity.

The following assumptions are made in order to reduce the complexity of the problem sufficiently to enable a solution to be obtained without a prohibitive amount of calculation. We assume symmetry about a plane which includes the fuselage axis and is perpendicular to the wing span axis; thus a longitudinal motion having no components perpendicular to the plane of symmetry or no component of angular velocity about an axis in that plane can introduce no asymmetric forces or moments. The forces on the lifting surfaces are assumed to be not affected by the rate of rotation of these surfaces. It is further assumed that aerodynamic forces and moments are proportional to the square of the airspeed in the case of the wings and tail and control surfaces used and to the first power of the angle of attack.

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Let us use the conventional symbols, as follows:

θ = angle between longitudinal axis of glider and the horizontal,

α = angle of attack of glider,

γ = angle between flight path and horizontal,

W = weight of glider,

V = velocity along flight path,

ρ = air density,

S = wing area,

C_L = lift coefficient,

C_D = drag coefficient,

C_m = pitching moment coefficient,

m = mass,

B = moment of inertia about lateral axis through the center of gravity,

δ = angular displacement of pitch control surface,

q = $\frac{d\theta}{dt}$ = rate of pitch,

c = mean aerodynamic chord.

Δ used as prefix means a small displacement from an equilibrium condition of the quantity following.

In steady flight, equilibrium may be expressed by the equations:

$$\left.\begin{aligned} W\sin\gamma + \tfrac{1}{2}\rho S V^2 C_D &= 0 \\ W\cos\gamma - \tfrac{1}{2}\rho S V^2 C_L &= 0 \\ \tfrac{1}{2}\rho S V^2 C_m &= 0 \end{aligned}\right\} \qquad (1)$$

Let us assume small displacements take place in V, γ, C_D, C_L, and C_m, denoted by the prefix Δ, and set the resultant force equal to the acceleration. This gives:

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$$\left.\begin{aligned} W\cos\gamma\Delta\gamma + \tfrac{1}{2}\rho S V^2 \Delta C_D + \rho S V C_D \Delta V &= -m\frac{dV}{dt} \\ -W\sin\gamma\Delta\gamma - \tfrac{1}{2}\rho S V^2 \Delta C_L - \rho S V C_L \Delta V &= -mV\frac{d\gamma}{dt} \\ \rho S c V C_m \Delta V + \tfrac{1}{2}\rho S V^2 c\, \Delta C_m &= B\frac{d^2\theta}{dt^2} \end{aligned}\right\} \qquad (2)$$

$\frac{dV}{dt}$ = acceleration tangent to flight path,

$V\frac{d\gamma}{dt}$ = acceleration normal to flight path,

$\frac{d^2\theta}{dt^2}$ = angular acceleration about lateral axis.

We assume that the effects of angular velocity and acceleration on C_L and C_D are negligible, and thus that C_L and C_D are functions of α and δ only; therefore we may write:

$$\Delta C_D = \frac{\partial C_D}{\partial \alpha}\Delta\alpha + \frac{\partial C_D}{\partial \delta}\delta \, , \qquad \Delta C_L = \frac{\partial C_L}{\partial \alpha}\Delta\alpha + \frac{\partial C_L}{\partial \delta}\delta . \qquad (3)$$

However, the effect of angular velocity on C_m must be taken into account. The pitching moment due to rate of pitch is almost entirely due to the fact that the angle of attack of the tail surface is affected by rotational velocity about the lateral axis.

If l is the distance from the center of gravity to the center of pressure on the tail surface, a positive rate of pitch causes the tail to move downward with a velocity ql relative to the center of gravity, which effectively changes its angle of attack by amount $\Delta\alpha_t$ given by

$$\tan \Delta\alpha_t = ql/V . \qquad (4)$$

This in turn changes the lift on the tail and gives rise to a pitching moment.

The effect of rate of change of α and δ on the pitching moment is often neglected, but with certain types of airplanes and gliders and

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with certain types of control methods, the effect is not negligible, and must be taken into account. It is due to the effect of downwash produced by the main wing on the tail surface. There is a time lag between the creation of the downwash by the wings and its action on the tail, the downwash on the tail at any instant being apparently that due to the wings when they were in the position which is now occupied by the tail. C_m is thus a function of α , δ , q , $\dot{\alpha}$, and $\dot{\delta}$. Thus we may write:

$$\Delta C_m = \frac{\partial C_m}{\partial \alpha}\Delta\alpha + \frac{\partial C_m}{\partial \delta}\delta + \frac{\partial C_m}{\partial q}q + \frac{\partial C_m}{\partial \dot{\alpha}}\dot{\alpha} + \frac{\partial C_m}{\partial \dot{\delta}}\dot{\delta}. \qquad (5)$$

In the above expressions the quantities $\Delta\alpha$, ΔV , q , $\dot{\alpha}$, $\dot{\delta}$, and δ are considered small, and terms involving products of two or more of them are neglected. From equations (1):

$$\left.\begin{aligned} W\cos\gamma &= \tfrac{1}{2}\rho S V^2 C_L \\ W\sin\gamma &= -\tfrac{1}{2}\rho S V^2 C_D \\ C_m &= 0 \end{aligned}\right\} \qquad (6)$$

Substituting in (2):

$$\left.\begin{aligned} &-\tfrac{1}{2}\rho S V^2 C_L \Delta\gamma - \rho S V^2 C_D \frac{\Delta V}{V} - \tfrac{1}{2}\rho S V^2 \frac{\partial C_D}{\partial \alpha}\Delta\alpha - \tfrac{1}{2}\rho S V^2 \frac{\partial C_D}{\partial \delta}\delta = m\frac{dV}{dt} \\ &\tfrac{1}{2}\rho S V^2 C_D \Delta\gamma - \rho S V^2 C_L \frac{\Delta V}{V} - \tfrac{1}{2}\rho S V^2 \frac{\partial C_L}{\partial \alpha}\Delta\alpha - \tfrac{1}{2}\rho S V^2 \frac{\partial C_L}{\partial \delta}\delta = -mV\frac{d\gamma}{dt} \\ &\tfrac{1}{2}\rho S V^2 c \frac{\partial C_m}{\partial \alpha}\Delta\alpha + \tfrac{1}{2}\rho S V^2 c \frac{\partial C_m}{\partial \delta}\delta + \tfrac{1}{2}\rho S V^2 c \frac{\partial C_m}{\partial q}q \\ &\quad + \tfrac{1}{2}\rho S V^2 c \frac{\partial C_m}{\partial \dot{\alpha}}\dot{\alpha} + \tfrac{1}{2}\rho S V^2 c \frac{\partial C_m}{\partial \dot{\delta}}\dot{\delta} = B\frac{d^2\theta}{dt^2} \end{aligned}\right\} \qquad (7)$$

Let

$$\left.\begin{aligned} &v = \frac{\Delta V}{V} \qquad L_\delta = \frac{\partial L}{\partial \delta} \qquad M_\alpha = \frac{\partial M}{\partial \alpha} \\ &L = \frac{\tfrac{1}{2}\rho S V^2 C_L}{m} \qquad D_\alpha = \frac{\partial D}{\partial \alpha} \qquad M_q = \frac{\partial M}{\partial q} \\ &D = \frac{\tfrac{1}{2}\rho S V^2 C_D}{m} \qquad D_\delta = \frac{\partial D}{\partial \delta} \qquad M_\delta = \frac{\partial M}{\partial \delta} \\ &L_\alpha = \frac{\partial L}{\partial \alpha} \qquad M = \frac{\tfrac{1}{2}\rho S V^2 c\, C_m}{B} \qquad M_{\dot{\alpha}} = \frac{\partial M}{\partial \dot{\alpha}} \\ &M_{\dot{\delta}} = \frac{\partial M}{\partial \dot{\delta}} \end{aligned}\right\} \qquad (8)$$

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We then obtain:

$$\left.\begin{array}{l} L\Delta\gamma + 2Dv + D_\alpha \Delta\alpha + D_\delta \delta + V\frac{dv}{dt} = 0 \\ -D\Delta\gamma + 2Lv + L_\alpha \Delta\alpha + L_\delta \delta - V\frac{d\gamma}{dt} = 0 \\ M_q(\dot{\gamma}+\dot{\alpha}) + M_\alpha \Delta\alpha + M_\delta \delta + M_{\dot{\alpha}}\dot{\alpha} + M_{\dot{\delta}}\dot{\delta} - \ddot{\gamma} - \ddot{\alpha} = 0 \end{array}\right\} \qquad (9)$$

These equations must be satisfied at each instant of flight.

Let us assume as solutions that $\Delta\gamma$, $\Delta\alpha$, and v, vary with the time according to laws of the form:

$$\Delta\gamma = \Delta\gamma_0 e^{\lambda t}, \quad \Delta\alpha = \Delta\alpha_0 e^{\lambda t}, \quad v = v_0 e^{\lambda t} \qquad (10)$$

and determine what values of λ will cause the above equations to be satisfied. If λ is positive, the quantities $\Delta\gamma$, $\Delta\alpha$, and v, will increase with the time, and the motion will be unstable. If λ is negative, these quantities will decrease and the motions will be stable. If λ is complex, the motions will be oscillatory, with increasing or decreasing amplitude depending upon the sign of the real part of λ.

Putting these values of $\Delta\gamma$, $\Delta\alpha$, and v into equations (9), we have the following equations to solve:

$$\left.\begin{array}{lll} L\Delta\gamma & + D_\alpha \Delta\alpha & + (2D + \lambda V)v + D_\delta \delta = 0 \\ -(D+\lambda V)\Delta\gamma & + L_\alpha \Delta\alpha & + 2Lv + L_\delta \delta = 0 \\ (\lambda M_q - \lambda^2)\Delta\gamma + (M_\alpha + \lambda M_q + \lambda M_{\dot{\alpha}} - \lambda^2)\Delta\alpha & & + (M_\delta + \lambda M_{\dot{\delta}})\delta = 0 \end{array}\right\} \qquad (11)$$

We thus have only three equations involving four variables. So far nothing has been said concerning the variation of δ with time.

2. Stability with Fixed Control Surfaces

Let us first consider the case of fixed control surfaces. ($\delta = 0$).
The solution of the above equations will give the resulting motion due to

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a small disturbance in any of the variables. To determine what values of λ satisfy the above equations, it is only necessary to determine what values of λ make the following determinant vanish.

$$\begin{vmatrix} L & D_\alpha & 2D+\lambda V \\ -D-\lambda V & L_\alpha & 2L \\ \lambda M_q-\lambda^2 & M_\alpha+\lambda M_q+\lambda M_{\dot\alpha}-\lambda^2 & 0 \end{vmatrix} = 0. \tag{12}$$

Solving the above determinant, we obtain the following equation for λ :

$$\begin{aligned} &\lambda^4+\left[\frac{3D}{V}-M_q-M_{\dot\alpha}+\frac{L_\alpha}{V}\right]\lambda^3+\left[\frac{2R^2}{V^2}-M_q\left(\frac{3D}{V}+\frac{L_\alpha}{V}\right)-M_{\dot\alpha}\left(\frac{3D}{V}\right)\right. \\ &\left.-M_\alpha+2\left(\frac{DL_\alpha-LD_\alpha}{V^2}\right)\right]\lambda^2+\left[-2M_q\left(\frac{R^2}{V^2}+\frac{DL_\alpha-LD_\alpha}{V^2}\right)\right. \\ &\left.-2M_{\dot\alpha}\left(\frac{R^2}{V^2}\right)-\frac{3D}{V}M_\alpha\right]\lambda-\frac{2R^2}{V^2}M_\alpha=0, \end{aligned} \tag{13}$$

where

$$R^2 = L^2 + D^2 .$$

We may write the above equation in the form

$$\lambda^4 + B\lambda^3 + C\lambda^2 + D\lambda + E = 0 \tag{14}$$

where

$$\left.\begin{aligned} B &= -M_q-M_{\dot\alpha}+\frac{L_\alpha+3D}{V} \\ C &= -M_\alpha-M_q\left(\frac{L_\alpha+3D}{V}\right)-M_{\dot\alpha}\left(\frac{3D}{V}\right)+2\left(\frac{R^2+DL_\alpha-LD_\alpha}{V^2}\right) \\ D &= -2M_q\left(\frac{R^2+DL_\alpha-LD_\alpha}{V^2}\right)-2M_{\dot\alpha}\left(\frac{R^2}{V^2}\right)-M_\alpha\left(\frac{3D}{V}\right) \\ E &= -2\frac{R^2}{V^2}M_\alpha \end{aligned}\right\} \tag{15}$$

Thus the determination of the values of λ which satisfy equation (14) depends upon the solution of a fourth degree equation. There is no simple direct way of solving fourth degree equations. However, there are various

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methods of attacking the problem. In some cases, it is possible to factor the biquadratic into two quadratics, each of which may be directly solved. (Ref. 1, page 5).

The possible solutions of a biquadratic are four real values, two real and one pair of complex values, or two pairs of complex values. The values of B , C , D , and E obtained for a conventional type aircraft are usually such that there are two pairs of complex values, one pair whose imaginary part is small compared to the imaginary part of the other pair. These correspond to two sinusoidal variations of the flight path, the angle of attack, attitude angle, and velocity along the flight path whose amplitudes increase or decrease exponentially with the time depending upon the sign of the real part. The real parts of all roots will be negative corresponding to the stable condition if all coefficients are positive and Routh's Discriminant ($BCD-D^2-B^2E$) is positive.

The pair giving a small imaginary part corresponds to the long-period oscillation, sometimes called the "phugoid", observed as a long-period oscillation in the airspeed, flight path, etc., while the pair giving a large imaginary part corresponds to the so-called "rapid incidence adjustment", which causes the glider to quickly attain its trim angle of attack.

Let us examine the coefficients of the various terms in the biquadratic in λ , and determine the important contribution of each term to the period and damping coefficients of the two oscillations. The three terms in B are of the same order of magnitude. In C , however, the term M_α is large compared to the other terms. In D the term $M_\alpha D/V$ is large compared to other terms. Thus the biquadratic in λ may be written:

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$$\lambda^4 + \left(-M_q - M_{\dot{\alpha}} + \frac{L_\alpha}{V}\right)\lambda^3 - M_\alpha \lambda^2 - \frac{3M_\alpha D}{V}\lambda - \frac{2L^2 M_\alpha}{V^2} = 0. \tag{16}$$

Let us consider the biquadratic to be the product of two quadratics

$$(\lambda^2 + B'\lambda + C')\left(\lambda^2 + \frac{D'}{C'}\lambda + \frac{E'}{C'}\right) = 0 \tag{17}$$

and determine what conditions must be satisfied between the coefficients in order that this approximation may be justified. Multiplying, we have:

$$\lambda^4 + \left(B' + \frac{D'}{C'}\right)\lambda^3 + \left(C' + \frac{B'D'}{C'} + \frac{E'}{C'}\right)\lambda^2 + \left(D' + \frac{B'E'}{C'}\right)\lambda + E' = 0. \tag{18}$$

Thus the conditions to be satisfied are:

$$B' \gg \frac{D'}{C'}, \qquad C' \gg \frac{B'D' + E'}{C'}, \qquad D' \gg \frac{B'E'}{C'}. \tag{19}$$

Since C' is large compared to all other terms, these conditions are usually satisfied. Thus we have:

$$\left[\lambda^2 + \left(-M_q - M_{\dot{\alpha}} + \frac{L_\alpha}{V}\right)\lambda - M_\alpha\right]\left[\lambda^2 + \frac{3D}{V}\lambda + 2\frac{L^2}{V^2}\right] = 0 \tag{20}$$

$$\lambda_1 = \frac{M_q + M_{\dot{\alpha}} - L_\alpha/V}{2} \pm i\sqrt{-M_\alpha - \left(\frac{M_q + M_{\dot{\alpha}} - L_\alpha/V}{2}\right)^2} \tag{21}$$

$$\lambda_2 = -\frac{3D}{2V} \pm i\sqrt{\frac{2L^2}{V^2} - \left(\frac{3D}{2V}\right)^2}. \tag{22}$$

The first pair λ_1, represents the so-called "rapid incidence adjustment". The period of the short period oscillation is determined chiefly by M_α, the pitching moment due to angle of attack change. Thus M_α may be thought of as a spring constant or restoring force. The damping of the short period oscillation is due to three effects, the pitching moment due to rate of pitch, the pitching moment due to the rate of change of α, and the term $\frac{L_\alpha}{V}$ which arises from the change in flight path due to changes in lift produced from angle of attack changes. It is this short-period

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oscillation which occurs when an aircraft flies suddenly into what may be called a sharp-edged gust; i.e., into air which is moving with a vertical velocity different from that of the air from which it has emerged. The large transient acceleration provides the "bump" felt by occupants of the airplane under these circumstances. This short-period oscillation also occurs when a glider is released from the parent aircraft. Since, in general, the angle of attack at release is quite different from the trim value, a large pitching moment is produced which puts the glider in trim with a highly damped short-period oscillation.

The second pair of solutions λ_2 represents a long-period oscillation which was first studied by Lanchester, considering an idealized airplane upon which the air reaction is always perpendicular to the direction of motion and proportional to the square of the speed. This is equivalent to neglecting the drag force. Since his assumptions correspond to a conservative field of force, he was able to compute simply and exactly all possible forms the flight path can take in a vertical plane. No general solutions have been found which take into account the drag. Since drag forces are usually fairly small compared to lift forces, the flight paths of Lanchester, which he called "phugoids", bear a close resemblance to actual flight paths. The long-period oscillations obtained may be considered to correspond to exchanges of kinetic and potential energy. During one part of the cycle the altitude of the flight path is at a minimum and the speed is at a maximum. One-half cycle later, the altitude reaches a maximum and the speed a minimum, and thus between these points kinetic energy is transformed into potential energy. The reverse takes place in

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the next half cycle. Since Lanchester dealt with a conservative system, his "phugoids" were undamped. However, it can be easily seen that the effect of drag would be such as to damp the oscillations. During the part of the cycle while the airplane is falling, it moves slightly faster than it would were the drag to remain constant, and while rising it moves slightly slower. Thus during the falling period the lift is higher, and during the rising period it is lower than it would have been were the drag to remain constant. A term is thus introduced which opposes the vertical motion, and is thus a damping term. The period obtained by Lanchester for oscillations of small amplitude is

$$T = \frac{\sqrt{2}\,\pi V}{g}. \qquad (23)$$

From the second solution of equation (22), the period is found to be:

$$T = \frac{2\pi}{\sqrt{\frac{2L^2}{V^2} - \left(\frac{gD}{2V}\right)^2}}, \qquad (24)$$

which, when we neglect the drag, and assume the lift equal to the weight ($L = g$), is the Lanchester result. In the complete solution of the biquadratic, the period is affected by both the drag and the damping terms in the coefficient "B" of the complete quartic.

3. Stability of Homing Gliders

So far we have only considered the motions of a glider with fixed control surfaces. Now let us consider the case of a glider with a servo system which moves the control surfaces in such a way as to make the glider fly toward a target; that is, a homing glider. As discussed in reference (2),

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it is necessary for accurate homing to keep the axis of the intelligence device pointed in the direction of the flight path. The SWOD Mark 12 and Mark 13 gliders fly with an angle of attack substantially independent of elevon position. The intelligence device is mounted at this angle of attack to the longitudinal axis, and thus remains pointed in the direction of flight.

The manner in which the control surfaces are caused to move in response to the homing intelligence depends upon the characteristics of the servo-mechanism. In general terms, the characteristics of a servomechanism may be represented in the following form. We may write

$$f(\delta, \dot{\delta}, \ddot{\delta}, \dots, \theta, \dot{\theta}, \ddot{\theta}, \dots) = 0, \qquad (25)$$

where f denotes a function dependent upon the particular servomechanism used.

It is not possible to compute the effect of a general functional relation of the type described by equation (25) on the longitudinal motion of the glider, and it is not practicable to consider all possible specific relations which have been used as a basis for the design of servomechanisms. It has in fact not been feasible to approximate the performance of the type of servomechanism used in SWOD Mark 7 and Mark 9, which involves an on-off link between the gyros and servo unit, by the functional relation (25), and the stability was studied by an electro-mechanical model of the glider in which the actual gyro and servo unit were incorporated. (See Ref. 3).

As an illustration of the effect of the application of a homing condition on the longitudinal stability of a glider, we shall consider a simple ideal servomechanism in which the control surface displacement is a linear function of the error angle and of the rate of change of error angle.

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Let us assume that equilibrium has been established in flight with the controls in such a position that the direction of flight is toward the target. We now impose the following condition which must be added to the three given in equations (11):

$$\delta + K\left(\Delta\theta + c\frac{d\theta}{dt}\right) = 0. \tag{26}$$

Equations (11) now become:

$$\left.\begin{array}{llll}
L\Delta\gamma & + D_\alpha\Delta\alpha & + (2D+\lambda V)v & + D_\delta\delta = 0 \\
-(D+\lambda V)\Delta\gamma & + L_\alpha\Delta\alpha & + 2Lv & + L_\delta\delta = 0 \\
(\lambda M_q - \lambda^2)\Delta\gamma & + (M_\alpha + \lambda M_q + \lambda M_{\dot\alpha} - \lambda^2)\Delta\alpha & & + (M_\delta + \lambda M_{\dot\delta})\delta = 0 \\
K(\lambda+c)\Delta\gamma & + K(\lambda+c)\Delta\alpha & & + \delta = 0
\end{array}\right\} \tag{27}$$

In order to determine the values of λ which satisfy the above equations, it is only necessary to determine what values of λ make the following determinant vanish.

$$\begin{vmatrix}
L & D_\alpha & 2D+\lambda V & D_\delta \\
-D-\lambda V & L_\alpha & 2L & L_\delta \\
\lambda M_q - \lambda^2 & M_\alpha + \lambda M_q + \lambda M_{\dot\alpha} - \lambda^2 & 0 & M_\delta + \lambda M_{\dot\delta} \\
K(\lambda+c) & K(\lambda+c) & 0 & 1
\end{vmatrix} \tag{28}$$

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Evaluating this determinant yields a fourth degree equation in given by

$$\lambda^4 + F\lambda^3 + G\lambda^2 + H\lambda + J = 0 \qquad (29)$$

where

$$F = \frac{\frac{L_\alpha + 3D}{V} + KM_\delta - M_q - M_{\dot\alpha} + K\left(\frac{3D}{V} + c\right)M_{\dot\delta}}{1 + KM_{\dot\delta}}$$

$$G = \frac{\frac{2(R^2 + DL_\alpha - LD_\alpha)}{V^2} - M_\alpha\left(1 + \frac{KL_\delta}{V}\right) + KM_\delta\left(\frac{L_\alpha + 3D}{V} + c\right)}{1 + KM_{\dot\delta}}$$

$$+ \frac{-M_q\left(\frac{L_\alpha + 3D}{V}\right) - M_{\dot\alpha}\left[\frac{2K(DL_\delta - LD_\delta)}{V^2} + \frac{3D}{V}\right] + KM_{\dot\delta}\left[\frac{2(R^2 + DL_\alpha - LD_\alpha)}{V^2} + \frac{3cD}{V}\right]}{1 + KM_{\dot\delta}}$$

$$H = \frac{-M_\alpha\left[\frac{2K(DL_\delta - LD_\delta)}{V^2} + \frac{KcL_\delta}{V} + \frac{3D}{V}\right] + KM_\delta\left[\frac{2(R^2 + DL_\alpha - LD_\alpha)}{V^2} + \frac{c(L_\alpha + 3D)}{V}\right]}{1 + KM_{\dot\delta}}$$

$$+ \frac{-M_q\frac{2(R^2 + DL_\alpha - LD_\alpha)}{V^2} - M_{\dot\alpha}\left[\frac{2Kc(DL_\delta - LD_\delta)}{V^2} + \frac{2R^2}{V^2}\right] + \frac{2cKM_{\dot\delta}(R^2 + DL_\alpha - LD_\alpha)}{V^2}}{1 + KM_{\dot\delta}}$$

$$J = \frac{-M_\alpha\left[\frac{2Kc(DL_\delta - LD_\delta)}{V^2} + \frac{2R^2}{V^2}\right] + cKM_\delta\frac{2(R^2 + DL_\alpha - LD_\alpha)}{V^2}}{1 + KM_{\dot\delta}} \qquad (30)$$

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In order to investigate the types of solutions obtained, let us determine which are the important terms in the above expressions. Terms in $M_{\dot{\delta}}$ may be neglected (except for large K), terms in M_q and $M_{\dot{\alpha}}$ may be neglected in all terms except F, and $3D$ may be neglected compared to L. Thus we may write:

$$\left.\begin{aligned} F &= \frac{L_\alpha}{V} - M_q - M_{\dot{\alpha}} + KM_\delta \\ G &= -M_\alpha\left(1 + K\frac{L_\delta}{V}\right) + KM_\delta\left(\frac{L_\alpha}{V} + c\right) \\ H &= -M_\alpha\left[\frac{2K(DL_\delta - LD_\delta)}{V^2} + \frac{cKL_\delta}{V} + \frac{3D}{V}\right] + \frac{cKL_\alpha M_\delta}{V} \\ J &= -M_\alpha\left[\frac{2cK(DL_\delta - LD_\delta)}{V^2} + \frac{2L^2}{V^2}\right] + cKM_\delta\frac{2(L^2 - LD_\alpha + DL_\alpha)}{V^2} \end{aligned}\right\} \tag{31}$$

Except for large values of K, G will be large compared to F, H, and J, and we may write as a first approximation:

$$\left(\lambda^2 + F\lambda + G\right)\left(\lambda^2 + \frac{H}{G}\lambda + \frac{J}{G}\right) = 0 \tag{32}$$

Inserting the approximate values of F, G, H, and J above, we have

$$\left.\begin{aligned} &\left[\lambda^2 + \left(\frac{L_\alpha}{V} - M_q - M_{\dot{\alpha}} + KM_\delta\right) - M_\alpha\left(1 + \frac{KL_\delta}{V}\right) + KM_\delta\left(\frac{L_\alpha}{V} + c\right)\right]\Bigg[\lambda^2 + \\ &\frac{\frac{3D}{V} + \frac{2K(DL_\delta - LD_\delta)}{V^2} + \frac{cKL_\delta}{V} - \frac{M_\delta}{M_\alpha}\frac{cKL_\alpha}{V}}{1 + \frac{KL_\delta}{V} - K\frac{M_\delta}{M_\alpha}\left(\frac{L_\alpha}{V} + c\right)} \\ &\quad + \frac{\frac{2L^2}{V^2} + \frac{2cK(DL_\delta - LD_\delta)}{V^2} - \frac{2cKM_\delta}{M_\alpha}\frac{(L^2 + DL_\alpha - LD_\alpha)}{V^2}}{1 + \frac{KL_\delta}{V} - K\frac{M_\delta}{M_\alpha}\left(\frac{L_\alpha}{V} + c\right)}\Bigg] = 0 \end{aligned}\right\} \tag{33}$$

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This equation is identical with equation (20) except for the terms involving K. Equating the quantity in the first set of brackets to zero, gives a pair of complex roots corresponding to a highly damped, short-period oscillation, the so-called "rapid incidence adjustment". For gliders whose pitch control is obtained from conventional type elevators on the tail surface, the effect of the application of the homing condition is to increase the damping and decrease the period of this oscillation.

Equating the quantity in the second set of brackets to zero, gives, for small values of K, a pair of complex roots corresponding to a damped long period oscillation or "phugoid". For larger values of K, it gives two real roots, and the "phugoid" is not obtained.

If the quantity $(DL_\delta - LD_\delta)$ is positive, that is, if the ratio L/D increases with increasing δ, the roots will both be negative, yielding two subsidences. If the quantity $(DL_\delta - LD_\delta)$ is negative, that is, if the ratio L/D decreases with increasing δ, it is possible to obtain a positive root which yields a divergence. It should be stated, however, that the controls on homing gliders are usually designed so that this quantity $(DL_\delta - LD_\delta)$ is positive under normal flight conditions. Such a condition of equilibrium with the quantity $(DL_\delta - LD_\delta)$ negative is generally not obtained unless the glider is released at an excessively low speed or at an excessively flat glide angle to the target.

It may be mentioned here that for very large values of K, a type of divergence is obtained in control systems when $M_{\dot\delta}$ is negative and has an appreciable value. If K is sufficiently large so that $-KM_{\dot\delta} > 1$ equations (29) will have a real positive root, yielding a divergence.

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It should be pointed out that all the above results are obtained by considering a particular type of ideal linear servomechanism and do not have general application.

4. Application to SWOD Mark 7 and Mark 9 Homing Gliders

The following is a table of values of the coefficients applicable to the SWOD gliders:

	Navy SWOD Mark 12	Navy SWOD Mark 13
W (lbs)	500	1500
S (ft^2)	18.3	64.4
c (ft)	2.20	2.75
B (lb ft sec^2)	90	180
$\frac{\partial C_L}{\partial \alpha}$	4.0	4.0
$\frac{\partial C_L}{\partial \delta}$	.8	.8
$\frac{\partial C_m}{\partial C_L}$	-.15	-.10
$\frac{\partial C_m}{\partial (\frac{qc}{V})}$	-2.5	-2.8
$\frac{\partial C_m}{\partial (\frac{\dot{\alpha} c}{V})}$	-2.0	-1.4
$\frac{\partial C_m}{\partial (\frac{\dot{\delta} c}{V})}$	-.4	-.3

These values were obtained from wind tunnel tests of the SWOD Mark 12 and Mark 13 gliders conducted at N.A.C.A. Laboratories at Langley Field, Va.

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The results on SWOD Mark 12 are presented in Reference (4) and for SWOD Mark 13 in Reference (5).

Since the publication of Reference (5) and as a result of data obtained in these tests, the center of gravity position was moved 3 inches aft, and the values in the above table take into account this change.

The values of the coefficients vary somewhat with position of eleven and angle of attack, and the values given are average values over the ranges commonly encountered in flight.

No measurements of the damping coefficients, $\frac{\partial C_m}{\partial(\frac{q\ell}{V})}$, $\frac{\partial C_L}{\partial(\frac{q\ell}{V})}$, and $\frac{\partial C_m}{\partial(\frac{\dot{\alpha}\ell}{V})}$ were made in these wind tunnel tests, and the values given are calculated from the physical dimensions of the glider and other wind tunnel determined coefficients.

The value of $\frac{\partial C_m}{\partial q}$ may be estimated, following the procedure given in Reference (1). Assume the glider rotates about its lateral axis with angular velocity q. A positive rotation q causes the tail to move downward with a velocity $q\ell$ relative to the center of gravity, where ℓ is the effective distance of the tail from the center of gravity. This causes a change in the effective angle of attack of the tail $\Delta\alpha_t$ given by:

$$\tan \Delta\alpha_t = \frac{q\ell}{V},$$

which for small angles under consideration may be replaced by:

$$\Delta\alpha_t = \frac{q\ell}{V}. \quad (34)$$

The change in moment due to the change in angle of attack of the tail is:

$$\Delta M = \eta_t \frac{1}{2}\rho S_t V^2 \ell \frac{\partial C_{L_t}}{\partial \alpha_t} \Delta\alpha_t, \quad (35)$$

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where $\frac{\partial C_{N_t}}{\partial \alpha_t}$ is the rate of change of normal force on the tail with angle of attack of the tail, S_t is the horizontal tail-surface area, and η_t is an empirical factor, called the tail efficiency, which has a value of the order of 0.7 to 0.8. Let us then write:

$$-\frac{\partial C_m}{\partial q} = K\eta_t \frac{\ell}{c}\frac{S_t}{S}\frac{\partial C_{N_t}}{\partial \alpha_t}\frac{\ell}{V}. \qquad (36)$$

The factor K is inserted to take into account the damping due to the wing. In general, the contribution of the wing is about 25% that of the tail; thus we may take $K = 1.25$. From Reference (5), Fig. (9), tests made with the wings off and stabilizer and fins on, the slope of the lift coefficient of the tail as a function of angle of attack of the tail is approximately:

$$\frac{S_t}{S}\frac{\partial C_{L_t}}{\partial \alpha_t} = 1.25.$$

Since the normal force is practically equal to the lift at normal angles of attack, we may use the above value for $\frac{\partial C_{N_t}}{\partial \alpha_t}$. The factor $\frac{S_t}{S}$ is to take into account the fact that the lift coefficients in Reference (5) are referred to the wing area instead of the horizontal tail surface area:

$$-\frac{\partial C_m}{\partial\left(\frac{qc}{V}\right)} = K\eta_t \frac{\ell^2}{c^2}\left(\frac{S_t}{S}\frac{\partial C_{L_t}}{\partial \alpha_t}\right). \qquad (37)$$

For SWOD Mark 13 ℓ may be taken to be about 4.13 ft, and thus $\frac{\ell}{c} = 1.5$. If we assume then $\eta_t = 0.8$ $\qquad K = 1.25$

$$\frac{\partial C_m}{\partial\left(\frac{qc}{V}\right)} = -2.6.$$

The values of $\frac{\partial C_m}{\partial\left(\frac{\dot{\alpha} c}{V}\right)}$ and $\frac{\partial C_m}{\partial\left(\frac{\dot{\delta} c}{V}\right)}$ may be obtained as follows: Denote the time lag between the creation of the downwash by the wings and

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the resultant effect on the tail in the downwash by Δt, and the resultant change in the angle of downwash by $\Delta\epsilon$. The effective change in angle of attack of the tail due to change in downwash angle is equal to $\Delta\epsilon$. Since the angle of downwash is a function of the lift, which in turn is a function of α and δ, we have

$$\Delta\alpha_t = \Delta\epsilon = \frac{\partial\epsilon}{\partial\alpha}\Delta\alpha + \frac{\partial\epsilon}{\partial\delta}\delta$$

$$= \frac{\partial\epsilon}{\partial\alpha}\dot{\alpha}\Delta t + \frac{\partial\epsilon}{\partial\delta}\dot{\delta}\Delta t$$

The time lag Δt is equal to $\frac{l}{V}$, so we have:

$$\Delta\alpha = \frac{\partial\epsilon}{\partial\alpha}\frac{l}{V}\dot{\alpha} + \frac{\partial\epsilon}{\partial\delta}\frac{l}{V}\dot{\delta}. \tag{38}$$

Substituting this value of $\Delta\alpha_t$ in equation (35):

$$\Delta M = \eta_t \frac{1}{2}\rho S_t V^2 l \frac{\partial C_{L_t}}{\partial\alpha_t}\left[\frac{\partial\epsilon}{\partial\alpha}\frac{l}{V}\dot{\alpha} + \frac{\partial\epsilon}{\partial\delta}\frac{l}{V}\dot{\delta}\right] \tag{39}$$

Thus we have:

$$\frac{\partial C_m}{\partial\dot{\alpha}} = K\eta_t \frac{l}{c}\frac{S_t}{S}\frac{\partial C_{L_t}}{\partial\alpha_t}\frac{l}{V}\frac{\partial\epsilon}{\partial\alpha} = \frac{\partial C_m}{\partial q}\frac{\partial\epsilon}{\partial\alpha} \tag{40}$$

$$\frac{\partial C_m}{\partial\dot{\delta}} = K\eta_t \frac{l}{c}\frac{S_t}{S}\frac{\partial C_{L_t}}{\partial\alpha_t}\frac{l}{V}\frac{\partial\epsilon}{\partial\delta} = \frac{\partial C_m}{\partial q}\frac{\partial\epsilon}{\partial\delta} \tag{41}$$

From Reference (5), $\frac{\partial\epsilon}{\partial\alpha}$ in the region of the tail is about 0.5.

Thus we may take $\frac{\partial C_m}{\partial\left(\frac{\dot{\alpha}c}{V}\right)} = -1.4$.

Since $\frac{\partial C_L}{\partial\delta} = 0.2\frac{\partial C_L}{\partial\alpha}$, $\frac{\partial\epsilon}{\partial\delta} = 0.2\frac{\partial\epsilon}{\partial\alpha}$.

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Thus we may take $\frac{\partial C_m}{\partial(\frac{q}{V})}$ = 0.2 (-1.4) = -0.28.

The lower value of $\frac{\partial C_m}{\partial C_L}$ for Mark 13 than for Mark 12 is due chiefly to the fact that the center of gravity is relatively farther back in Mark 13. This shift in the center of gravity was necessary in Mark 13 in order to maintain a more nearly constant angle of attack for all positions of the elevons. The elevon type control was used in Mark 12 and 13 in order to obtain an airframe that would maintain a nearly constant angle of attack with elevon position. This is accomplished by balancing the negative pitching moment on the wing produced by lowering the elevons by a positive pitching moment produced by the increase in downwash angle at the tail, which in turn is due to the increased lift on the wing. Since the horizontal tail surface is relatively lower in Mark 13 than in Mark 12, it is in a region of smaller downwash. This necessitates a movement of the center of gravity to the rear to maintain the balance between these moments, and to produce a nearly constant angle of attack with elevon position. The values of $\frac{\partial C_m}{\partial \alpha}$ and $\frac{\partial C_m}{\partial \delta}$ for Mark 12 are somewhat larger than those for Mark 13 due to the above-mentioned fact that the angle of downwash at the region of the horizontal tail surface is larger on Mark 12 than on Mark 13.

Let us now substitute the above values into the stability equations for Mark 13 for a typical condition of flight, with fixed controls in pitch.

Assume C_L = 0.3 and C_D = 0.06, which corresponds approximately to δ = -10°. At equilibrium this gives a velocity given by:

$W = C_L \cdot 1/2 \rho S V^2 = mg$ $\qquad\qquad V = 415$ ft/sec.

At this lift coefficient, the following quantities have the values given:

$L = 32$ $\qquad D = 6.4$ $\qquad L_\alpha = 427$ $\qquad D_\alpha = 38.4$ $\qquad$ (4a)

$M_\alpha = -30.6$ $\qquad M_q = -1.4$ $\qquad M_\delta = -.7$

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Substituting these values in equations (15):

$B = 3.18$ $\qquad$ $C = 32.2$ $\qquad$ $D = 1.47$ $\qquad$ $E = 0.378$

$$\lambda^4 + 3.18\lambda^3 + 32.2\lambda^2 + 1.47\lambda + 0.378 = 0. \qquad (43)$$

Let us assume this biquadratic to be factored into the two following quadratics:

$$(\lambda^2 + a_1\lambda + b_1)(\lambda^2 + a_2\lambda + b_2) = 0. \qquad (44)$$

Multiplying out, we have:

$$\lambda^4 + (a_1+a_2)\lambda^3 + (a_1a_2+b_1+b_2)\lambda^2 + (a_1b_2+a_2b_1)\lambda + b_1b_2 = 0. \qquad (45)$$

Thus we must determine a_1, a_2, b_1, and b_2 to satisfy the following relations:

$$B = a_1 + a_2 \qquad C = a_1a_2 + b_1 + b_2$$
$$D = a_1b_2 + a_2b_1 \qquad E = b_1b_2 \qquad (46)$$

As a first approximation, let $a_1 = B = 3.18$, $\quad b_1 = C = 32.2$

Then $\quad b_2 = \frac{E}{C} = 0.01173 \qquad a_2 = \frac{D}{C} - \frac{BE}{C^2} = 0.0444$

As a second approximation, let $a_1 = B - a_2 = 3.136$, $\quad b_1 = C - b_2 - a_1a_2 = 32.05$.

Repeating this process, we obtain finally:

$$(\lambda^2 + 3.135\lambda + 32.05)(\lambda^2 + 0.0447\lambda + 0.01180) = 0$$
$$\lambda_1 = -1.566 \pm 5.44i \qquad (47)$$
$$\lambda_2 = -0.0224 \pm 0.106i$$

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Thus the quantities $\Delta\alpha$, $\Delta\gamma$, and v will be given by equations of the type:

$$\Delta\alpha, \Delta\gamma, v = A_1 e^{-1.568t} \cos(5.44t + \epsilon_1) + A_2 e^{-0.0224t} \cos(0.106t + \epsilon_2) \qquad (48)$$

where A_1, A_2, ϵ_1, and ϵ_2 are arbitrary constants to be evaluated in each case. The first term on the right represents the "rapid incidence adjustment" discussed previously, which is a damped oscillation of period $T = \frac{2\pi}{5.44} = 1.16$ second, which damps to $\frac{1}{e}$ of its initial amplitude in 0.64 seconds. The second term in the right member is the so-called "phugoid", which for this case has a period of 59 seconds, and damps to $\frac{1}{e}$ of its initial amplitude in 45 seconds.

If we use the approximations discussed previously and given by equations (21) and (22), we obtain:

$$\Delta\alpha, \Delta\gamma, v = A_1 e^{-1.626t} \cos(5.31t + \epsilon_1) + A_2 e^{-0.0232t} \cos(0.108t + \epsilon_2) \qquad (49)$$

which solution differs very little in this case from the more exact values above.

Figure 1 shows the airspeed, altitude, and attitude in space as a function of the time of fall for a SWOD Mark 12 glider released from a parent airplane. The glider contained a single gyro for roll stabilization, but with the elevons fixed in average position ($\delta = 0$) for the first 36 seconds of flight. Then they were moved to full glide position ($\delta = +20°$), where they remained for the remainder of the flight. The "rapid incidence

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adjustment" is shown at the beginning of the flight, with a period of about one second, which compares favorably with the calculated value above. The long-period oscillation or "phugoid" is augmented by moving the elevons to full glide position. Its period is seen to be about 40 seconds. Calculating the period from the simplified formula, equation (23), using the average speed (about 165 knots = 280 ft/sec) from Figure 1 we obtain:

$$T = \frac{\sqrt{2}\,\pi\,(280)}{32} = 39.4 \text{ seconds,}$$

which agrees favorably with the period obtained from the above curve.

If we attempt to investigate the longitudinal stability of SWOD Mark 9 with its homing equipment and servo control system in operation, we are led to the result given in Part 3, e.g., that it is not feasible to approximate the performance of the servomechanism used in SWOD Mark 7 or Mark 9 by a functional relationship of the type given by equation (25). However, as an illustration of the effect of the application of a homing condition on the stability of the Mark 13 glider, we will consider the effect of the simple ideal servomechanism discussed in Part 3 on its longitudinal stability, and discuss briefly the effect of varying the parameters e and K of this servomechanism.

Let us assume the same typical condition of flight discussed in Part 4 for the case of fixed control surfaces, with the constants given in equations (42). The following additional constants for this flight condition are needed:

$$L_\delta = 55.3 \qquad D_\delta = 0 \qquad M_\delta = 0 \qquad M_{\dot\delta} = -0.14 \qquad (50)$$

Substituting these values in equations (30), we obtain:

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$$F = \frac{3.18 - .00648K - .14cK}{1 - .14K}$$

$$G = \frac{32.2 + 6.36K - .00648cK}{1 - .14K}$$

$$H = \frac{1.47 + .194K + 6.36cK}{1 - .14K}$$

$$J = \frac{.378 + .194cK}{1 - .14K}$$

The values of these coefficients for certain values of K and c are given in the following table:

Case No.	K	c	F	G	H	J	λ
1	0	0	3.18	32.2	1.47	.378	$-1.57 \pm 5.44i, -0.0224 \pm 0.1063i$
2	1	0	3.69	44.8	1.94	.440	$-1.83 \pm 6.43i, -0.0214 \pm 0.0972i$
3	1	.5	3.61	44.8	5.63	.552	$-1.74 \pm 6.44i, -0.0630 \pm 0.0918i$
4	1	1	3.53	44.8	9.33	.665	$-1.66 \pm 6.43i, -0.1052 \pm 0.0637i$
5	1	2	3.36	44.8	16.73	.891	$-1.49 \pm 6.44i, -0.317, -0.0643$
6	2	0	4.40	62.4	2.58	.525	$-2.18 \pm 7.58i, -0.0205 \pm 0.0893i$
7	2	.5	4.21	62.4	11.42	.794	$-2.02 \pm 7.59i, -0.0921 \pm 0.0665i$
8	2	1	4.01	62.4	20.3	1.064	$-1.84 \pm 7.61i, -0.265, -0.0656$
9	2	2	3.62	62.4	37.9	1.603	$-1.50 \pm 7.64i, -0.579, -0.0457$

Case No. 1 is, of course, the case with fixed controls discussed previously. In all cases except 5, 8, and 9, the biquadratic in λ has two pairs of complex roots, one pair corresponding to a highly damped short-period oscillation or "rapid incidence adjustment", and the other pair to a damped long-period oscillation, similar to the "phugoid" of the case with fixed controls. In cases 5, 8, and 9, however, the biquadratic in λ has one pair of complex roots, corresponding to the "rapid incidence adjustment",

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and two real negative roots, corresponding to two subsidences, one fairly rapid and one slow.

From Cases 1, 2, and 6, it is seen that increasing K , with c equal to zero, increases the damping and shortens the period of the rapid oscillation, and decreases the damping and increases the period of the slow oscillation.

From Cases 2, 3, 4, and 5, and again from Cases 6, 7, 8, and 9, it is seen that increasing c , with K remaining fixed, decreases the damping of the rapid oscillation, leaving its period virtually unchanged. The damping of the long-period oscillation is increased, and its period increased, until in Cases 5, 8, and 9, two subsidences are obtained in place of a damped oscillation. The rate of damping of the rapid subsidence depends largely upon the constants of the servomechanism. The slow subsidence appears as one of the main terms in variations of speed along the flight path, and its rate of damping is small because of the small accelerations produced by the effects of drag and rate of change of the ratio of lift to drag with elevon position.

October 15, 1945

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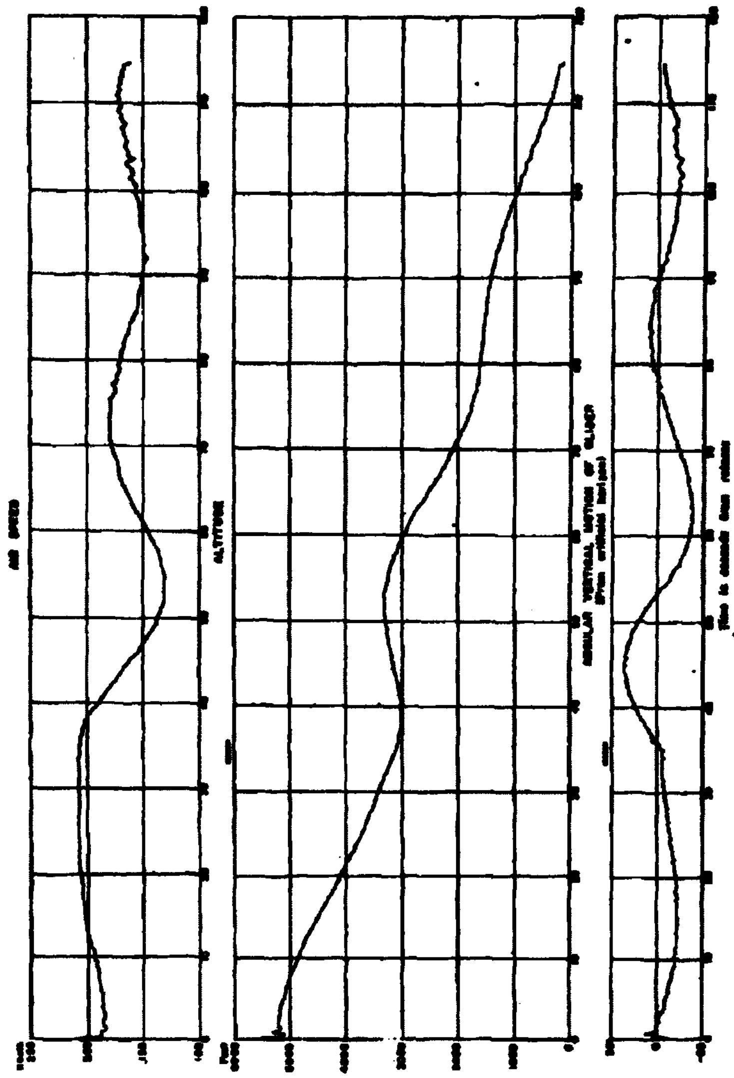

FIG. 1

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