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**DYNAMICS OF ULTRALIGHT AIRCRAFT -
DIVE RECOVERY OF HANG GLIDERS**

Robert T. Jones

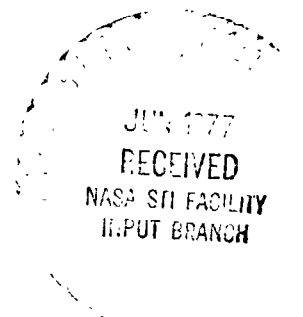
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DYNAMICS OF ULTRALIGHT AIRCRAFT -

DIVE RECOVERY OF HANG GLIDERS

Robert T. Jones

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SUMMARY

Longitudinal control of a hang glider by weight shift is not always adequate for recovery from a vertical dive. According to Lanchester's phugoid theory, recovery from rest to horizontal flight ought to be possible within a distance equal to three times the height of fall needed to acquire level flight velocity. A hang glider, having a wing loading of 5 kg/m^2 and capable of developing a lift coefficient of 1.0, should recover to horizontal flight within a vertical distance of about 12 m. This paper shows that the minimum recovery distance can be closely approached if the glider is equipped with a small all-moveable tail surface having sufficient upward deflection.

INTRODUCTION

Numerous hang-glider accidents have occurred because of inability to recover from a vertical dive. With longitudinal control provided by weight shift the condition of weightlessness in free fall is obviously a critical condition for control. The conditions which lead to possible recovery, or lack of it, have been analyzed by W. H. Phillips for a glider of the Rogallo type (see refs. 1 and 2). Phillips showed that recovery depends on a marginally positive value of the pitching moment coefficient, C_m at zero lift. Such a positive or nose-up pitching moment requires that the airfoil have a reflex camber near the trailing edge. Using a typical value for a Rogallo wing, it was found that recovery to horizontal flight required vertical distances of the order of 30 to 90 m and involved accelerations of 5 to 6 g.

When it is realized that a glider, having a wing loading of only 5 kg/m^2 will acquire flight velocity after a fall of less than 5 m, these recovery distances seem unduly large. It was thought worthwhile, therefore, to explore the possibility of improving the dive recovery by employing an aerodynamic elevator control.

MINIMUM ALTITUDE FOR RECOVERY AT A CONSTANT LIFT COEFFICIENT

In his book "Aerodnetics" published in 1906 (ref. 3) F. W. Lanchester described the diving and undulating motions of an airplane and gave accurately drawn curves of the paths which he called "phugoid" motions. Lanchester's drawing of the phugoid curves is dated 1897, 6 years before the Wright brothers' flight. In calculating these curves, Lanchester assumed that the lift is proportional to the square of the velocity (i.e., the airplane maintained a constant angle of attack and hence a constant lift coefficient) and that the drag is negligible in comparison to the lift.

Figure 1 shows a few flight paths traced from Lanchester's curves. The distance H below the horizontal datum line is proportional to the square of the velocity acquired in a free fall from this line, that is,

$$v^2 = 2gH$$

The line H_0 represents the height needed to acquire level flight velocity in free fall. For a glider, having a wing loading of 5 kg/m^2 and a lift coefficient of 1.0, the velocity V_0 will be 9 m/s and this velocity will be acquired in a fall of 4 m . Referring to figure 1 it will be noted that one of the flight paths touches the line of zero velocity. In this case, the aircraft starts from rest in a vertical dive and recovery takes place along a circular arc which becomes horizontal at a distance $3H_0$ below the datum line. Using this particular calculation of Lanchester's as a model, we may say that the minimum altitude needed to recover from a vertical dive is just three times the height needed to acquire level flight velocity. For the example given above we have $3 \times 4 = 12 \text{ m}$.

Since recovery takes place in three times the distance needed to acquire level flight velocity, the square of the velocity at the bottom of the recovery curve is also just three times V_0^2 , where V_0 is the velocity for level flight at one g . Since the lift coefficient is constant throughout the motion, the acceleration at the bottom of the recovery curve will be $3g$, independent of the wing loading, the lift coefficient, or the air density.

Converting Lanchester's formula, we obtain for the radius R of the phugoid curve

$$R = 3 \frac{W}{S} \frac{1}{C_L \rho g}$$

where W/S is the wing loading, C_L is the lift coefficient, and ρ the air density, assumed constant throughout the recovery. In the case of the Boeing 747, the wing loading is approximately 700 kg/m^2 , or about five times the weight per unit surface area of a grand piano. Assuming a lift coefficient of 1.0, we obtain

$$R \approx 1800 \text{ m}$$

for the recovery radius and altitude. Again recovery takes place at 3 g - a maneuver the 747 could undoubtedly negotiate without difficulty.

The actual minimum height for recovery will be somewhat greater than given by Lanchester's theory because of several factors such as the drag, the damping of rotation in pitch, and the moment of inertia of the aircraft. The effect of the drag on the recovery path is shown in figure 2. Here we have assumed drag coefficients of 0, 0.1, and 0.2, the latter corresponding to L/D ratios of 10 and 5, respectively. The drag, of course, reduces the velocity of the glider but leads to a small increase in the recovery altitude. With an L/D of 5, the recovery distance is increased by about 1.2 m, from 12 to 13.2 m. The most important effect of the drag is to reduce the peak acceleration during recovery. Thus, with a drag coefficient of 0.2, the maximum load is reduced from 3 to 2 g.

CONTROL MOMENTS NEEDED TO FOLLOW MINIMUM RECOVERY PATH

In these calculations based on Lanchester's theory, we have assumed that the pilot had sufficient control to maintain the glider at a constant lift coefficient throughout the recovery path. Since the path is a perfect circle and the velocity is given by $V^2 = 2gH$, it is not difficult to compute the control moments needed to maintain this condition. Figure 3 shows the result of this calculation. Also shown are estimates of the control moments available from an aerodynamic elevator control and from a weight shift of 10% of the wing chord. It is evident from this diagram that one of the difficulties of the ideal recovery path is in getting started. The inertia of the glider in pitch is difficult to overcome at the beginning. During most of the path, however, the primary resistance is offered by the aerodynamic damping in pitch, $C_{m\dot{\theta}}$. Figure 4 illustrates the origin of this damping term.

A simple calculation shows that the projection of the horizontal tail away from the curved flight path is sufficient to increase its angle of attack by 17°. Assuming an all-moving tail, 17° of upward deflection is needed just to bring the tail to zero lift. The indication is that very large elevator deflections will be needed to approximate the ideal recovery path. In the case of a more heavily loaded, conventional airplane the radius of curvature of the flight path will be much greater in proportion to the dimensions of the airplane and hence, such large control deflections are not needed.

It is interesting that a shift of the "weight," although it produces no moment at the beginning, nevertheless produces a constant moment coefficient throughout the motion, just as an aerodynamic control surface does. This will be true, however, only if the fall starts with the glider at a positive angle of attack. If the glider starts at zero angle of attack, the rearward weight shift will be ineffective, as pointed out by Phillips.

RECOVERY STARTING FROM ZERO LIFT ATTITUDE

Figure 5 shows a comparison of the recovery paths computed for a glider having an aerodynamic elevator control compared with a path computed by Phillips for a glider of the Rogallo type with control by weight shifting. Recovery of the Rogallo glider requires approximately 50 m, and involves a peak loading of 5.5 to 6 g. Recovery of the glider with the elevator control takes place in 14 m and involves a peak acceleration slightly more than 3 g. We have assumed in each case that the glider starts from rest at an attitude of zero lift. The recovery of the glider with elevator control takes somewhat longer than indicated by Lanchester's theory because of the rotation required at the beginning.

Figure 6 shows the effect of elevator control power on the height needed for recovery and shows the importance of large elevator deflections in the case of ultralight aircraft. Stalling of the horizontal tail is not of concern in this situation since, as mentioned earlier, the curvature of the flight path results in a large positive angle of attack (17°).

The time required to start the rotation in pitch results in somewhat greater loads during fast recovery than indicated by Lanchester's theory (i.e., 3 g). Figure 7 shows the peak loadings encountered and also the maximum lift coefficients plotted against the nose-up pitching moment coefficient. In making these calculations, it was found that the drag had little influence on the recovery height but had a significant influence on the peak acceleration, as figure 7 shows.

APPENDIX

EQUATIONS OF MOTION AND CHARACTERISTIC PARAMETERS

The flight paths were computed by a stepwise integration of the following equations of longitudinal motion:

$$\dot{F} - 2 \cos \gamma = - \frac{F}{\mu} C_D$$

$$\dot{F}\dot{\theta} + 2F\ddot{\theta} = \frac{F}{\mu r_y^2} C_m$$

$$F\dot{\gamma} + \sin \gamma = \frac{F}{2\mu} C_L$$

Here F is the Froude number:

$$F = V^2/gc$$

μ is the relative density of the aircraft

$$\mu = \frac{m}{\rho sc}$$

and

$$\dot{F} = \frac{dF}{ds}$$

where

$$ds = \frac{V}{c} dt$$

γ is the flight path angle measured from the vertical, equal to 90° when the flight path is horizontal.

$$r_y = \frac{K_y}{c}$$

where K_y is the radius of gyration in pitch. The pitch angle θ is $\theta = \gamma + \alpha$ where α is the angle of attack measured from zero lift.

The drag coefficient C_D was assumed constant and the coefficients C_L and C_m were assumed to vary linearly with angle of attack and pitch rate. The lift coefficient of the wing was calculated from the formula:

$$C_L = C_{L_I} + C_{L_{II}} + C_{L_{III}}$$

$$C_{L_I} = \frac{\pi}{2} \left(\dot{\alpha} + \frac{1}{2} \frac{\dot{F}}{F} \alpha \right)$$

$$C_{L_{II}} = \left[\alpha + \dot{\theta} \left(\frac{1}{2} - \frac{x_{cg}}{c} \right) \right] \frac{dC_L}{d\alpha}$$

$$C_{L_{III}} = \frac{1}{4} \dot{\theta} \frac{dC_L}{d\alpha}$$

The term C_{L_I} is an estimate of the lift produced by the "virtual mass" of the wing and has its center of pressure near the center of area. In $C_{L_{II}}$ the largest term is $\alpha(dC_L/d\alpha)$. The terms involving $\dot{\theta}$ account for the apparent camber of the wing in curvilinear flight. The contribution $C_{L_{II}}$ has its center of pressure at the aerodynamic center of the wing or $0.25 c$ behind the leading edge. $C_{L_{III}}$ was assumed to act at the $0.50 c$ point, x_{cg} is the distance of the center of gravity behind the leading edge, and \bar{X} is the "static margin," that is, the distance of the center of gravity ahead of the aerodynamic center of the aircraft. In the calculations given the following values were used:

$$\mu = 2.26$$

$$r_y^2 = 0.5$$

$$\frac{dC_L}{d\alpha} = 4.5$$

$$X_{ac} = 0.357 c \text{ (includes the effect of the tail)}$$

$$\bar{X} = 0.05 c$$

$$\frac{dC_{L_t}}{d\alpha_t} = 4$$

$$S_t = 0.10 s$$

$$l_t = 2 c$$

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1. Phillips, W. H.: Recovery from a Vertical Dive. Ground Skimmer, Aug. 1975.
2. Phillips, W. H.: More on Dive Recovery or Lack Thereof. Ground Skimmer, Nov. 1975.
3. Lanchester, F. W.: Aerodnetics. Constable and Co., Ltd., London, 1910.

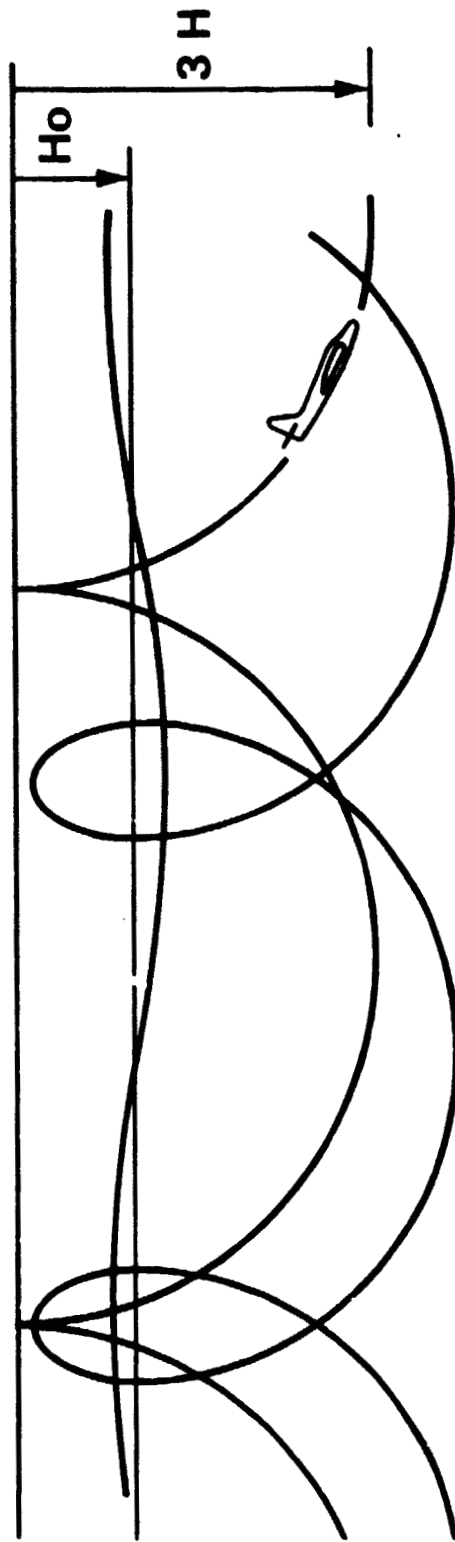


Figure 1.- Lanchester's phugoid motions: Nov. 1897 H_0 is the height of free fall required to develop level flight velocity. $V_0^2 = 2gH_0$. $3H_0$ is the minimum height for recovery from c vertical dive.

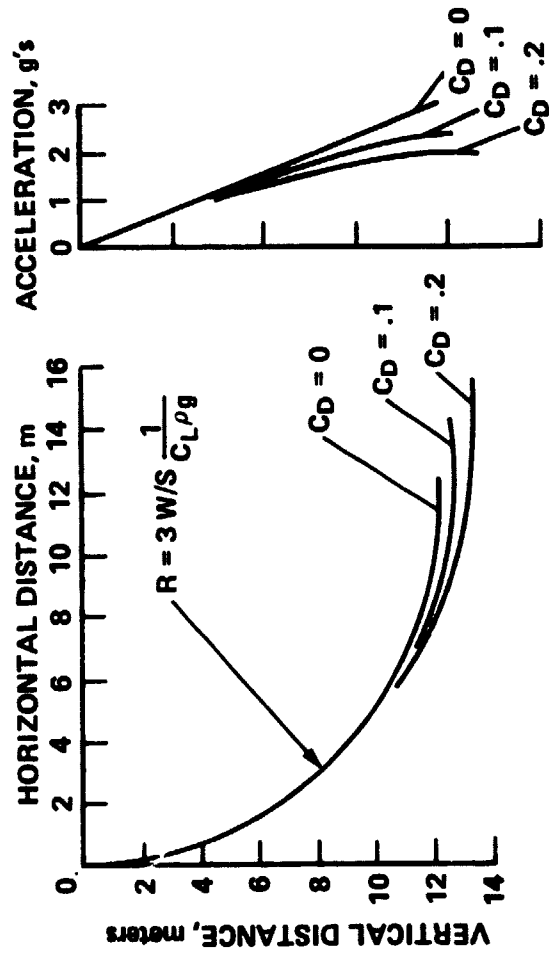


Figure 2.- Effect of drag on dive recovery at constant lift coefficient
 $C_L = 1.0$, $W/S = 5 \text{ kg/m}^2$.

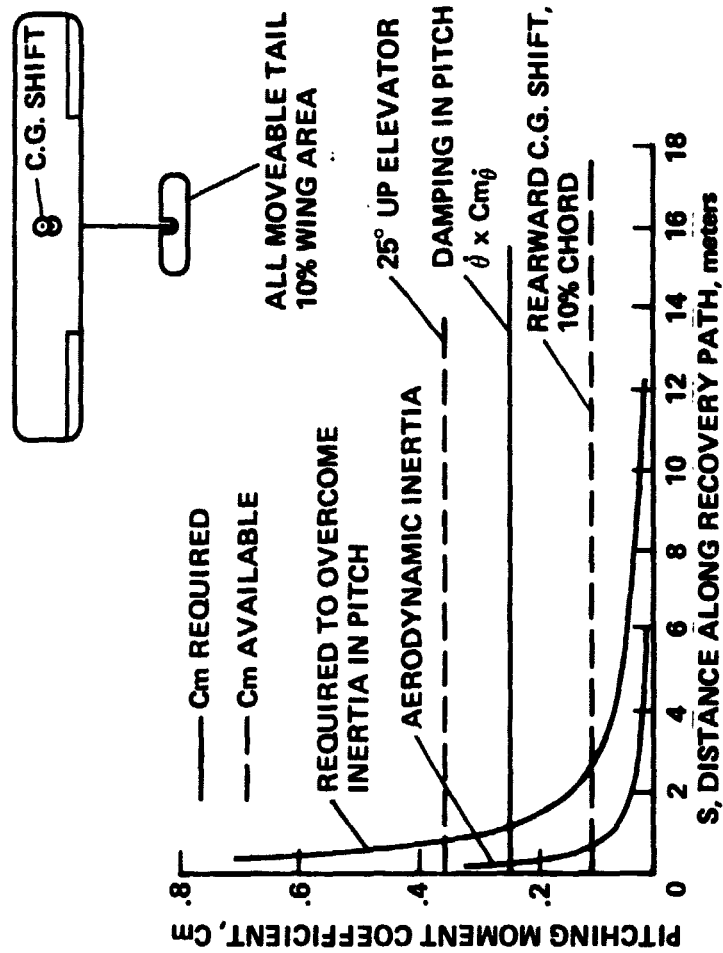
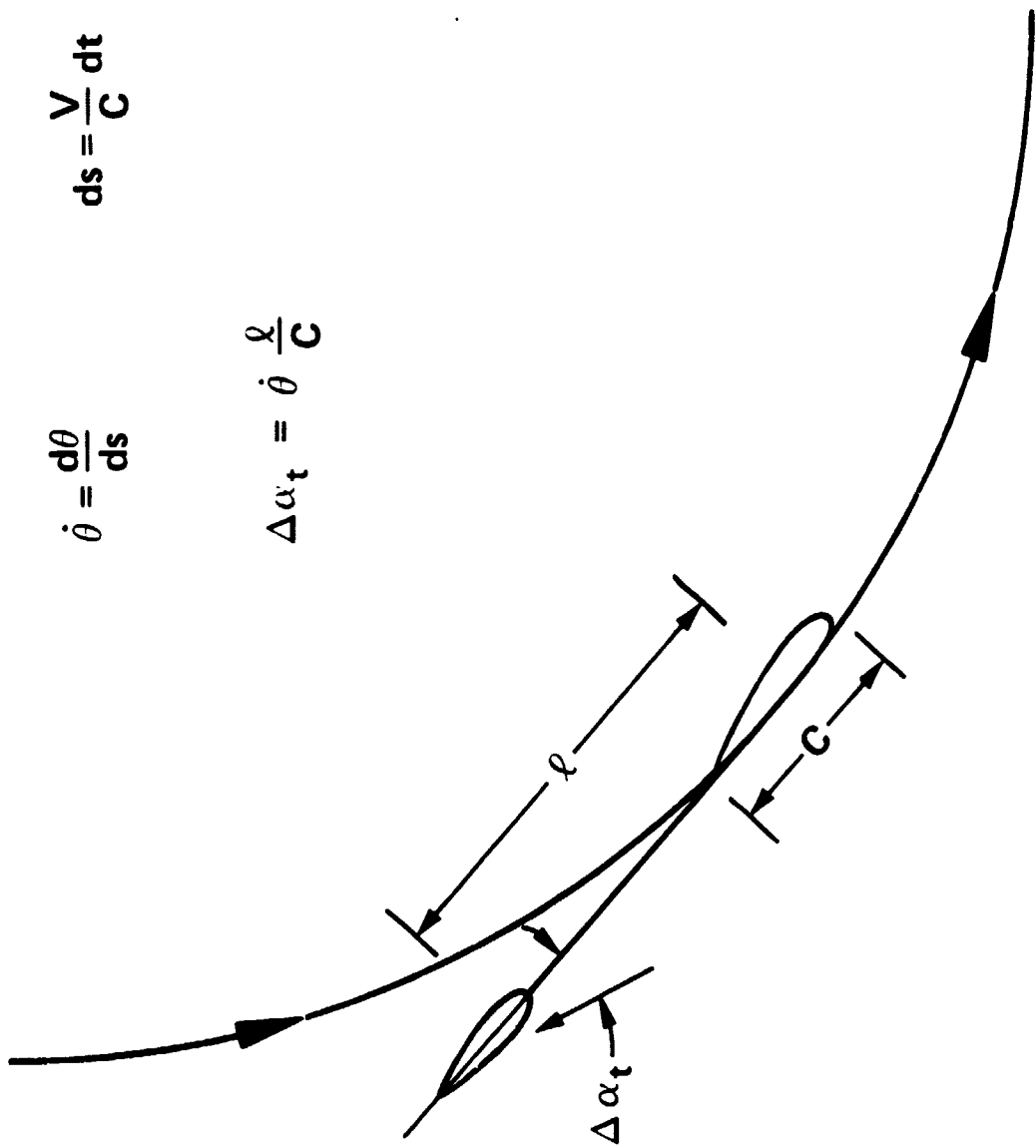


Figure 3.- Comparison of pitching moments available with those required for optimum recovery path.



$$ds = \frac{V}{C} dt$$

$$\dot{\theta} = \frac{d\theta}{ds}$$

$$\Delta\alpha_t = \dot{\theta} \frac{l}{C}$$

Figure 4.- Origin of damping in pitch $C_{m\dot{\theta}}$.

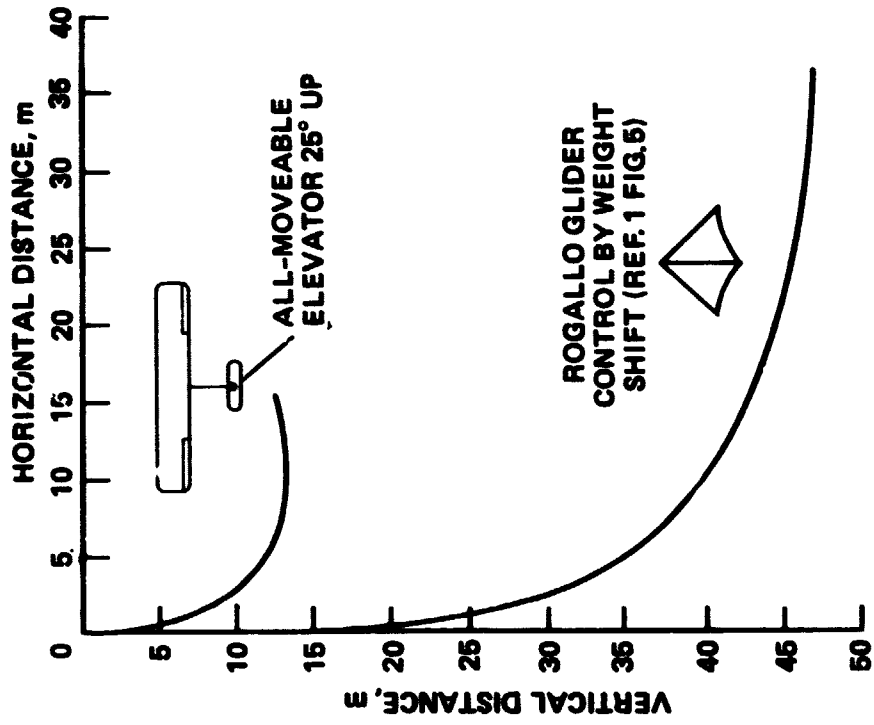


Figure 5.- Comparison of recovery paths with and without aerodynamic elevator control.

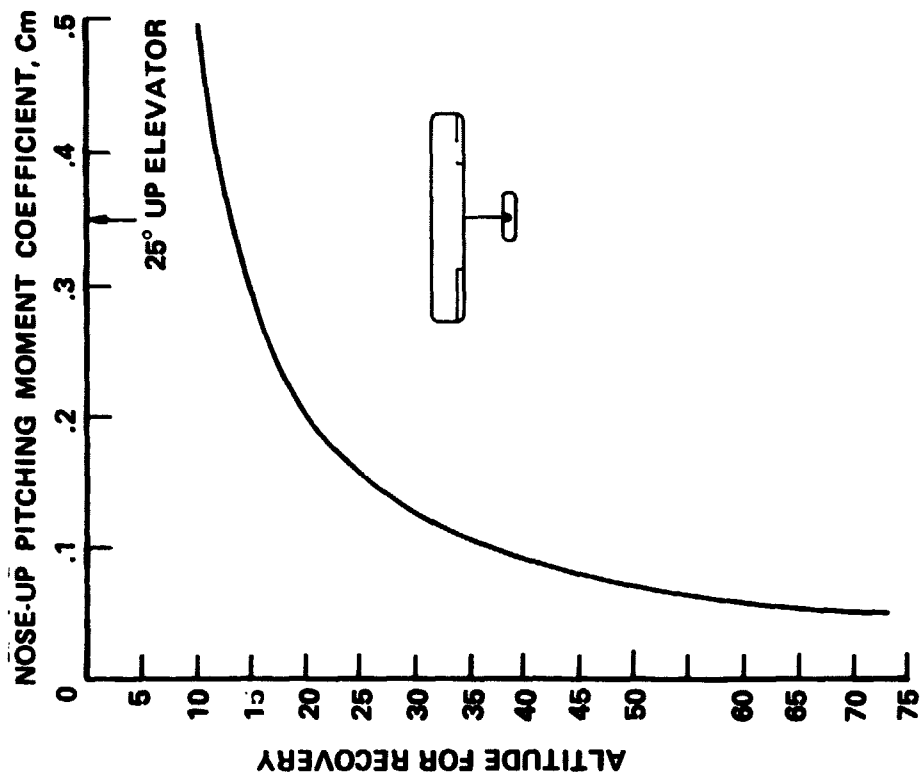


Figure 6.- Effect of elevator control power on altitude needed for dive recovery.

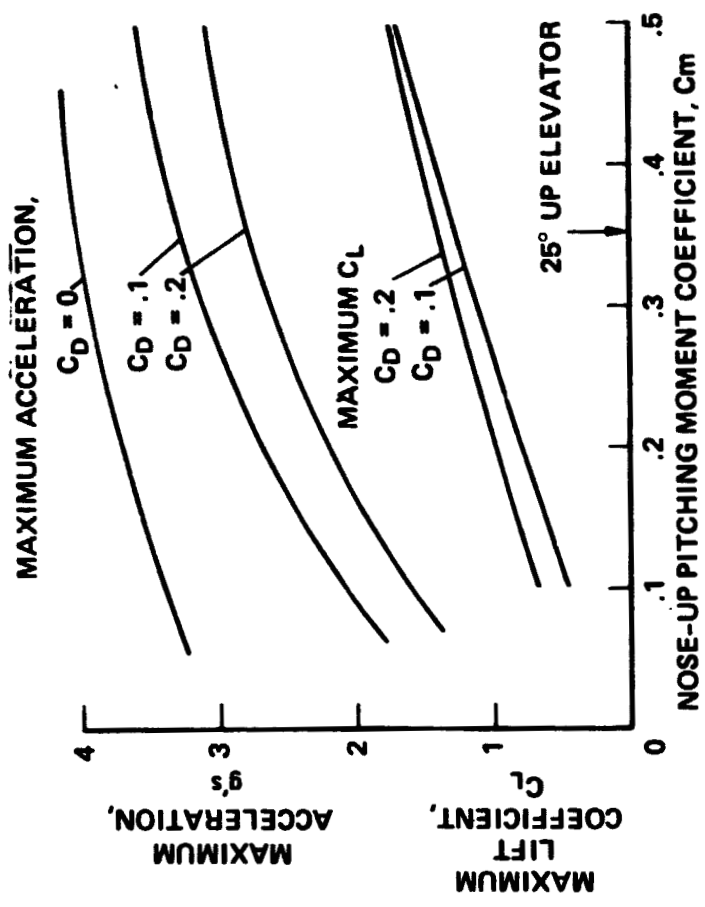


Figure 7.- Peak accelerations and lift coefficients in dive recoveries with elevator control.