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DYNAMICS OF ULTRALIGHT AIRCRAFT – MOTION IN VERTICAL GUSTS

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MOTION IN VERTICAL GUSTS

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SUMMARY

This report extends gust load calculations to the range of conditions encountered by ultralight aircraft such as hang gliders. Having wing loadings of the order of 5 kg/m^2, these gliders acquire a substantial fraction of the motion of a gust within a distance of 1 or 2 m. Comparative loads and displacements for a small powered airplane having a wing loading of 50 kg/m^2 and for a commercial jet with 500 kg/m^2 are shown.

INTRODUCTION

Hang gliders in current use have wing loadings of the order of 5 kg/m^2, about half that of the Wright's 1903 flyer. For comparison, a modern "light" two-passenger airplane will have a loading of 50 kg/m^2. Going upward on the scale, we find that large commercial jets have loadings of 500 to 700 kg, about five times the weight per unit surface area of a grand piano or a heavy automobile.

In view of these large differences it is not surprising that the foot-launched glider is more susceptible to gusts than other aircraft. To estimate the magnitude of the difference, I have considered three airplanes having wing loadings of 5, 50, and 500 kg/m^2, each in a steady glide at a lift coefficient of 1.0 and each encountering the same downward gust of 4.6 m/sec extending over a distance of 15 m.

PRELIMINARY ESTIMATE OF THE PENETRATION DISTANCE

The primary effect of the gust will be to reduce the angle of attack and hence the lift, causing the aircraft to accelerate downward. The downward motion, however, tends to restore the original angle of attack and after a certain distance the aircraft will be moving down along with the gust.

A simple calculation assuming no rotation in pitch shows

$$w_{airp} = w_{gust}(1 - e^{-\lambda x}) \tag{1}$$

where w is the downward velocity, x is the horizontal distance and

$$\lambda = \frac{1}{2} \frac{\rho g}{W/S} \frac{dC_L}{d\alpha} \tag{2}$$

Here ρ is the air density, g the acceleration of gravity, and $dC_L/d\alpha$ is the slope of the lift coefficient curve. Utilizing formula (1) it develops that

$$x_{1/2} = \frac{0.69}{\lambda}$$

where $x_{1/2}$ is the distance within which the glider acquires half the velocity of the gust.

It will be clear from equations (1) and (2) that the penetration distance (i.e., $x_{1/2}$) will be directly proportional to the wing loading W/S. Assuming $dC_L/d\alpha = 4.5$ and $\rho = 0.125$ in equation (2), we obtain

(1) Ultralight glider	$W/S = 5\ kg/m^2$	$V = 9$ m/sec	$x_{1/2} = 1.5$ m
(2) Small airplane	$W/S = 50\ kg/m^2$	$V = 29$ m/sec	$x_{1/2} = 15$ m
(3) Large jet	$W/S = 500\ kg/m^2$	$V = 90$ m/sec	$x_{1/2} = 150$ m

With a given wing loading the penetration distance is not altered by flying at different speeds within the flight envelope. Reducing the angle of attack and flying at a higher speed will, however, lead to greater vertical accelerations and greater loads on the aircraft — in direct proportion to the speed — but will reduce the actual displacements because of the shortened time within the gust. In most cases the loads developed are more important and hence it is advisable to slow down when encountering gusty air.

EFFECT OF LAG IN THE DEVELOPMENT OF LIFT

For a more accurate calculation of the loads and displacements one should take account of the lag in the development of lift. Quite a few years ago, Th. von Karman and W. R. Sears in the U.S. (ref. 1) and H. G. Küssner in Germany (ref. 2) calculated the growth of lift on a straight airfoil of high aspect ratio as it penetrated a sharp-edged gust. They found that the airfoil had developed about half of its final lift by the time the trailing edge had reached the gust. The remainder of the lift developed more slowly. Sears and Küssner found another very surprising result, even though only a small portion of the airfoil nose had penetrated the gust the incremental lift appeared at the normal aerodynamic center of the airfoil, i.e., at the 25% chord point. Moreover, although the lift is small at the beginning, the distribution of the incremental lift over the chord retains the same shape throughout, i.e., the same shape as the lift distribution on a thin uncambered airfoil at an angle of attack in steady flow. These conclusions were verified experimentally by dropping a weighted airfoil through the horizontal jet of an open throat wind tunnel. With the center of mass of the airfoil at 0.25 c no pitching rotation was observed.

In NACA TR-681 (ref. 3), I have extended these calculations to elliptic wings of finite aspect ratio (AR = 3 and 6) and the results are shown in figure 1. For wings having swept leading edges, the above conclusions will not apply. In the limiting case of a slender delta planform ($AR < 1.0$) the lift will appear only on that portion of the wing immersed in the gust and the final lift coefficient of

$$\Delta C_L = \frac{w_g}{V} \frac{\pi}{2} AR$$

will appear when the trailing edge has reached the edge of the gust.

In the foregoing calculations, the airfoil was not allowed to move vertically in response to the gust. To take account of the vertical motion of the aircraft, we have to consider the development of lift following a stepwise increment in angle of attack. In this case there is an initial impulsive lift which is associated with the inertia of the air in the vicinity of the wing (called the "virtual inertia" or "virtual mass"). After the initial pulse the lift coefficient drops to a value approximately $\pi\Delta\alpha_g$ where $\Delta\alpha_g = w_g/V$ and then builds up to twice this value in the case of infinite aspect ratio. The curve for $AR = \infty$ shown in figure 2 was obtained by H. Wagner in 1926 (ref. 4). The curves for AR = 3 and 6 were calculated by the present writer and are given in NACA TR-681.

As figure 2 shows, the distribution of lift throughout the motion again retains the same shape as in the case of steady flow and also in the case of gust penetration. The initial impulsive lift, proportional to the virtual mass and to the rate of change of angle of attack, however, has its center of pressure at the 50% chord point and is distributed elliptically over the chord.

For a wing of high aspect ratio the virtual mass m' is approximately equal to the mass of air in a circular cylinder having a diameter equal to the wing chord and extending along the span of the wing. Thus

$$m' = \rho \frac{\pi}{4} c^2 b = \rho \frac{\pi}{4} Sc$$

For a glider weighing 90 kg having a wing area of 18 m^2 and a chord of 1.8 m, we have

$$m' = 3.21$$

$$W' = gm' = 31.5 \text{ kg}$$

Hence the "weight," W', of air involved is about 35% of the weight of the glider.

For a wing of low aspect ratio the virtual mass is greater. Exact calculation for a circular planform ($A\!\!R = 1.27$) gives $m' = 4.8$ or

$$W' = 47 \text{ kg}$$

which is more than half the weight of the glider.

In the case of vertical motions without pitching rotation, the effect of the virtual mass simply adds the mass m' to the inertia of the glider. However, if the gust velocity around the glider is accelerating at a rate dw_g/dt, the glider will acquire a certain fraction of this acceleration immediately, i.e.,

$$\frac{dw}{dt} = \frac{m'}{m + m'} \frac{dw_g}{dt}$$

or about 1/4 the vertical acceleration of the gust for the high-aspect-ratio wing and about 1/3 for the low aspect ratio.

If we carry out these calculations for a small powered airplane having a normal wing loading of 50 kg/m^2, we find that the virtual mass is quite negligible in comparison to the mass of the airplane.

To calculate the actual lift developed by an aircraft in free flight we have to consider the gust lift curve of figure 1, the relief due to vertical motion which will involve figure 2, and the effect of the virtual mass which adds to the inertia of the glider. A useful parameter which characterizes the inertia of the aircraft is called the "relative density" μ, and is given by

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

The mathematical technique of combining these three effects is described in NACA TR-681. Results of the calculations for various values of μ are shown in figure 3. The curve $\mu = \infty$ corresponds to an airplane so heavy that it does not move vertically in response to the gust. This curve is therefore the same as that plotted in figure 1 (for $A\!\!R = 6$). Progressively lighter aircraft corresponding to smaller values of μ develop smaller lift increments and respond sooner to the gust. The curve labelled $\mu = 0.25$ corresponds to something like a large butterfly which would follow the up and down motions of the gust with very small lift coefficient increments but with large vertical accelerations.

Although figure 3 indicates that the lift coefficient per unit angle-of-attack change caused by the gust is smaller for lighter aircraft, the actual angle-of-attack change caused by a given gust velocity w_g will be greater. In spite of the reduction in $\Delta C_L/\Delta\alpha_g$ the actual stress on the aircraft as measured by the vertical acceleration in "g's" is greater for the lighter aircraft because the angle-of-attack change for a given gust velocity is greater. Since the lighter, slower aircraft spends more time in the gust, its vertical displacements will be greater also.

To illustrate the differences of behavior in a given gust pattern, I have estimated the gust loading in "g's" and the vertical displacement in feet for three aircraft, "ultralight," "light," and "heavy" assuming a 4.6-m/sec downgust extending for a distance of 15 m. Each aircraft is assumed to be gliding at a moderately high lift coefficient of 1.0. The following table lists the results of this calculation:

	Wing loading, kg/m^2	Flight speed, m/sec	Maximum down lift, g	Loss of height in 15 m
(1) Ultralight glider	5	9	1.2	5.8 m
(2) Small airplane	50	30	.6	.73 m
(3) Large jet	500	90	.2	2.5 cm

Graphs of vertical acceleration and displacement in feet during penetration of the gust are shown in figures 4 and 5. Referring to figure 4, it will be noted that the 4.6-m/sec downgust is not quite strong enough to lift the pilot of a small airplane out of his seat (-0.6 g). The ultralight glider, however, shows negative accelerations exceeding 1 g for a short period as shown by the shaded area of curve (A), and during this period the pilot may be in free fall, disconnected from the glider.

Figure 5 shows the marked effect of wing loading and flight speed on the vertical displacement produced by the gust. The ultralight aircraft acquires almost all of the downward velocity of the gust within a distance of 6 m. At the end of 15 m it has dropped about 6 m below its normal glidepath and has acquired a downward velocity of 4.5 m/sec.

The downward load of 1.2 g is sufficient to put the glider into the negative lift range and in the case of the Rogallo type would cause the sail to "luff" and the pilot to become momentarily uncoupled from the glider. Of course the 4.6-m/sec downgust is a rather severe one, though not severe enough to require the use of the seat belt in a typical small airplane.

What can the pilot of the ultralight aircraft do to minimize the effect of such gusts? By reducing his angle of attack, flying at a higher speed he could reduce the vertical displacement caused by the gust. The vertical accelerations and loads on the glider would be increased, however. Alternatively, one might envision some extraordinary development in aerodynamics or mechanical engineering which would make the extremely light aircraft less sensitive to gusts. Unfortunately, techniques that come readily to mind would also interfere with the pilot's ability to control his flight path. Perhaps one should not give up hope, however, especially since birds do fly successfully with wing loadings of 5 kg/m^2 or less. In the meantime, pending the development of a complete set of bird controls, the pilot of an ultralight glider will be well advised to avoid even moderately gusty winds.

In conclusion, the writer would like to acknowledge the assistance of Dr. Bijan Davari of Ames Research Center in making these calculations.

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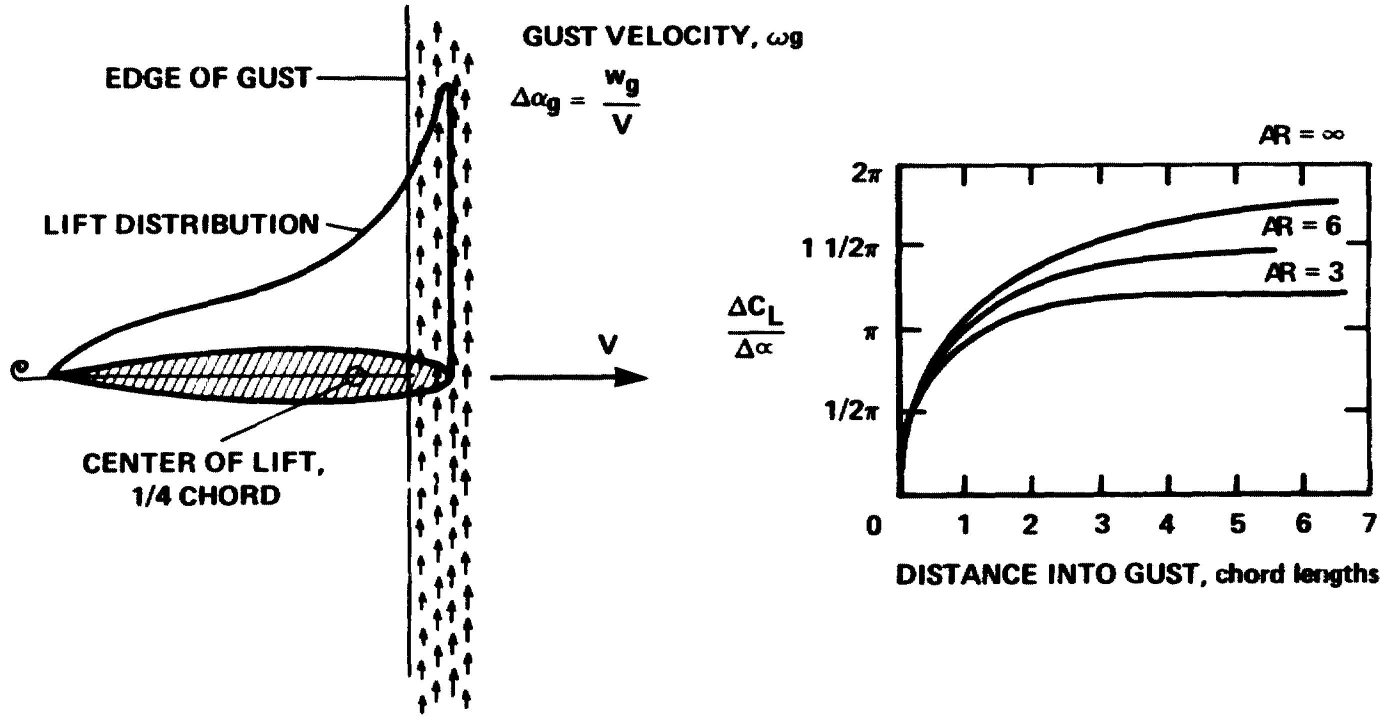

Figure 1.- Development of lift on an airfoil flying into a sharp-edged gust.

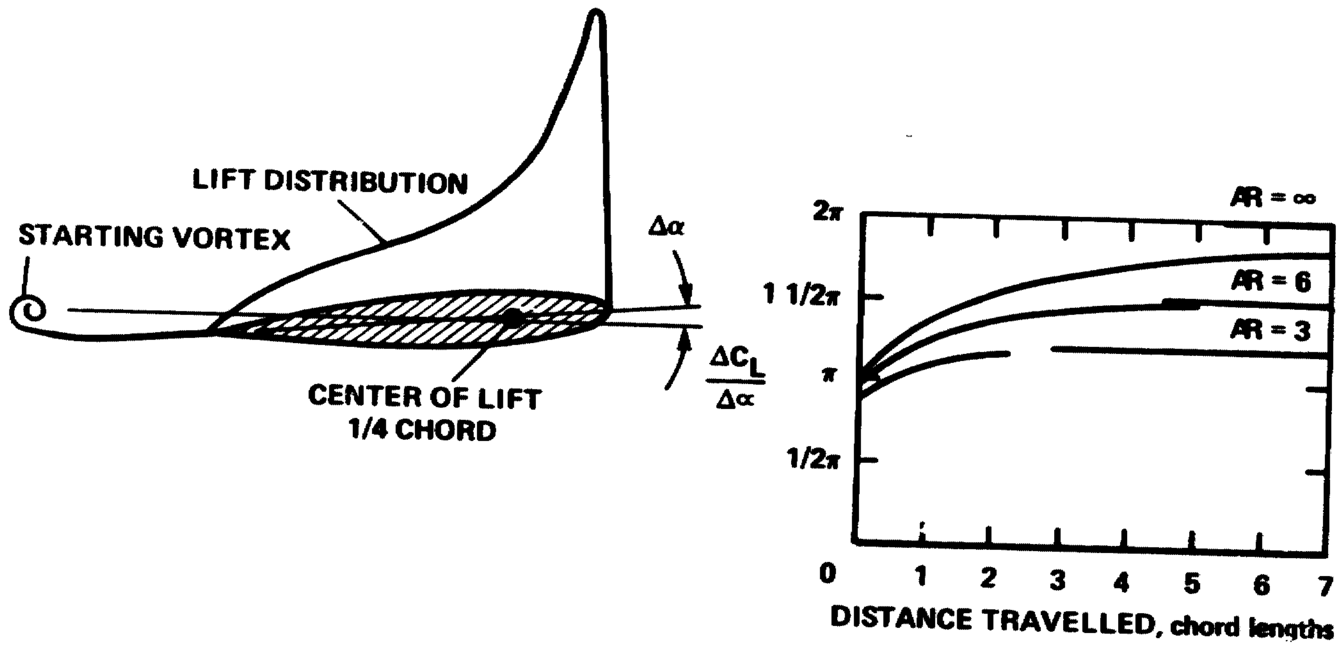

Figure 2.- Development of lift following a sudden change in angle of attack.

$$\Delta\alpha_g = \frac{w_g}{V}$$

$$\mu = \frac{m}{\rho s c}$$

ULTRALIGHT GLIDER

$\frac{W}{S} = 5 \frac{kg}{m^2}$ $\mu = 2.5$

SMALL AIRPLANE

$\frac{W}{S} = 50 \frac{kg}{m^2}$ $\mu = 25$

LARGE JET

$\frac{W}{S} = 500 \frac{kg}{m^2}$ $\mu = 50$

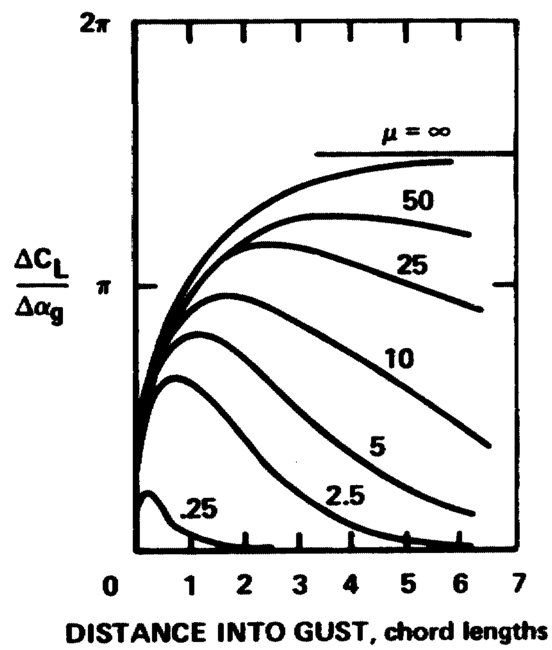

Figure 3.- Relieving effect of vertical motion on lift developed in a sharp-edged gust, AR = 6.

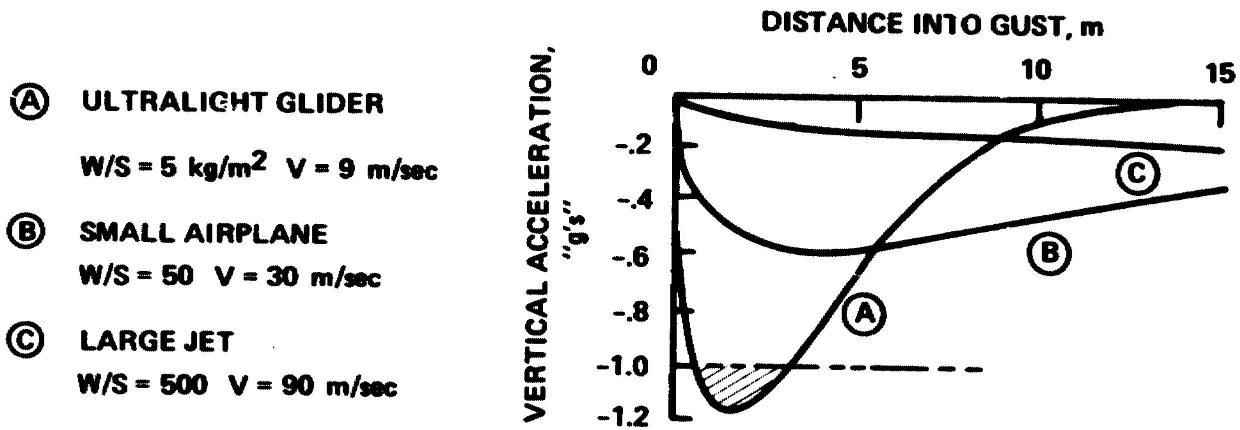

Figure 4.- Vertical accelerations produced by 4.6-m/sec downward gust.

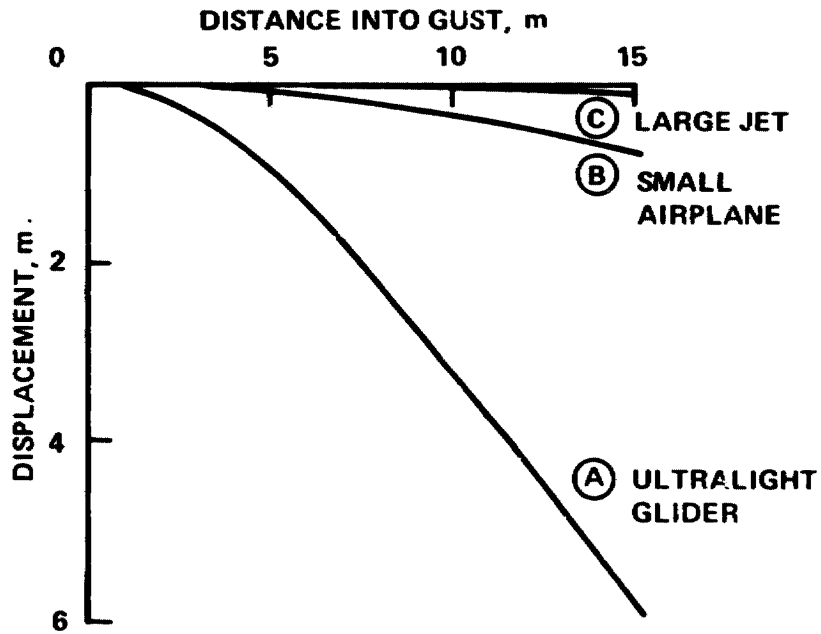

Figure 5. Vertical displacements caused by 4.6-m/sec downward gust.