TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 678

INCREASE IN THE MAXIMUM LIFT OF AN AIRPLANE WING DUE TO A SUDDEN INCREASE IN ITS EFFECTIVE ANGLE OF ATTACK RESULTING FROM A GUST

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INTRODUCTION

Various observations led to the surmise that the maximum lift coefficient $c_{a\,max}$, as measured in a steady air flow, may undergo considerable variation in connection with gusts, wing flutter and sudden maneuvers. For example, motion pictures of the flow about cylinders show that, even with this unfavorable shape, perfect potential flow occurs at first and that the separation of the flow and the formation of a dead-water region takes place gradually. When the flow is transferred to a wing moving at a uniform speed but with a rapidly increasing angle of attack, it may be inferred that the lift also increases very rapidly and in harmony with the calculations for the unsteadily moving wing, (reference 1), while, on the other hand, the separation of the flow is retarded, thus leading to greater lifts and angles of attack.

The confirmation of this inference would explain the observations, which have led pilots to the conclusion that gusty air affords a better support and, in particular, the incomprehensibly high lift coefficients obtained in gust measurements during flight. (Reference 2.) For the solution of this problem, an experimental investigation was undertaken in the Aachen wind tunnel, in which the phenomena of a wing entering a vertical gust were simulated and the resulting stresses were measured.

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*"Die Zunahme des Maximalauftriebes von Tragflügeln bei plötzlicher Anstellwinkelvergrösserung." Zeitschrift für Flugtechnik und Motorluftschiffahrt, April 14, 1932, pp. 185-189.

APPARATUS

Figure 1 shows the arrangement of the apparatus, while Figure 2 is a photograph of the same. The flow simulating the vertical gust was produced by means of a vane-type shutter, such as had already been used by Katzmayr. (Reference 3.) This was built into the entrance cone of the wind tunnel and had six rotatable vanes K of symmetrical cross section. The faired uprights, on which the vanes were mounted, also served as end disks. In the middle, the distance between the vanes was doubled, in order to prevent the measurements from being affected by the wakes of the vanes. The vanes were held parallel by a pushrod and could be operated more or less quickly and at almost uniform angular velocity by the weight A connected with the oil damper D.

With this arrangement the direction of flow was continuously varied up to a certain maximum. For a model M mounted behind the shutter, there was a difference, facing a vertical gust, only in the divergent course of the dynamic pressure. The latter increases somewhat in the vertical gust, due to the vectorial addition of flight speed and gust velocity. In the test, however, the dynamic pressure remained practically constant. This discrepancy is permissible, since $c_{a\,max}$ is dependent on the dynamic pressure to only a very small degree. In order to follow the actual course of the dynamic pressure behind the shutter, a hot-wire anemometer was installed at the point H. In subsequent experiments this instrument made it possible to determine, simultaneously with the course of the gust forces and the changing direction of the current, also the course of the dynamic pressure at this point, which is but little affected by the circulation about the model.

The wing model was installed at an angle of attack of 15° to the horizontal and at 70 cm (27.6 in.) behind the shutter. Its angle of attack could be varied from 0 to 30°. In simulating the gust impact on the model, the rate of change had to be increased to correspond to the short wing chord. The change in direction had to be made very quickly (in about 1/30 second). It is obvious that, with such brief impacts, the natural frequency of the model had to be very high in the test direction. Hence the normal stresses of the model were transmitted through a strong support S and the measuring instrument Q to a solid base F, while the tangential forces were transmitted through a wire.

The supporting strut was forked, as shown in Figure 3, since a simple strut attached to the middle of the wing would allow the latter to vibrate and render any accurate measurement impossible. The ends of the fork were applied at the natural vibration nodes of the wing and the effect of the bending vibration of the wing was thus eliminated. The natural frequency of the wing model, with this arrangement in the test direction, was about 300 periods per second. This proved adequate for the measurements in question.

The measuring instrument should not reduce the natural frequency of the wing and should, moreover, have a range of 1 to 50 kg (2.2 to 110 lb.). The simple scratch method was not adapted to these requirements, since the stresses in the supporting rod were much too small. Hence a complicated electric method had to be employed. The forces were recorded by the piezo-electric method. (Reference 4.) This method has the advantages of exceptionally high pressure rigidity (the natural frequency of the wing remaining unaltered), easy variation of the sensitivity (by turning a condenser) and the use of electrical amplification for making a record of suitable magnitude. The disadvantages are the relative bulk and cost of the apparatus, which required frequent calibration due to inherent defects.

Figure 3 shows the combined apparatus for this method of electrical force measurement. Between the supporting rod and the base are introduced the quartz plates, whose pressure fluctuations are amplified by the tube R and recorded by the oscillograph Θ. The oscillograph was simultaneously employed to record the other test data, like the dynamic pressure, direction of flow and time marks, thus combining all the data on a single diagram.

The flow behind the shutter was carefully investigated. The model polar obtained in the unobstructed air stream was compared with that obtained behind the shutter. The agreement was perfect as regards the maximum lift. On the other hand, a deflection of the shutter vanes of 10° produced a deflection of only 8.5° in the flow and the polar showed a slight deformation. The calibration of the pressure record was made by loading the surfaces with known weights and then making the oscillograms. The calibration was repeated often, in order to eliminate sources of error.

TEST RESULTS

With the above-described apparatus, systematic investigations were made of the behavior of three wing models at a suddenly increased angle of attack. The models had an aspect ratio of 5 and a symmetrical profile (Göttingen 459) and a cambered profile (Göttingen 398). The tests confirmed the original surmise that the maximum lift must increase with suddenly increasing angle of attack. Figure 4 shows two oscillograms obtained with the same model for different rates of change. In these oscillograms, the course of the normal force is shown at the top, and under it the dynamic pressure, the variation in the angle of attack and the time marks. It is obvious that, in the lower oscillogram, a higher maximum lift corresponds to the higher rate of change.

All the data thus obtained are plotted in Figure 5. In these diagrams the maximum normal-force coefficient $c_{n\ max}$ is plotted against the angular rate of change $d\alpha/dt$. All three airfoils were tested at the two pressures 25 and 100 mm (0.98 and 3.94 in.) water column. From this diagram, it may first be seen how the maximum lift, beginning with its value in a steady flow, increases proportionally with increasing rate of change in the angle of attack. Furthermore the profile shape must have very little influence on the observed effect, for both upper diagrams show the same increase in the maximum lift (although based, under otherwise like conditions, on fundamentally different profiles).

In transferring the test data of such an unsteady flow from the model to a full-scale wing, there is, in addition to the well-known Reynolds Number, another important characteristic, which has been calculated by P. Raethjen and designated as the dynamic characteristic S. (Reference 5.) This characteristic is obtained by adding, to the Reynolds requirement that the frictional and steady acceleration forces shall stand in the same ratio in the transfer, the further requirement that the unsteady acceleration forces shall also preserve this ratio. If the

Euler equations are then introduced, the dynamic characteristic is

$$S = \frac{l\,b}{v^2}$$

in which l is a linear dimension, b the unsteady acceleration and v the velocity. If the rate of angular variation $d\alpha/dt$ is introduced instead of the acceleration, it becomes

$$S = \frac{l}{v}\frac{d\alpha}{dt}.$$

The diagrams in Figure 5 show that the requirement of the dynamic characteristic, even at the low Reynolds Numbers obtainable in the tests, is very well fulfilled. In all the diagrams, with the doubling of the velocity (increasing the dynamic pressure from 25 to 100 millimeters of water) the increase in lift is reduced about half for the same rate of change in the angle of attack. Of course, this transition cannot take place exactly, because any change in the dynamic pressure involves a change in the Reynolds Number. In order to obviate this change, the third model (lowest diagram) was tested. This model had the same profile on half the scale of the model for the middle diagram. If all the requirements of the dynamic characteristic were fulfilled, the rise in the lift curve in the middle diagram for the dynamic pressure of 25 (.98 in.) would have to be four times as great as in the bottom diagram for the dynamic pressure of 100 mm (3.94 in.) because, with the same Reynolds Number, the velocity was doubled and the chord halved. This requirement was substantiated.

Since it is thus shown that the observed effect depends no more than all other model data on the Reynolds Number, that the requirement of the dynamic characteristic is exactly fulfilled and that the profile shape has little influence, the lift increase can be generally approximated by the expression

$$c_{a\ max_d} = c_{a\ max_{st}} + 0.36\,\frac{t}{v}\,\frac{d\alpha}{dt}$$

in which

$c_{a\ max_d}$ = the maximum dynamic lift coefficient,

$c_{a\ max_{st}}$ = the maximum steady lift coefficient,

t = wing chord in meters,

v = flight speed in meters per second,

$d\alpha/dt$ = rate of change of angle of attack in degrees per second.

CAUSES OF THE LIFT INCREASE

There would seem to be several possible causes of the lift increase. In the first place it might be imagined that the additional dynamic forces would increase the lift. Calculation shows, however, that these forces are negligibly small at the angular velocities involved. This fact was confirmed experimentally, for when the changing of the direction of flow ceased at a point where it was steady, the oscillograph showed the correct steady lift. There was thus no momentary oscillation involving an excessive value which subsequently returned to the normal value.

Neither could a change in the pressure distribution on the upper side of the wing be the cause of the greater lift. A more favorable lift distribution would correspond to a lowering of the high vacuum at the leading edge and a shifting of the center of pressure toward the rear. On entering a gust, the leading edge experiences the greater lift, because, in the increasing vertical velocity, it always has a somewhat greater aerodynamic angle of attack than the trailing edge. The pressure distribution, on entering a gust, is unfavorably affected and can offer no explanation of the observed effect.

The lag of the flow-separation phenomenon offers the most plausible explanation of this effect. Observation of motion pictures of the separation process shows that the flow does not separate from the wing all at once. There is at first a backwash in the boundary layer on the upper side of the wing toward the point of greatest vacuum near the leading edge, where it is carried away by the free flow. The air thus carried away reduces the velocity of the free flow in the critical region and increases the backwash. These phenomena become more and more pronounced until the final complete separation of the flow from the profile. These processes require more time than the processes in the considerably faster free flow. Hence it is obvious that, with a rapidly increasing angle of attack, a greater lift is obtained than in the steady condition.

PRACTICAL RESULTS

The load assumptions of the D.V.L. (Deutsche Versuchsanstalt für Luftfahrt) of December, 1930, calculate the safe load factor for gust stresses on the assumption that the lift is proportional to the increase in the angle of attack caused by the gust. They take no account of the apparent limit set to this increase by the maximum lift determined from steady tests. For the low wing loading of 30 kg/m² (6.14 lb./sq.ft.) and a speed of 30 m/s (98.4 ft./sec.), the maximum lift coefficients run up to 2 for the assumed maximum velocity of the gust of 10 m/s (32.8 ft./sec.). If the airplane has a symmetrical profile, it seems incomprehensible why such high stresses should need to be taken into consideration.

The present tests show that the assumption agrees with the facts. An airplane having a symmetrical wing section with a chord of 1 m (3.28 ft.) and flying at a speed of 30 m/s (98.4 ft./sec.) attains the maximum lift coefficient of 2 at an angular velocity of 70° per second. The gust must accordingly reach its maximum velocity of 10 m/s after about 8 m (26 ft.) of flight. This increase is so gradual, that considerably steeper gust fronts can be met and the maximum lift coefficient of 2 be so much more surely attained. The gust formula is therefore in accord with the test results.

The gust formula shows that airplanes with small wing loadings (light sport planes and gliders) undergo the greatest stresses. Hence in the further course of the work under consideration, an investigation was made of the stresses occurring in these airplane types, in connection with which any calculation must have been illusory due to the separation of the air flow. It is not possible to include these calculations within the scope of the present article. Hence we shall only mention the result.

The result is the numerical determination of the corrective factor η, as employed in the D.V.L. gust formula to account for the dynamic characteristics of the airplane and for the introduction of the change in the direction of the flow. In this calculation, the actual wing was replaced by a rigid wing with a correspondingly elastic mount. It was possible to disregard the effect of the tail, but not the mass of the wing. Furthermore, the effect of the discontinuity surface released from the trailing edge in the unsteady phenomena and the increase in the dynamic pressure from the additional vertical velocity of the gusts were disregarded. The effect of the discontinuity surface has not been calculated for a wing of finite span. It leads to a slight reduction of the stresses, which was approximately offset in the case under consideration by disregarding the increase in the dynamic pressure.

Calculations were made for a cantilever high-performance glider and a conventional cantilever sport plane. Figures 6 and 7 give the corrective factor η of these two airplanes for a vertical gust of 10 m/s (32.8 ft./sec.) as plotted against the width of the mixing zone (the transition zone between the quiet air and the vertical gust). No practical observations of the minimum width of this mixing zone have yet been made. If it is assumed that the mixing zone for a vertical gust of 10 m/s has a minimum width of 5 m (16.4 ft.), we then obtain a corrective factor of 76 per cent for the glider and 79 per cent for the sport plane.

SUMMARY

Wind-tunnel tests are described, in which the angle of attack of a wing model was suddenly increased (producing the effect of a vertical gust) and the resulting forces were measured. It was found that the maximum lift coefficient increases in proportion to the rate of increase in the angle of attack. This fact is important for the determination of the gust stresses of airplanes with low wing loading. The results of the calculation of the corrective factor are given for a high-performance glider and a light sport plane of conventional type.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

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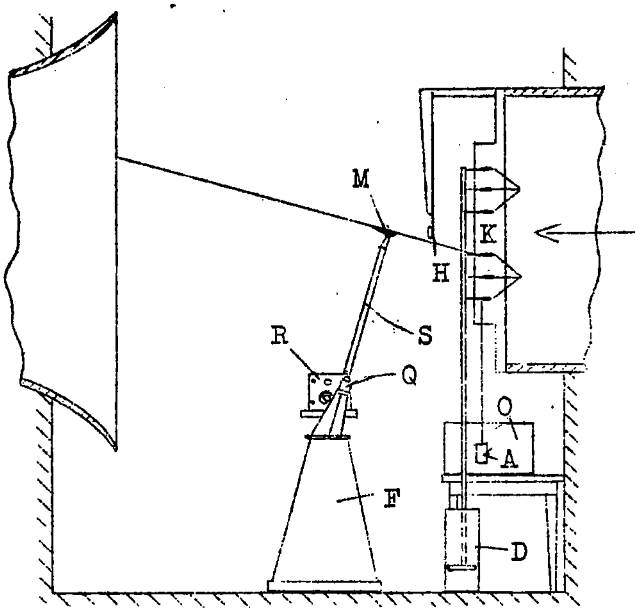

A, weight
D, damper
F, base
H, hot-wire anemometer
K, shutter vanes
M, model
O, oscillograph
Q, piezo quartz
R, amplifying tube
S, support

Fig. 1 Arrangement of apparatus.

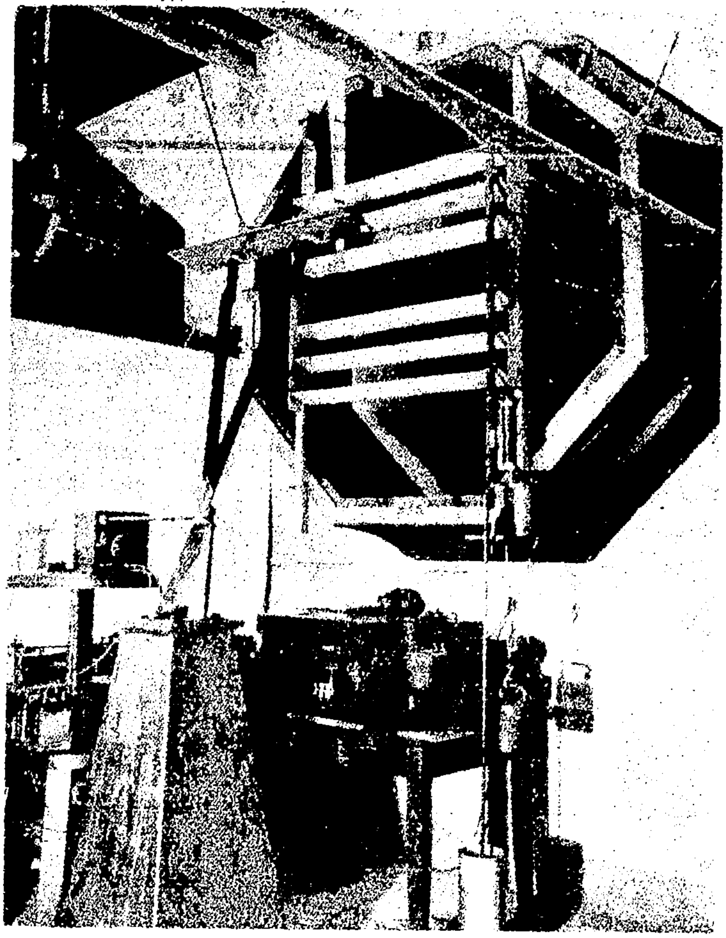

Fig. 2

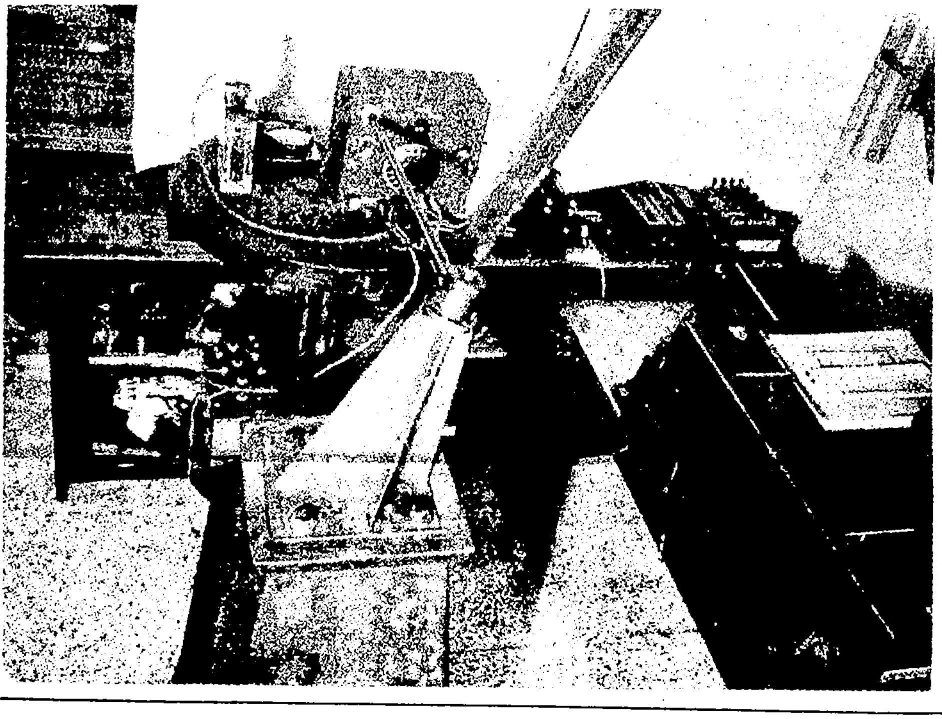

Fig. 3

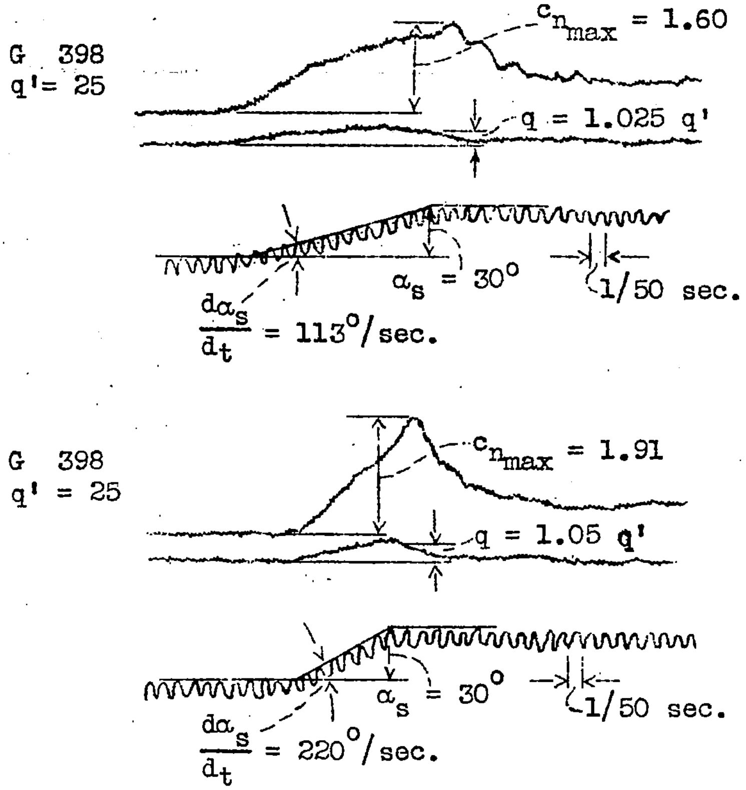
G 398
q' = 25
$c_{n_{max}}$ = 1.60
q = 1.025 q'
α_s = 30°
1/50 sec.
$\frac{d\alpha_s}{d_t}$ = 113°/sec.
G 398
q' = 25
$c_{n_{max}}$ = 1.91
q = 1.05 q'
α_s = 30°
1/50 sec.
$\frac{d\alpha_s}{d_t}$ = 220°/sec.

Fig. 4

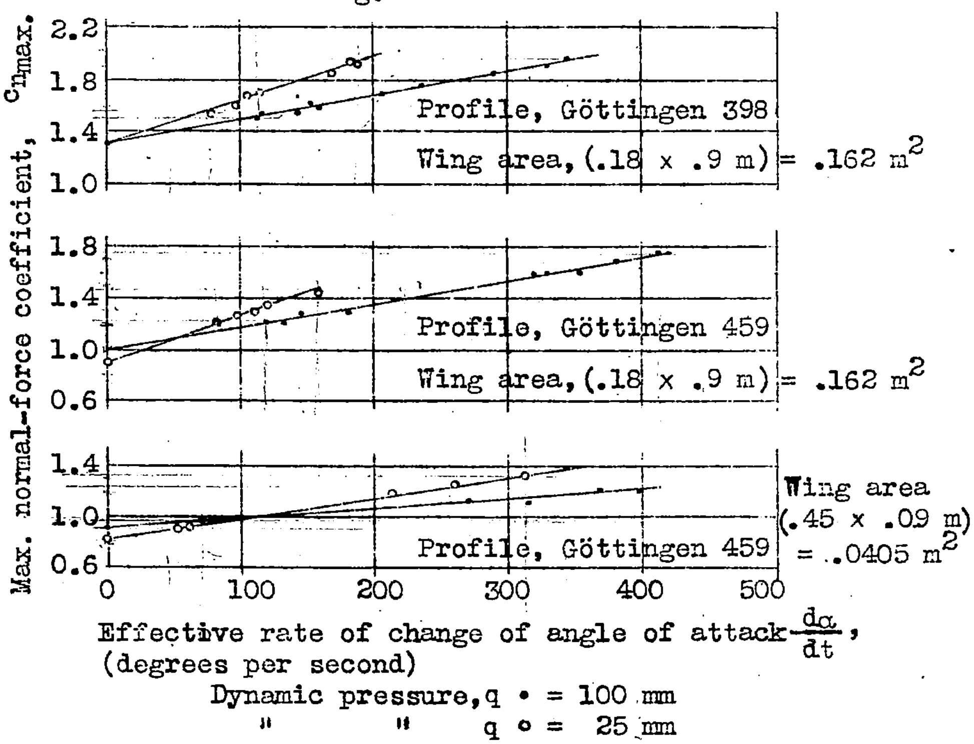
Max. normal-force coefficient, $c_{n_{max.}}$
2.2
1.8
1.4
1.0
Profile, Göttingen 398
Wing area, (.18 x .9 m) = .162 m²
1.8
1.4
1.0
0.6
Profile, Göttingen 459
Wing area, (.18 x .9 m) = .162 m²
1.4
1.0
0.6
Profile, Göttingen 459
Wing area
(.45 x .09 m)
= .0405 m²
0
100
200
300
400
500
Effective rate of change of angle of attack $\frac{d\alpha}{dt}$,
(degrees per second)
Dynamic pressure, q • = 100 mm
" " q ∘ = 25 mm

Fig. 5

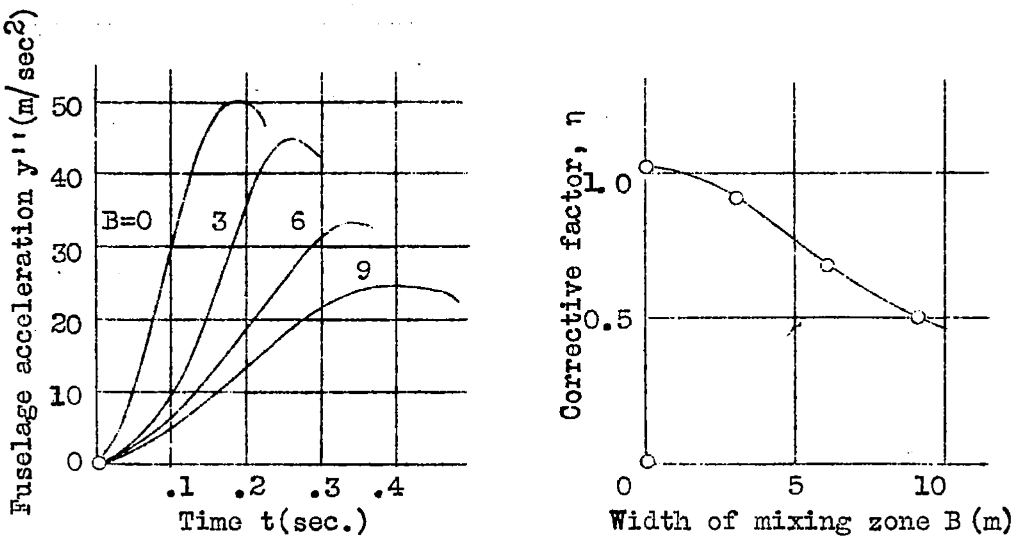

Fig. 6 Stresses of a sport plane flying at 30 m/s (98.4 ft./sec.) in a vertical gust of 10 m/s (32.8 ft./sec.).

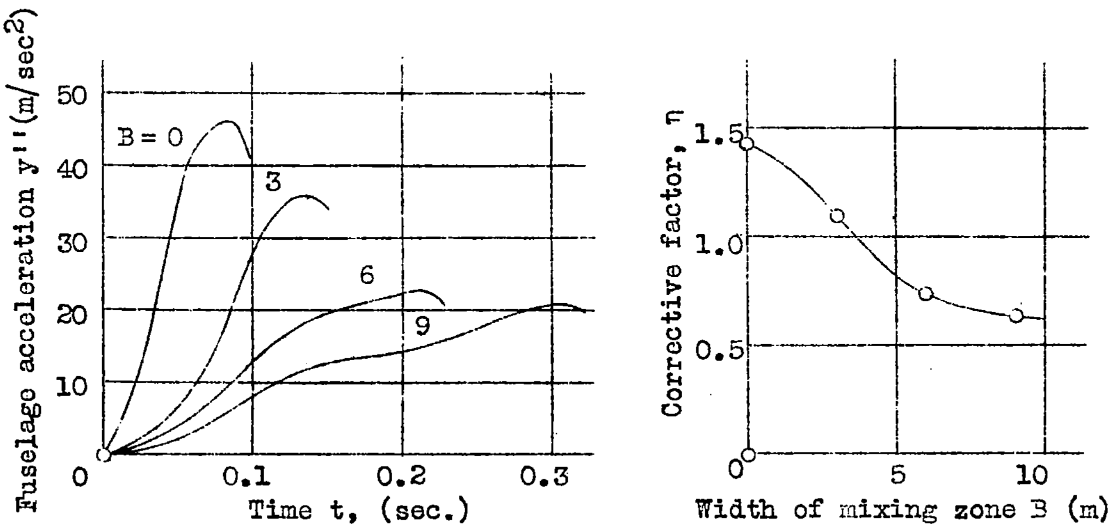

Fig. 7 Stresses of a glider flying at 20 m/s (65.6 ft./sec.) in a vertical gust of 10 m/s (32.8 ft./sec.).