A METHOD OF SELF-INDUCED ALLEVIATION OF AIRFRAME LOADS

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Summary—The possibilities are considered of applying a coupling of aileron deflections with wing bending deflections in order to reduce the variable aerodynamic wing load increments imposed by gusts and manoeuvring. It may be possible in this way to increase considerably the safe fatigue life of basic wing structure components without apparent weight penalty. Some experimental results obtained from elastic wing model tests in a wind tunnel are presented and analysed. The results of this analysis are discussed in particular with reference to the structure fatigue conditions for an example of a typical gust load spectrum.

1. INTRODUCTION

THE problem of fatigue in aeroplane structures is as yet of permanent importance presenting many difficulties in aircraft design, manufacturing and operation. The purpose of very extensive recent research is to obtain the most correct knowledge of load spectrum under different flight conditions, on the one hand, and to explain the fatigue properties of different materials and all the fatigue problems of different airframe structures, on the other hand. These investigations will give the possibility of selecting the most correct design methods of the basic aeroplane structure components under dynamic loading conditions. In this way the prospects of increasing the safe fatigue life of aircraft are continually enlarged.

The strength of the main structural components of present aircraft are based on the static loads requirements only, even if avoiding any significant stress concentrations, in most cases does not assure a satisfactory safe fatigue life of the structure. Owing to the very great scatter of the fatigue properties of materials and structural components, additionally increased by the influence of many different, difficult to verify, causes, it is necessary to apply very high safety factors. Therefore, in order to assure a satisfactory safe fatigue life of the aircraft often it is necessary to reduce considerably the stress of the components in tension in reference to the static strength requirements. If this stress reduction were achieved simply by a suitable augmentation of cross-section dimensions of basic structural components in tension it would obviously result in a corresponding increase of airframe weight.

Some alleviation of this problem could be achieved if (both in design and in service) instead of safe-life the fatigue fail-safe approach were applied. In this case it would be admitted that a degree of damage might happen from unforeseen causes and might remain undetected for some time, possibly propagating meanwhile. An aircraft with a fail-safe structure will accommodate such a damage while still retaining sufficient strength to operate with reasonable safety. The main advantages of this approach are that the safety of the aircraft is no longer dependent so much on the accuracy of predictions, but in this case, too, some considerable structure weight penalty is unavoidable.

Simultaneously the problem of fatigue of the aircraft structures may be approached in another way, too, by using the possibilities of influencing the magnitude of the aerodynamic loads or their distribution by the loads themselves or by the deformation of the structure. In this way a remarkable increase of aircraft safe fatigue life without structure weight penalty, or a reduction of the weight retaining the same safety conditions, might be achieved.

The character of variation of the aerodynamic loads to which the different aircraft components are subjected in operation might be influenced by a corresponding continuous variation of the aerodynamic characteristics of these components with the aid of a suitable device controlled by the loads themselves. For example, such a device might be controlled by the accelerations or by the structural deflections imposed by the aerodynamic loads.

It seems that there is as yet insufficient attention concentrated on these possibilities. This paper presents some results of simple experimental wind tunnel investigations of an elastic wing model on which the aileron deflection was controlled by a simple coupling with the wing deflection produced by the aerodynamic bending moment.

2. THE PRINCIPLE OF WING LOADS ALLEVIATION BY AILERON DEFLECTION COUPLED WITH WING BENDING DEFLECTION

The considered principle is simple. If the aileron deflections were coupled with the wing bending deflection, produced by the increasing aerodynamic load, in such a way that the aileron would at the same time rotate in the same direction, the increase of the aerodynamic loads on the outer wing parts (along the aileron span) would be reduced in comparison with the inner wing part (beyond the aileron span).

Under gust flight conditions the increase of the aerodynamic loads imposed on the outer wing parts (along the aileron span) by the vertical gust (respectively, positive or negative) would be reduced according to the aileron deflection while the aerodynamic characteristics of the inner wing part would remain practically unaffected. In consequence, the resultant wing lift and the aircraft acceleration would be reduced and, in particular, a considerable wing bending moment and deflection reduction would be obtained.

Somewhat different loading relations would occur in manoeuvring flight conditions, for example during the pull-up from diving. In this case, if the aircraft pull-up path should remain unchanged and hence the corresponding resultant wing lift should remain the same, then the aileron-wing deflection coupling would cause not only a corresponding lift reduction on the outer wing parts but also an increase of lift on the inner wing part of the same value. Hence only a shifting in spanwise load distribution—from outer to inner wing part—would occur producing a considerable wing bending moment reduction.

In order to get some more specific information about the possibilities of the aerodynamic wing load reduction in different flight conditions on the basis of the above described principle some elementary experimental investigations were carried out on a wing model in the wind tunnel. The adapted experimental conditions were corresponding rather to the gust flight condition, on the assumption that the aircraft as a whole, being, for example, in horizontal flight, does not yield (due to its very great inertia) to any vertical movements or pitching. In general, the assumed experimental conditions might be applied also in the case of manoeuvring loads.

3. WIND TUNNEL MODEL MEASUREMENTS

For the wind tunnel experiments a rectangular half wing model, elastic in bending, with symmetrical NACA 0018 profile and 700 mm half span and 150 mm chord length, fixed in the plane of symmetry on a plate (Fig. 1) was used. The wing model was a single spar wooden structure with the spar placed at 28·7 per cent of chord, the axis of which coincided with the axis of rotation of the plate to which the wing model was fixed. The aileron, with the dimensions shown in Fig. 1, could be fixed relative to the wing (locked) or could be hinged on it rotationally and connected with a stiff rod fixed on the same plate. Due to the connection with this rod the aileron was deflected proportionally to the bending deflection of the wing produced by its loading. The plate together with the wing model and the entire set on it could be turned from the symmetrical position of the profile in the flow to about 10 degrees of incidence under the action of a spring. The wing rotation was limited by a stiff stop placed on the plate.

The measurements were taken in a wind tunnel at a flow velocity $V = 40$ m/sec. Motion pictures of the displacements of three points on the wing tip at 0·025 second time intervals were taken during each wing rotation, i.e. each corresponding wing incidence increasing producing an increased aerodynamic loading and bending. The first point was placed at the wing spar centre (coinciding with the axis of rotation before wing deformation), the second one at the aileron hinge axis and the third one at the trailing edge. The displacements of the first point indicate the wing deflections, while the relative displacements of the points 1–2 and 2–3 determine, respectively, the wing incidence and aileron deflection.

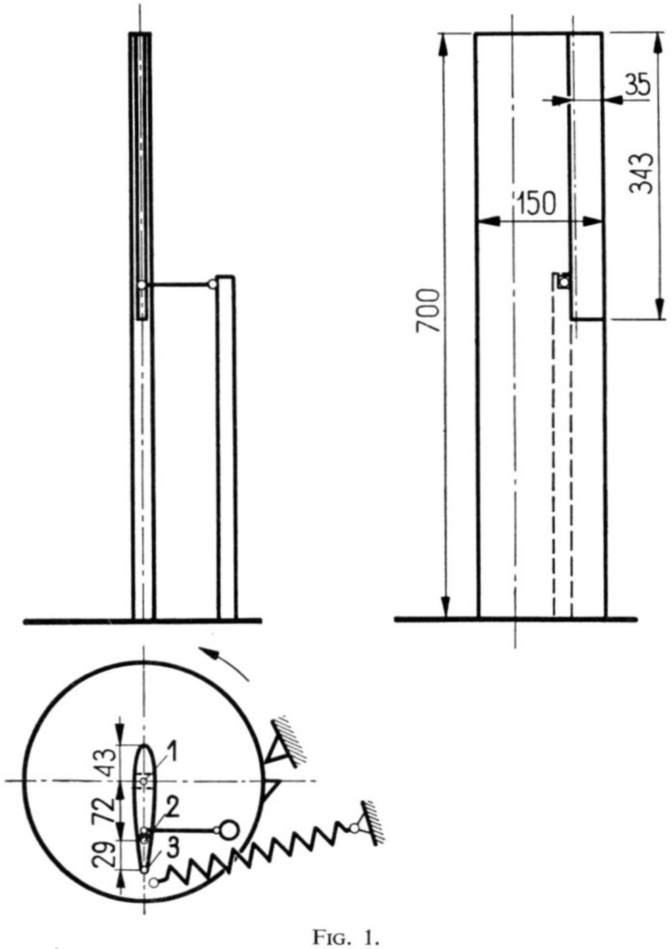

FIG. 1.

4. ANALYSIS OF THE EXPERIMENTAL RESULTS

The representative results of the described experiments are shown on the diagrams of Figs. 2 to 6. On the diagrams of Fig. 2A the displacements of the points 1 and 2 are shown measured at successive moments of rotation of the wing model with the aileron locked. The curves 1 and 2 represent the approximated functions of mean displacements of the corresponding points neglecting their oscillations which are hardly perceptible

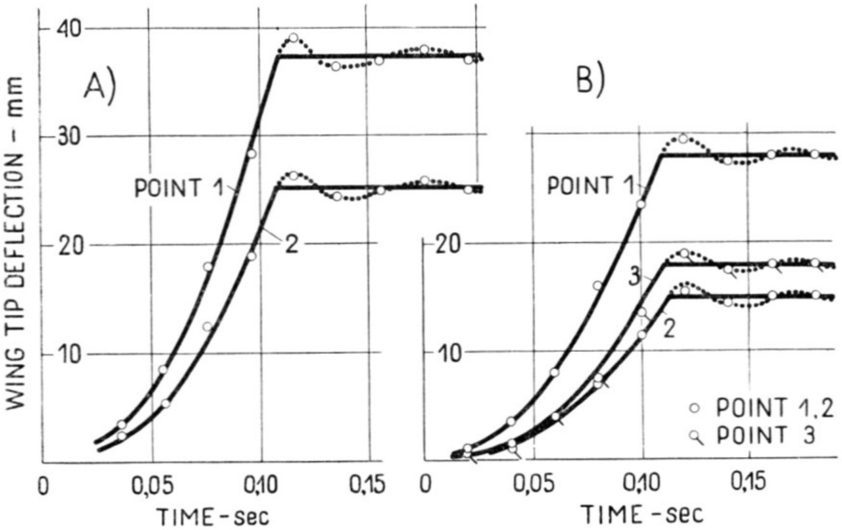

FIG. 2.

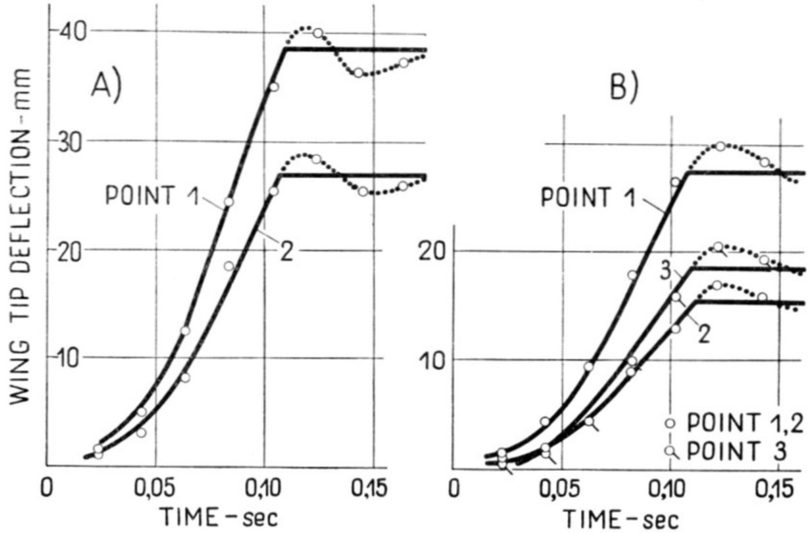

FIG. 3.

during the rotation (i.e. increase of incidence) of the wing. Some apparent but relatively small oscillations observed after that period (dotted lines) are rather excited by the shock at the instance of stopping the rotation.

In the same way in Fig. 2B the displacements of the points 1, 2 and 3 are presented in the case of aileron deflections being coupled with the wing bending deflections. The curves 1 in Fig. 2 represent in both cases (A and B), respectively, the dependence of mean wing bending deflections on the time of model rotation, i.e. of wing incidence variation.

Figure 3 shows likewise the results of tests in the same two cases (A and B) but in somewhat changed dynamical conditions of model rotation (a somewhat increased moment of inertia of the plate).

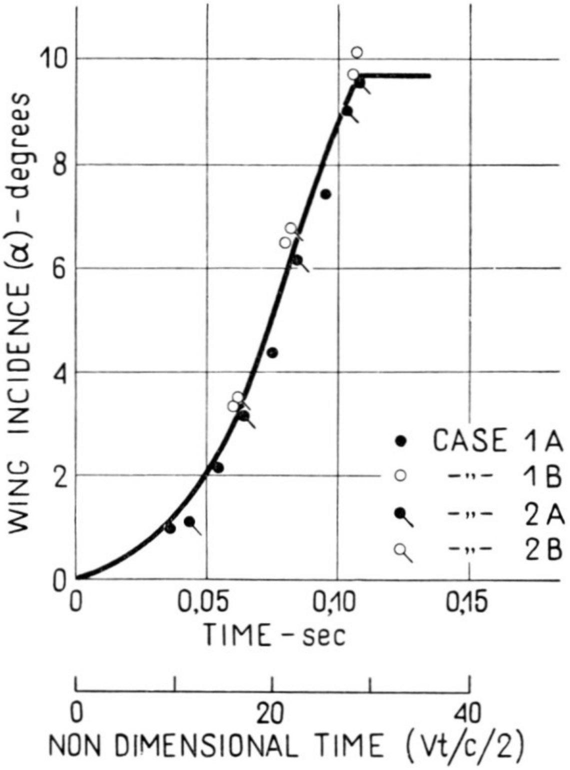

FIG. 4.

The diagram of wing incidence (α) in function of the time during the model rotation, deduced from the displacement diagrams of the points 1 and 2, is shown in Fig. 4. It can be seen on the diagram that this relation is approximately the same in all examined cases and can be expressed by one mean curve only which is similar to the curves 1 in Figs. 2 and 3.

From the curves 1 in Figs. 2 and 3 and the diagram in Fig. 4 are deduced the relations between the bending deflections and the angle of attack α of the wing in the investigated cases, shown in Fig. 5. All these relations are approximately linear. From these diagrams it can be seen that in the realized experimental conditions by the coupling of aileron deflections with wing deflections the last ones are reduced to about 2/3 within the entire investigated wing incidence region.

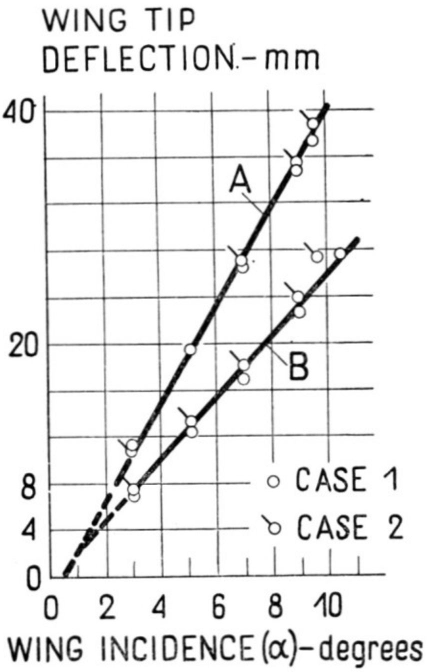

FIG. 5.

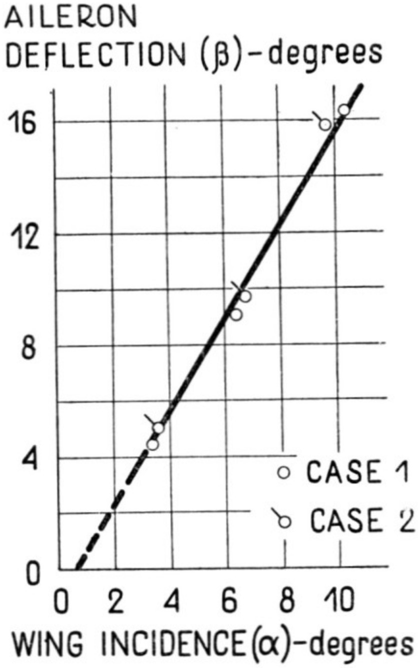

FIG. 6.

In Fig. 6 the diagram of coupled aileron deflection angle β in relation to wing incidence α is shown, deduced from the curves 2 and 3 in Figs. 2B and 3B and the diagram in Fig. 4. These relations, too, can be approximated in both cases by one straight line only.

From the presented wind tunnel test results, and particularly from the diagram in Fig. 5, it can be seen that the lag in aerodynamic response to the wing incidence variation, corresponding to the gust effect in gust flight condition, is very small. The most important observation to be made from that diagram is that the differences between the above mentioned response and the aileron deflection response is hardly perceivable. That scarcely perceptible delay can be explained by a very small aileron deflection lag (visible on the diagram in Fig. 6), due to the play in the aileron coupling joints.

This statement leads to an important conclusion that by applying the described principle of aileron-wing deflection coupling the desired effect of wing loading reduction even at small wing incidence changes (small gusts) can be achieved if only a correct continuous coupling response by a suitable coupling arrangement be assured.

In the discussed wind tunnel test conditions the ratio of the maximum wing incidence variation velocity, $d_\alpha/dt = \omega_\alpha$ ($\approx$ 80 degrees per second) to the flow velocity ($V = 40$ m/sec) referred to the wing half chord ($c/2 = 0{\cdot}075$ m) is $\omega_\alpha/(V/c/2) \approx 0{\cdot}30$ degrees per half chord (flown). The aileron deflection velocity $d_\beta/dt = \omega_\beta \approx 1{,}6\ \psi_\alpha$.

In order to compare the obtained test results with the gust flight conditions a vertical gust velocity $w = 3$ m/sec, the value whose percentage contribution to the cumulative fatigue damage is considered, on an average, to be the greatest, and a gust gradient $dw/dx = 1/10(dx = V dt)$ will be assumed. For the same conditions in flight as in tunnel tests,

$$57{\cdot}3\,\frac{d}{dt}\left(\frac{w}{V}\right)\Big/\frac{V}{c/2} = 0{\cdot}30\ \frac{\text{degrees}}{\text{half chord}}$$

the flight speed referred to the wing half chord is

$$V/c/2 \approx 19{\cdot}1 \text{ half chord per second.}$$

If for example a chord length $c = 3$ m is taken then the corresponding flight speed is $V = 28{\cdot}65$ m/sec $= 103$ km/hour.

Under the chosen wind tunnel test conditions the relation $\beta = f(\alpha)$ shown in Fig. 6 was fulfilled. That relation, however, depends on the flow velocity because the aileron deflection is closely connected with wing deflection which at a given angle of attack varies with V^2. In order to define more exactly the influence of the airspeed and other flight conditions on load alleviation effect of aileron-wing coupling more extensive investigations are required.

As regards the influence of the airspeed only, for example, an approximate relation in a simple manner could be deduced. Assuming namely that the relative load alleviation effect $\Delta z/z$ (z—deflection of the wing with locked aileron, Δz—decrease of this deflection due to aileron-wing coupling), known for a definite airspeed V_0, is proportional to the ratio β/α, β being proportional to (z—Δz), we receive for any other chosen airspeed V an approximation

$$\left(\frac{\Delta z}{z}\right)_V = \frac{k(V/V_0)^2}{1+k(V/V^0)^2}$$

From the considered experimental results—$\Delta z/z \approx 1/3$ at $V = V_0 = 40$ m/sec—we have $k \approx 1/2$. Then, for example, for two different V values, say $V_0/\sqrt{2}$ and $V_0\sqrt{2}$, we obtain corresponding values of relative load alleviation effect of about 1/5 and 1/2 respectively. The corresponding β/α ratios are then about 0·96 and 2·40, respectively.

These relations appear very interesting under gust flight conditions. For a wing with locked ailerons the ratio of the gust imposed increment of wing deflection to this deflection in an unaccelerated horizontal flight, z/z_1, is approximately proportional to the flight speed. It can be easily proved, that, for the same aircraft with aileron-wing deflection coupling applied, if the ratios $(z-\Delta z)/z_1$ and $\Delta z/z$ for a definite airspeed V_0 are known, then for any other chosen airspeed V, with the previous assumptions, we obtain approximately

$$\left(\frac{z-\Delta_z}{z_1}\right)_V = K\frac{V}{V_0}\left(1-\frac{\Delta_z}{z}\right) = K\frac{V}{V_0}\left[1-\frac{k(V/V_0)^2}{1+k(V/V_0)^2}\right]$$

If for example an unaccelerated horizontal flight speed $V_0 = 100$ m/sec at the wing incidence $\alpha = 3$ degrees be assumed at a vertical gust velocity $w = 3$ m/sec (neglecting the gust induced aircraft vertical motion) the ratio $z/z_1 \approx 0{\cdot}57$. Applying for this aircraft such an aileron-wing coupling for which a ratio $\Delta z/z = 1/3$ (as in the test results) in the assumed conditions would be achieved we would have k 1/2, $(z-\Delta z)/z_1 \approx 0{\cdot}57.2/3 = 0{\cdot}38$ and $K = 0{\cdot}57$. Then, for example, for two different airspeeds, say $V_0/\sqrt{2}$ and $V_0\sqrt{2}$, we obtain for an aircraft with aileron-wing coupling corresponding relative gust imposed wing deflection increments

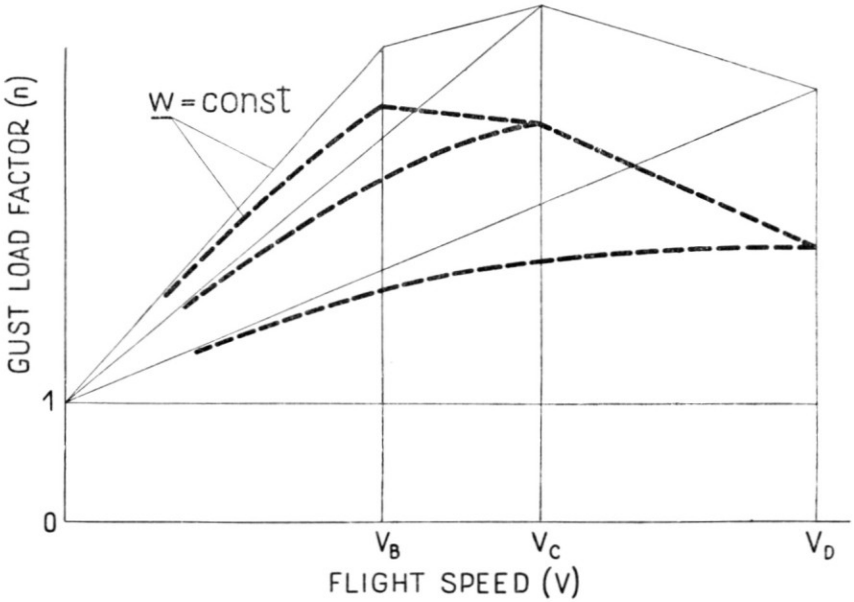

FIG. 7.

$(z-\Delta z)/z^1 \approx 0{\cdot}32$ and 0·40, respectively, while for the same wing with ailerons locked the values of corresponding increments would be about 0·40 and 0·80. Thus doubling the flight speed (from about 70 m/sec to 140 m/sec) in the first case due to the achieved load alleviation effect we obtain about 25 per cent increase of gust imposed load while in the second case these loads would be doubled.

That is an important conclusion because by applying aileron-wing deflection coupling the whole gust loading envelope for the wing structure can be considerably changed. The straight lines for $w = \text{const}$ would change into corresponding curves as shown in Fig. 7 (dashed lines). The advantage of such a gust loads diagram transformation need no furthe explanation.

Likewise in the case of manoeuvring loading, for example at pull-up from diving or in turn flight at a definite load factor, the load alleviation due to the applied aileron-wing deflection coupling would be relatively greater at higher than at lower flight speeds.

5. INFLUENCE OF THE AILERON-WING DEFLECTION COUPLING ON THE SAFE FATIGUE LIFE OF THE WING STRUCTURES

For a comparative analysis of this problem the cumulative damage rule will be used, for the sake of simplicity. In Fig. 8 a typical load spectrum is shown, corresponding to 10,000 hours flying and a typical *S-n* curve for a wing structure component (for example a spar). For this load diagram the curve 1 on the right in Fig. 8 is shown indicating the percentage contribution of these loads to the damage.

The surface of the diagram 1 in Fig. 8 $\Delta_1 \approx 0{\cdot}33$ represents the percentage damage of the component in 10,000 hours flying. So, dividing this number of flying hours through Δ_1 we receive the safe fatigue life of this component which is in this case about 30,000 hours.

If on the same aircraft an aileron-wing deflection coupling be applied in such a way that in the same conditions the gust loads would be reduced to say 75 per cent the fatigue life of the structure would be remarkably improved (Fig. 8). Corresponding to these reduced loads curve 2 on the right in Fig. 8 of the percentage contribution to the damage determines the surface $\Delta_2 \approx 0{\cdot}105$ which represents the percentage damage of the considered component in 10,000 hours flying. Since $\Delta_2 \approx \Delta_1/3$ the safe fatigue life of that wing structure component would increase more than three times in comparison with the previous fatigue conditions.

At the same time it can be seen that if the cumulative damage rule is true the band of the loads over which most of the damage is done will be narrower. In that case it will be reduced from about 4 to 14 per cent to about 3 to 10 per cent of ultimate loads while the most damaging level is dropping from 8 to 5 per cent of ultimate. In terms of gusts the most damaging velocity is dropping from the value of 3 to 2 m/sec.

It would be useful also to consider the possibilities of applying an aileron-wing deflection coupling with variable gearing ratio. In this way applying higher gearing ratios within the limits of smaller wing deflections, corresponding to a relatively narrow load band of the most damaging loads (gusts), reduced gradually with increasing wing deflections (loads) we could obtain still more advantageous fatigue loads as shown by the dashed curve in Fig. 8. In consequence the diagram surface Δ on the right in Fig. 8 (dashed curve) indicating the percentage damage of a wing structure component in 10,000 hours flying would be still more reduced and the most damaging loads level would become still lower.

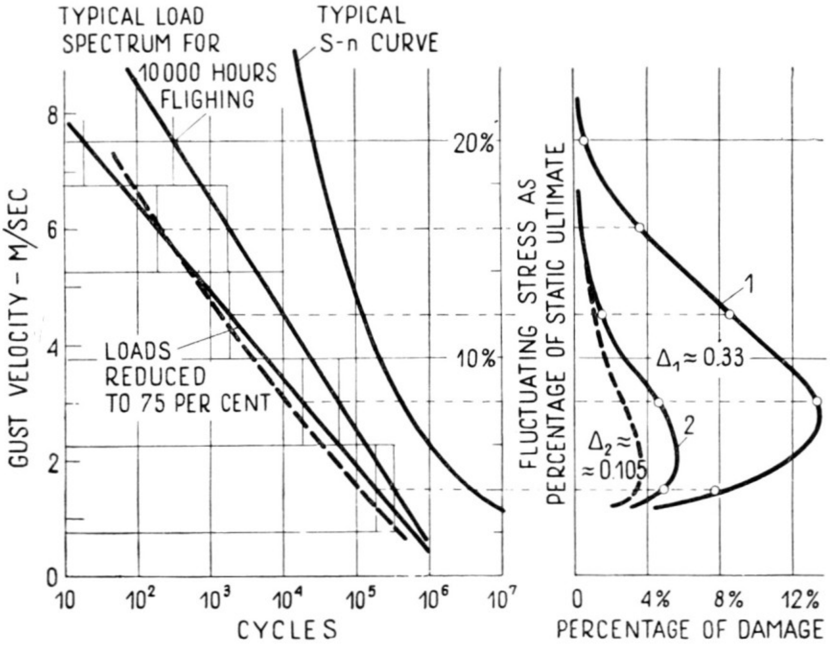

FIG. 8.

It should be taken into consideration that the discussed load alleviating principle would work also in the case of aircraft whose safe fatigue life depends mainly on the manoeuvring loads spectrum. In these conditions, too, with the aileron-wing deflection coupling a considerable wing bending moment reduction due to the displacement of aerodynamic load increments along the wing span from its outer to inner parts could be achieved.

In principle the discussed load alleviation should not be taken into consideration in static strength calculations of the structure both in gust and in manoeuvring flight conditions keeping in mind the possibility of accidental damage or the necessity of switching off of the coupling device in some flight conditions.

6. GENERAL CONCLUSIONS

From the present few simple wind tunnel test results and these short considerations the possibilities of applying the aileron-wing deflection coupling for an advantageous load alleviation in different flight conditions are evident.

The gust load conditions were considered most extensively. By applying the described method we may obtain not only remarkably reduced gust loads and thereby a reduced percentage fatigue damage of the structure during a definite period of time of flight but also narrowed limits of the most damaging loads due to the gust loads spectrum and their level lowered. In consequence, in this way it may prove feasible to increase several times the safe fatigue life of the structure.

The possibilities of a considerable reduction of the airspeed influence on the gust loads (Fig. 7) should also not be underestimated.

Likewise no less advantageous is the application of the aileron-wing deflection coupling in the case of aircraft submitted mainly to the manoeuvring loads. In this case, too, a considerable increase of structure fatigue life could be achieved.

It seems that the aileron-wing deflection coupling in the described way should have also, in some conditions, an advantageous influence on the flutter. It depends however on numerous factors, particularly on the elastic properties of the structure and the aerodynamic characteristics of the system. Therefore this problem calls for further investigations.

The presented experimental results are by far inadequate for answering all the important questions which might arise in connection with the problem. It demands still more extensive investigations, particularly in different flight conditions.

DISCUSSION

A. VAN DER NEUT: No mention was made of the effect of aerodynamic lag. This effect is important since with great lag the alleviating force will build up too late so that it is ineffective in reducing wing bending. The important parameter is $\omega c/V$. I suspect that this parameter was small, that therefore lag was small and the alleviation fairly large. (From the figures in the papers it follows in fact that the parameter was about 0·003, which yields negligible lag.)

My second remark is concerned with the fact that this alleviating system introduces an aerodynamical reduction of the torsional stiffness and consequently of the flutter speed.

F. MISZTAL: It is shown in the paper on the diagram of Fig. 5 that under the test conditions, at the value of the parameter $\omega c/2V$ of about 0·0057, the aerodynamic lag is very small. It is shown, too, that for an aircraft with a wing chord length of 3 m in flight at a gust gradient of 1/10 this value of $\omega c/2V$ corresponds to a flight speed of 103 km/hour. From this it can be supposed that the aerodynamic lag influence would be yet at much greater flight speeds and gust gradients considerably small, so that the effective load alleviation of the proposed system would cover in average conditions a great gust flight region of prevailing contribution to the cumulative fatigue damage.

As to the second remark concerning the flutter, this problem is mentioned in the conclusions of the paper. It seems that the aileron-wing deflection coupling in the described way would rather have in most cases an advantageous influence on the flutter speed. Besides, there always exists the possibility of putting out the coupling device at high flight speeds.