Flight Measurement of Dynamic Loads on Gliders

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1. Introduction

Dynamic loads on a flying aircraft produced by turbulent atmosphere and control deflections constitute a basis for dynamical computation of the structure; their knowledge is therefore essential for aircraft design.

The classical approach consists in assuming the velocity and the spectrum of a single gust or the amount by which the controls are displaced in a rapid manner for an assumed flight velocity. Hence the loads and stresses are computed with many simplifying assumptions. In design practice these simplifying assumptions are very far reaching. Thus, for instance, it is assumed usually that the aircraft is a rigid body and is fixed in space thus having no degree of freedom, and that the gust spectrum has the form of a jump. It is also assumed that the aerodynamic forces in a gust reach immediately their steady state value. The loads thus computed are then multiplied by the so-called coefficient of the aircraft depending on the wing load and geometry, the slope of the curve of lift in function of the incidence, etc.

In the years 1950–1960 there appeared some reports pointing out the necessity of a different approach to the problem. A number of publications concerning both experimental and theoretical work show the necessity of treating the problem of dynamic loads from the statistical viewpoint [3], [4]. The necessity of a statistical approach to the problem of dynamic loads originates above all from the fact that these loads appear constantly during flight and have a random character. The continual variation of the load during flight has drawn the attention of designers to the problem of fatigue strength of aircraft. It is known that failure may occur not necessarily as a consequence of a single load of maximum value but as a result of fatigue due to a great number of smaller loads.

Thus an analysis of the overload produced by a single gust or a single displacement of controls is therefore unable to give adequate strength criteria. On the other hand, the random character of the loads does not enable a rigorous theoretical description of a function expressing the loading process in flight.

The turbulence of the atmosphere and the displacement process of the controls and, therefore, the load on an aircraft depend on many factors in an involved manner not yet sufficiently known. Measurements of gusts in the atmosphere show no regularity and do not enable the determination of a typical distribution of gust velocity in space, nor the gust frequency and maximum magnitude. These measurements have shown that the atmospheric turbulence may be described in the statistical sense only.

A direct source of information on the gust loads in flight is furnished by load measurements during normal work of an aircraft. In order that the result of such measurements might be used as statistical data the measurement period must be sufficiently long. A serious disadvantage of this method is the fact that experimental data concerning the loads on a single type aircraft cannot be transferred automatically to other types, the flight loads depending on the design parameters of the aircraft and its handling properties, etc.

In practice, a quantity easily measured and adopted as a measure of dynamic load on an aircraft is the acceleration of its centre of gravity. There are many types of accelerometers recording the acceleration on a tape but their application to statistical measurements during many flight hours is very difficult and requires considerable labour for reading the results. In addition, continuous acceleration recording is not necessary. It suffices for the accelerations to be recorded discontinuously and to count how many times a definite acceleration level has been exceeded.

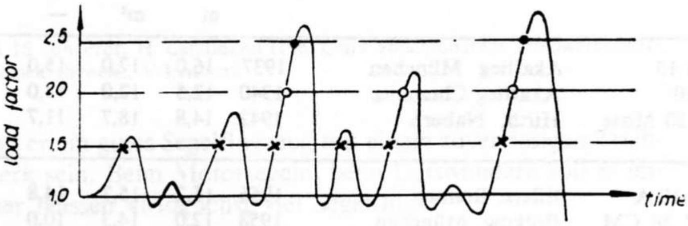


Fig. 1

If the continuous acceleration record is as shown in Fig. 1 an instrument designed for acceleration levels spaced by 0,5 g, for instance, will show that the level 1,5 g has been exceeded 6 times, the level 2,0 g — 3 times, the level 2.5 g — twice.

Such a counting accelerometer has found a broad application in statistical load measurements on transport aircraft.

Numerous publications ([4], [5], for instance) give results of measurements of dynamic loads on aeroplanes analysed from the statistical viewpoint and applied to fatigue computation. On the other hand no experimental data are available for flight loads on gliders. In connection with the rapid development of glider structures and the ever-increasing requirements concerning their performance, weight and strength, the knowledge of the real loads, their magnitude and number, acting on a glider during its service is essential.

The Department of Flight Mechanics, Politechnika Warszawska (Technical University of Warsaw), has been occupied for a year with collecting experimental data concerning flight loads on gliders.

The first stage of the work was that of constructing a counting accelerometer for statistical measurements.

2. The Counting Accelerometer

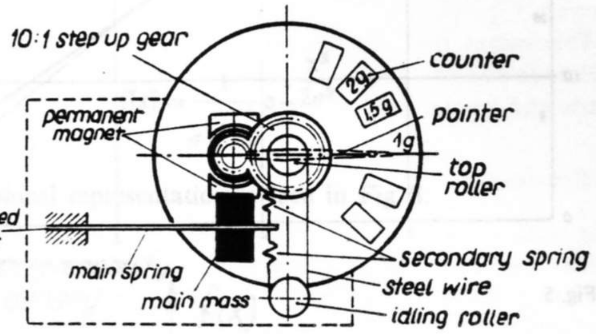
The basic layout is that of the counting accelerometer used on transport aircraft [1], [2]. The counting device was the only part to undergo a serious modification. The accelerometer designed in the Department of Flight Mechanics is destined for load measurement on gliders if the fundamental frequency of the wings does not exceed 4 Cps.

On the basis of resonance tests of high performance of more than ten types it has been found that this frequency is of the order of 3 Cps. The full range of accelerations recorded by the instrument is from 4 g to 7 g. In the interval of 1 g — 3 g accelerations loads are spaced by 0,5 g, in the remaining part of the total range by 1 g. It appears that in view of the fact that the range of loads acting on a glider in flight is large, a denser spacing is not necessary.

Of the two possible methods of acceleration counting: electrical and mechanical, the latter has been chosen.

The aim was to have an instrument as simple as possible not susceptible to atmosphere influences and reliable. In this respect the method of recording by means of mechanical counting devices is undoubtedly of advantage over the electric one.

The layout of the counting accelerometer is shown in Fig. 2.



Diagrammatic sketch of counting accelerometer

Fig. 2

A 0,9 kg weight is attached to the end of a flat spring. This large mass was necessary to ensure a force sufficient for the deplacement of the mechanical counters without affecting the correctness of the readings.

The other end of the spring is rigidly connected with the structure of the aircraft by means of the housing of the instrument. Two coil springs are attached to the free end of the spring. They are connected in series with a cable thus forming a closed circuit passing over two pulleys. The cable just mentioned converts the motion of the spring end into a rotating motion of the upper pulley. The attachement of the cable to the upper pulley is such that it allows a rotation of this pulley through an angle of ±360°. The axle of the upper pulley carries an arm by which the counters are displaced. The rotation angle of the arm is in direct proportion to the acceleration acting on the housing of the instrument.

In addition the upper pulley drives, through a 10:1 transmission, an aluminium cylinder located in the field of a permanent magnet. Eddy currents in the cylinder produce a moment of resistance proportional (within 1 %) to the angular velocity. Such a device is very advantageous because it gives a damping almost linear and practically independent of the time and atmosphere influences.

For counting the acceleration peaks mechanical counters are used. They are arranged along the path of the arm.

The mechanism driving the digit wheels of the counters requires special attention. Fig. 3 shows the arm and the counters arranged radially on the dial. For space economy both ends of the arm are arranged to displace the counters. Thus, counters counting acceleration peaks corresponding to neighbouring acceleration levels are mounted at opposite points of the dial. Fig. 4 shows the displacing mechanism of the counters. If the acceleration exceeds a certain value the arm moves a ratchet lever of the counter, thus spanning a soft spring.

If the arm passes over the ratchet lever or goes back, this soft spring causes the lever to assume its original position, the digit wheel thus being rotated through one digit. During the back motion, when the acceleration decreases, the arm passes freely over the counters due to a special ratchet at its end.

This mechanism must be designed to eliminate the possibility of displacing the digit wheel through two digits or more during one passage of the arm. With quick motions of the arm the inertia of the mechanism creates such a danger. To avoid it a system of ratchets and stops have been devised but not shown in the figure. Tests have shown that the counters work correctly with sudden acceleration changes not exceeding 5 g.

During the initial tests a considerable difficulty was experienced connected with the necessity of starting the recorder after take-off and stopping it before landing. It is known that the character of the loads acting on an aircraft during take-off and landing is quite different from that of flight loads and the instrument should record flight accelerations only. A mechanical blocking device was first used. This was controlled by the pilot by means of a Bowden cable. The

Fig. 3

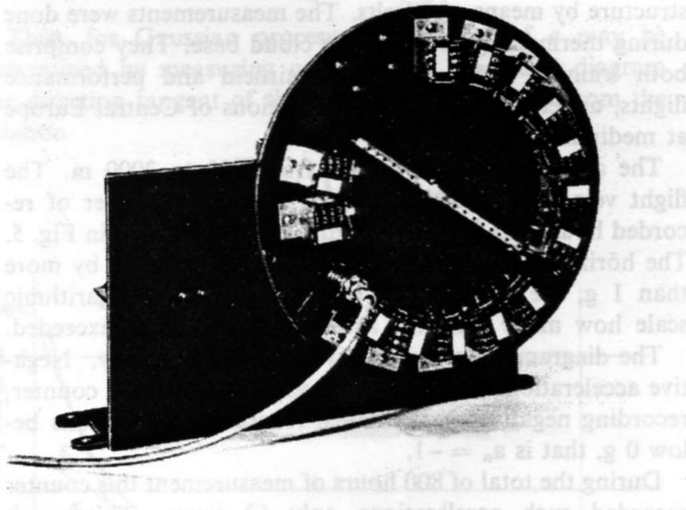
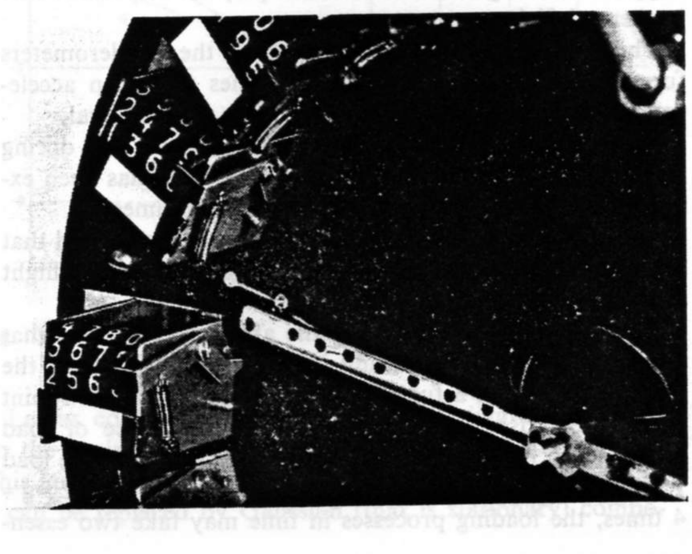


Fig. 4



blocking device consisted of locking the main spring in the neighbourhood of the weight. This system proved to be inadequate in practice because it occurred often that the pilot forgot to block the instrument before landing. This involved the necessity of rejecting the record. In addition a hard landing, on an accidental landing place for instance, means often a damage to the instrument.

Good results were obtained in 1961 when an automatic electrical blocking was used. The transmitter of the automatic blocking device is a special altimeter having an electric contact on its dial. If the arm of the altimeter exceeds a certain value (200 m for instance) an electric circuit is closed, thus starting an electric motor, fed from four 4,5 V batteries, which moves the blocking bolt.

At heights below 200 m the instrument is blocked. With this automatic device the pilot's task was only to set the arms of the altimeter on the zero position and inscribe into the diary the indication of the counter before and after flight and the duration and kind of flight.

3. Test Results

Most measurements have been done at the Gliding Centre at Leszno using the high performance gliders of the SZD-22 B Mucha-Standard and SZD-9 Jaskólka types. A short characteristic of these gliders is given in Table 1. The accelerometers were located in luggage holds in the neighbourhood of the gravity centre of the glider and rigidly fixed to the structure by means of 4 bolts. The measurements were done during thermal flights below the cloud base. They comprise both training flights above the airfield and performance flights, under average thermal conditions of Central Europe at medium altitudes.

The altitude of flight ranged from 200 to 2000 m. The flight velocity was 65–120 km/h. The total number of recorded hours was 800. The results are summarized in Fig. 5. The horizontal axis is that of acceleration increase by more than 1 g, the vertical axis (N) showing on a logarithmic scale how many time the acceleration level was exceeded.

The diagram concerns positive accelerations only. Negative accelerations recorded were very few. The first counter, recording negative accelerations, recorded accelerations below 0 g, that is $a_n = -1$.

During the total of 800 hours of measurement this counter recorded such accelerations only 63 times. This result suggests that negative accelerations play no important role in thermal flights.

The data read from the counters of the accelerometers furnish information on how many times the given acceleration level has been exceeded in a given time interval.

Thus for instance from diagram 5 it is seen that during 781 flight hours the load increase by $a_n = 1$ g has been exceeded 1138 times and that by $a_n = 3$ g – 26 times.

By extrapolating the diagram for larger loads we find that the load increase appearing only once during 800 flight hours was $a_n = \sim 5$ g.

The information obtained in the above way is somewhat incomplete, however, it being impossible to reproduce the loading process as a function of time. From the viewpoint of fatigue it is important to know the sequence of load maxima and minima. If, for instance, we read that the load 1,5 g has been exceeded 4 times, 2 g – 4 times, and 2,5 g – 4 times, the loading processes in time may take two essentially different forms (Fig. 6). In order to be able to interprete the result we must have recourse to a continuous recording of acceleration. It suffices, however, to make a continuous acceleration record under typical flight conditions for a short time interval. as compared with the entire measurement period, and to consider this acceleration process as representative. On the basis of an acceleration record of about 30 minutes of flight and similar measurements on transport aircraft it may be stated that the process (b) in Fig. 6 approaches best the real one.

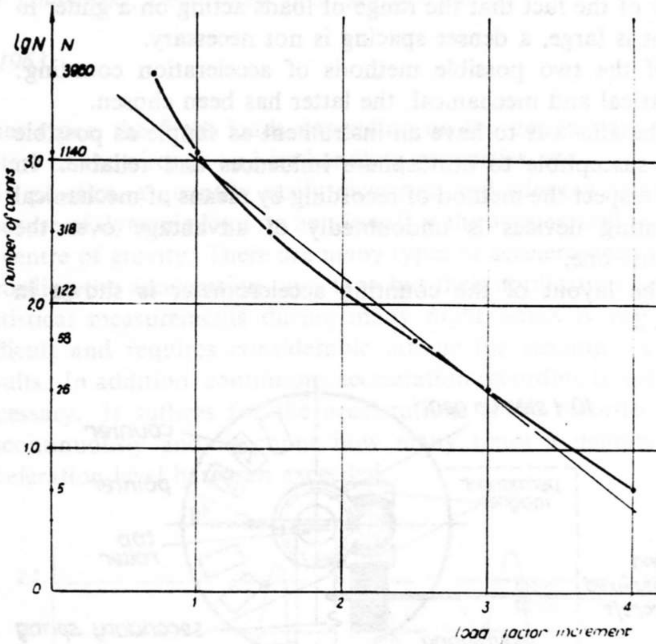


Fig. 5

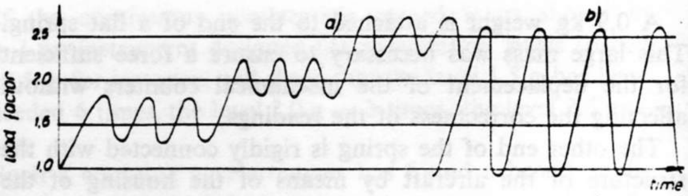


Fig. 6 Two patterns of acceleration changes

4. An Analysis of the Data

From the statistical point of view the overloads recorded by the accelerometer during flight constitute random variables.

They are not, of course, of uniform probability. Any way of relating a random event with the corresponding degree of probability is called the probability distribution. For random variables constituting continuous sets (in contrast to discontinuous or discrete sets as in the play of heads or tails) this distribution is described by a function called the probability distribution of the random event. In statistical practice we use the so-called distribution density function. It is the first derivative of the distribution function and is introduced for simpler interpretation of the probability of a random event X. It is expressed as

$$(1) \qquad P[\alpha < x < \beta] = \int_{\alpha}^{\beta} f(x)\,dx$$

and constitutes the area under the corresponding part of the f (x) curve, cf. Fig. 7.

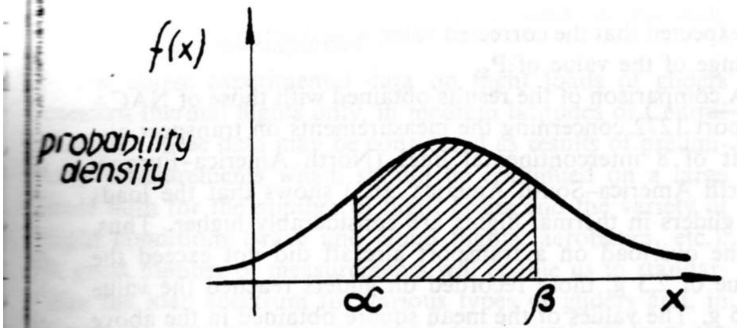


Fig. 7

One of the most frequent density distributions is the normal or Gaussian distribution where the density function has the form

$$f[x] = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}} \tag{2}$$

Its graphical representation is seen in Fig. 8.

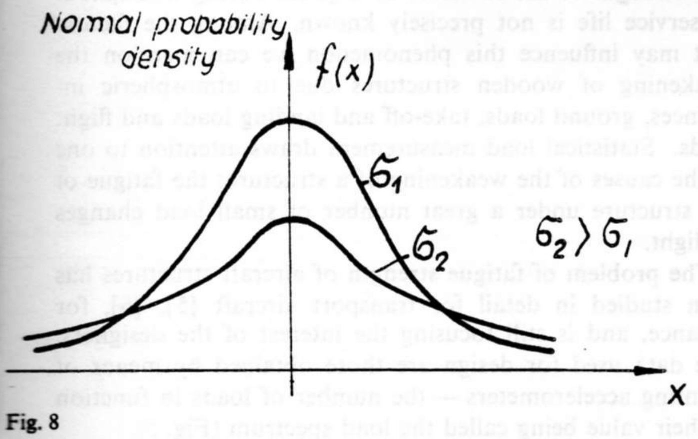


Fig. 8

σ is a constant parameter and is called the mean square. Let us explain this notation. The mean value a_n (t) in the time interval T is defined by the equation

$$\bar{a}_n = \frac{1}{2T}\int_{t_o-T}^{t_o+T} a_n(t)dt \tag{3}$$

This may be illustrated by the graphical example in Fig. 9.

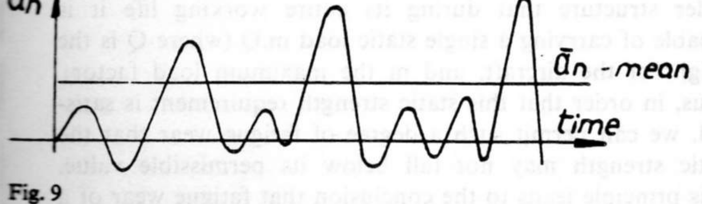


Fig. 9

The mean square is expressed thus

$$\sigma^2 = \frac{1}{2T}\int_{t_o-T}^{t_o+T} [a_n(t) - \bar{a}_n]^2 dt \tag{4}$$

The process a_n (t) is stationary if this expression tends to a constant value for T —> ∞. It is seen that the process described by the Gaussian distribution is stationary. Let us observe that the knowledge of σ enables us to determine the density distribution and, in consequence, the probability of being subject during flight to overloads contained in the interval considered.

Two questions now arise:

1. Are the data obtained during flight sufficient for the process to be treated as stationary?

2. How to determine σ from the results obtained?

These two questions have been answered by the work of Rice and Press [4]. The final relation found in this reference for a Gaussian process is

$$N[a_n] = N_o e^{-\frac{a_n^2}{2\sigma^2}} \tag{5}$$

where a_n – overload increase by more than 1 g.

N (a_n) – number of times the value a_n was exceeded

σ – mean square

N_o – constant (see below).

By finding the logarithms if both numbers of the equation we have

$$\lg N[a_n] = \lg N_o - \frac{\lg e}{2\sigma^2} a_n^2 \tag{6}$$

which means that the relation between lg N (a_n) and $a_n{}^2$ is linear with the direction tangent $-\frac{\lg e}{2\sigma^2}$

Thus, for Gaussian processes the value of σ may be determined by measuring on the lgN(a_n) = f(a_n^2) diagram the direction tangent of the straight line obtained from the relation

$$\sigma = \sqrt{\frac{\lg e}{2\,\mathrm{tg}\alpha}} \cong \sqrt{0{,}217\,\mathrm{ctg}\alpha}$$

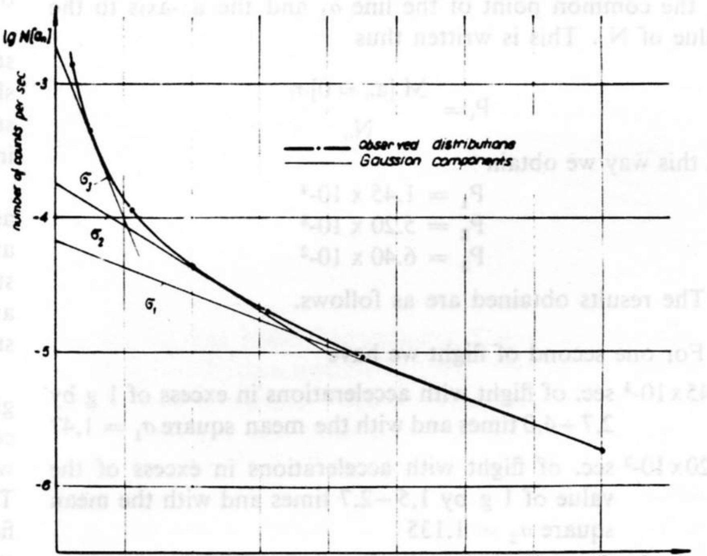


Fig. 10

Let us consider the lgN(a_n) (Fig. 10) diagram prepared on the basis of flight test results. It is not a straight line. This means that the real process is not stationary. However, it can be replaced by Gaussian (that is stationary) components by approximating the curve by straight line segments tangent to it. Thus the fundamental equation (5) holds for each of these lines (of different slope and, therefore, different value of the mean square). The total number of times a given value a_1 was exceeded will be obtained as a sum

$$M[a_n] \cong \sum_1 P_i N_{oi} e^{-\frac{a_n^2}{2\sigma_i^2}} \tag{7}$$

where

N_{oi} – is the expected number of excesses of the value $a_n = a$ per second. This is a quantity characteristic of the aircraft and the load conditions. By introducing certain assumptions concerning the description of the turbulence of the atmosphere it is considered to be constant for a given aircraft.

P_i – is, for a given mean square, constant and denotes the fraction of a second during which the flight conditions were constant.

σ_i – is the corresponding mean square of the overload.

Thus, the above sum may be rewritten in the form

$$M[a_n] = N_o \sum P_i e^{-\frac{a_n^2}{2\sigma_i^2}} \tag{8}$$

Accurate determination if the value of N_o presents some difficulties and requires additional measurements. By extrapolating the $M(a_n)$ diagram to the intersection with the an axis we read in an approximate manner $N_o \cong 1$. The curve is approximated by three tangent lines. The values of the mean square corresponding to each of these times are

$$\sigma_1 = 1.47;\ \sigma_2 = 1.135;\ \sigma_3 = 0.611$$

The values determined from the ratio of the value of $M(a_n)$ at the common point of the line σ_1 and the a_n-axis to the value of N_o. This is written thus

$$P_i = \frac{M[a_n = 0]\sigma_i}{N_o}$$

In this way we obtain

$$P_1 = 1.45 \times 10^{-4}$$
$$P_2 = 5.20 \times 10^{-3}$$
$$P_3 = 6.40 \times 10^{-2}$$

The results obtained are as follows.

For one second of flight we have

$1{,}45 \times 10^{-4}$ sec. of flight with accelerations in excess of 1 g by $2{,}7 \div 4{,}0$ times and with the mean square $\sigma_1 = 1{,}47$

$5{,}20 \times 10^{-3}$ sec. of flight with accelerations in excess of the value of 1 g by $1{,}5 \div 2{,}7$ times and with the mean square $\sigma_2 = 1{,}135$

$6{,}40 \times 10^{-2}$ sec. of flight with accelerations in excess of the value of 1 g by $0{,}8 \div 1{,}5$ times and with the mean square $\sigma_3 = 0{,}611$.

It is seen that the sum P_1 is considerably less than one second. This means that the flight proceeded mostly under conditions of small overload (the value 1 g being exceeded by, at most. 0.8 g). It seems that although the value of N_o has not been determined in an accurate manner it should not be expected that the corrected value would bring any essential change of the value of P_1.

A comparison of the results obtained with those of NACA Report 1272 concerning the measurements on transport aircraft of 8 intercontinental lines (North America–Europe, North America–South America, etc.) shows that the loads on gliders in thermal flights are considerably higher. Thus, if the overload on a transport aircraft did not exceed the value of 2,3 g, those recorded on gliders reached the value of 5 g. The values of the mean square obtained in the above report are from 0,104 g to 0,430 g. The corresponding quantities obtained from the glider data just mentioned are contained between 0,611 g and 1,770 g.

A comparison of values of P_1 reveals the same fact: a glider passes more time with higher loads than a transport aircraft.

This means that the specific character of flight loads of gliders as compared with transport aircraft consists in higher loads and greater load dispersion.

5. Conclusions

The strength of the structure of a glider during throughout its service life is not precisely known. Among the factors that may influence this phenomenon we can mention the weakening of wooden structures due to atmospheric influences, ground loads, take-off and landing loads and flight loads. Statistical load measurement draws attention to one of the causes of the weakening of a structure: the fatigue of the structure under a great number of small load changes in flight.

The problem of fatigue strength of aircraft structures has been studied in detail for transport aircraft [5], [6], for instance, and is still focusing the interest of the designers. The data used for design are those obtained by means of counting accelerometers — the number of loads in function of their value being called the load spectrum (Fig. 5).

Some proposals have also been made to introduce a standard load spectrum in the form of a straight line. Fig. 5 shows that the a-N diagram may be approached by a straight line. The slope h of this line is a measure of load intensity.

If it is assumed that the load spectrum is known as well as the fatigue properties of the glider structure and that we are able to determine the service period after which the strength will be reduced by a certain percentage, we must answer the question as to what degree of fatigue wear of the structure may be considered to be permissible.

It seems to be obvious that it is always required for a glider structure that during its entire working life it is capable of carrying a single static load m.Q (where Q is the weight of the aircraft, and m the maximum load factor). Thus, in order that this static strength requirement is satisfied, we can permit such a degree of fatigue wear that the static strength may not fall below its permissible value. This principle leads to the conclusion that fatigue wear of a structure is permitted only if the structure is somewhat overdimensioned from the viewpoint of static strength. This principle can also be realized in a somewhat different manner, by reducing m after a certain period of service.

It is obvious that the computation of the "fatigue life" requires the knowledge of the fatigue strength of the structural element considered, that is the so-called Sa–N or load endurance curves obtained by laboratory tests for pulsating loads of constant amplitude.

The above experimental data on flight loads of gliders concern thermal flights only, in medium latitudes of Central Europe. These data may be considered as results of preliminary measurements which should be continued on a large scale both for the number of flight hours and the variety of flight conditions (wave and cloud flights, aerobatics, etc.): A great number of measurements will enable us to standardize the load spectrum for various types of gliders and, in future, to introduce new improved design methods from the viewpoint of strength. Of course the number of recorded flight hours must be greatly increased.

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