A FATIGUE TEST ON A SAILPLANE WING

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ABSTRACT

In 1976-1977 a full-scale fatigue test on a sailplane wing was carried out in the Laboratory of Light Structures of Helsinki University of Technology. The wing was of glass fibre construction, with carbon fibre reinforced wing spar caps. The fatigue test program consisted of portions representing ground loads due to ground runs, ground-air-ground cycles in launching and landing, and gust loads due to atmospheric turbulence in flight. Gust loads due to atmospheric turbulence were calculated by using a power spectral method according to the mission analysis criterion. The mission profile consisted of parts representing launching, circling in thermals, flight over start and finish lines, and various types of cross-country flight. In calculating the response of the airplane to gusts, the elasticity of the airplane was taken into account by using an unsteady aeroelastic calculation method. The fatigue testing program covered a flight time of 4000 hours with a safety factor four. The fatigue test was divided into 40 blocks, each block representing 400 hours of flight.

INTRODUCTION

In 1973 a complete full-scale static and fatigue test was made at Helsinki University of Technology, Finland, on a PIK-20 sailplane wing, based mainly on a similar investigation of the "Cirrus" sailplane (References 7,12). The results of this test were successfully applied to the development of early versions of the PIK-20. However, it later became apparent that the results of this early test could not be applied to the more recent models of this airplane, for two reasons. First, the method for calculating the load spectrum was found to be very conservative, and consequently the strain level of the wing was very low. Second, in the new models of the airplane, extensive use was made of a new material -- carbon fibre -- in the primary structure of the wing. It thus seemed that a new full-scale fatigue test might be useful. This paper presents a short summary of the new full-scale fatigue test; a more detailed exposition will be found in Ref. 10.

The test was performed in 1976 and 1977 at the Laboratory of Light Structures of Helsinki University of Technology on a PIK-20D sailplane wing. This wing is made of glass fibre/epoxy composite with spar caps made of carbon fibre/epoxy. The same wing was used for both static strain tests and the fatigue test. For the static tests, loads were calculated according to OSTIV Airworthiness Requirements for Sailplanes. For the fatigue test, loads due to atmospheric turbulence were calculated by power spectral methods according to the mission analysis criterion proposed by the Federal Aviation Agency (Reference 4; see also Reference 11). Load spectra due to ground runs and ground-air-ground cycles were calculated by using the same methods as in the previous test (Ref. 7, 12).

In the present case, atmospheric turbulence is the main source of fatigue loads during flight. Fatigue due to maneuvering is less important, since the sailplane in question is rarely used for aerobatics. Thus, special emphasis was put on obtaining a realistic load spectrum due to atmospheric turbulence. The power-spectral method used for the PIK-20D wing fatigue test is subsequently discussed in more detail.

LOAD SPECTRA DUE TO ATMOSPHERIC TURBULENCE

In power-spectral methods, the magnitude of any load (e.g. strain at a given location on the wing) is assumed to be a random function of time (see Fig. 1), satisfying certain assumptions. According to FAA proposal (Ref. 4), for each flight segment the frequency of exceedance N of a load x can be written as follows:

$$(1) \quad N_x(y) = N_{0x}\left[P_1 \exp\left(-\frac{|y-y_1|}{\bar{A}b_1}\right) + P_2 \exp\left(-\frac{|y-y_1|}{\bar{A}b_2}\right)\right]$$

(see Eq. (4-2) on p. 16 of Ref. 4), where

- y is the value of the load x in question
- y_1 is the value of x in the reference flight condition (usually level flight)
- $\bar{A}$ is the amplification factor
- N_{ox} is the zero-crossing frequency of x
- P_1, P_2 are proportions of time flown in non-storm (CAT) and storm turbulence, respectively
- b_1, b_2 are gust intensity parameters (average turbulence intensities) for non-storm and storm turbulence, respectively).

In equation of form (1) can be written for any load of interest. In Eq. (1), $N_x(y)$ denotes the number of such events per unit time when the

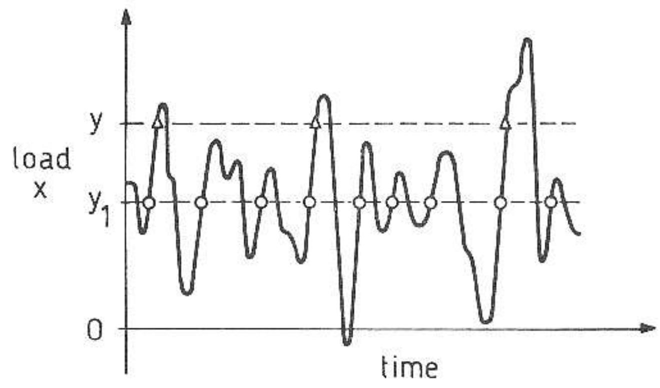

Figure 1. A random load

load x exceeds the value y in a positive direction (marked by small triangles in Fig. 1). Furthermore, N_{ox} is the number of such events per unit time when the increment $y-y_1$ of x crosses the value zero in a positive direction (marked in Fig. 1 by small circles).

The amplification factor $\bar{A}$ is defined as the ratio of the intensity σ_x of the load to the intensity σ_w of the gust velocity, or

$$(2) \quad \bar{A} = \frac{\left[\int_0^\infty \phi_x(\omega)\,d\omega\right]^{1/2}}{\left[\int_0^\infty \phi_w(\omega)\,d\omega\right]^{1/2}} = \frac{\sigma_x}{\sigma_w}$$

where ϕ_x is the power-spectral density function of the load x,
ϕ_w is the power-spectral density function of gust velocity, and
ω is the circular frequency (rad/s)

The zero-crossing frequency is calculated from the formula

$$(3) \quad N_{0x} = \frac{1}{2\pi\sigma_x}\left[\int_0^\infty \omega^2 \phi_x(\omega)\,d\omega\right]^{1/2}$$

Depending on the mathematical mode used, a number of alternative formulas can be derived for the power-spectral density function ϕ_w of the gust velocity. In the present case, the von Kármán spectrum

$$(4) \quad \phi_w(\omega) = \frac{\sigma_w^2 L}{\pi V}\,\frac{\left[1+\frac{8}{3}(1.339\,\omega L/V)^2\right]}{\left[1+(1.339\,\omega L/V)^2\right]^{11/6}}$$

was used as suggested in the FAA proposal (Ref. 4). In Eq. 4, V is the velocity of flight (TAS) and L the scale of turbulence. Houbolt (Ref. 5) suggests slightly lower values for L than the FAA proposal; in the present case, 200 m was considered an appropriate value.

The power-spectral density function $\emptyset_x$ of the load x is obtained from the equation

$$(5) \qquad \emptyset_x(\omega) = \left|H(i\omega)\right|^2 \emptyset_w(\omega)$$

where H is the transfer function between the gust velocity w and the load x. For the present investigation, the power-spectral densities of loads and transfer functions were calculated using the AEPAC aeroelastic program package developed at the Helsinki University of Technology (Ref. 8). Details of these calculations are presented elsewhere (Ref. 9) and will not be discussed here.

By substituting printouts of the AEPAC programs in Eqs. (2) and (3), amplification factors $\bar{A}$ and zero-crossing frequencies N_{ox} could readily be calculated for all loads of interest by simple numerical quadratures. In practice, it is impossible to extend the integrations to infinity, as written in Eqs. (2) and (3). However, because the power-spectral density of the gust velocity decreases rapidly with the frequency, the integration can be cut off at a finite value of ω. In the present case, the value 5 Hz was chosen for the cutoff frequency; this value is close to the upper validity limit of the AEPAC method.

Amplification factors and zero-crossing frequencies were calculated for upper surface strains at the main spar at four spanwise wing stations. The most severely loaded of these was taken as the basis of the fatigue spectrum.

THE FLIGHT PROFILE

In a fatigue analysis carried out according to the mission analysis criterion, Eq. (1) must be written separately for each segment of the flight profile. Frequencies of exceedance thus obtained must then be weighted by times spent in each individual profile segment, and summed up to obtain the total frequencies of exceedance for the complete flight. In the present context, the phrase "flight profile" as used in the original formulation of the mission analysis criterion is somewhat misleading. This is because the flight of a transport airplane proceeds in much the same way from flight to flight, whereas the flight profiles of a sailplane are quite different for every individual flight. Here, the flight profile must be interpreted as the average, or typical flight profile of an airplane throughout its whole service life.

To obtain a realistic flight profile for a modern glider, a survey was made among users of the PIK-20 sailplane in Finland. The results of this survey are summarized in Tables 1 and 2.

Table 1 Use of PIK-20 sailplanes in Finland in 1976

Type of flight	Time of flight h	Percent of total time of flight
Cross-country	790	37
Cloud flying	13.5	1
Other	1361	62

Table 2 Method of launching of PIK-20 sailplanes in Finland in 1976

Method of launching	Number of launchings	Percent of total number of launchings
Winch	457	28
Aero tow	1203	72

Prior to constructing the flight profile, the transfer function H was calculated at 16 points throughout the flight envelope of the airplane (see Fig. 2) to obtain an overall picture of loads due to turbulence in different flight conditions. These calculations were performed for

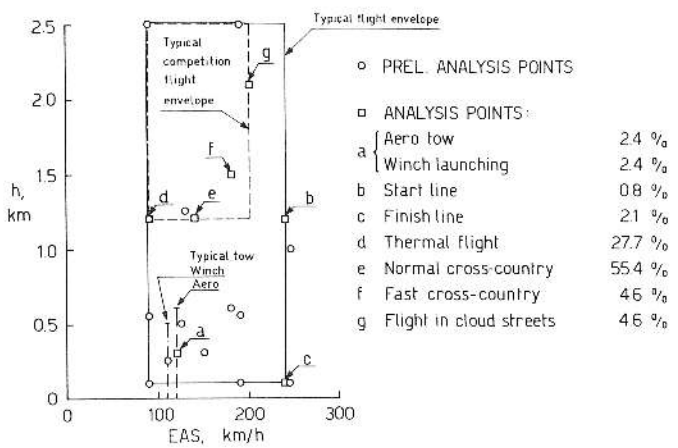

Figure 2. The flight profile

the airplane both with and without water ballast; the case with no ballast proved to be critical in all cases. Thus, in all subsequent gust-spectral calculations, no water ballast was assumed. Based on these preliminary calculations, on the survey referred to above, and on a number of discussions with glider pilots, seven points on the flight envelope were chosen as representative of the flight profile, as shown in Fig. 2. The percentage shares of the seven chosen flight conditions were selected on the basis of discussions with glider pilots. It became apparent that during a cross-country flight, about 70 per cent of the time is spent in straight flight and the remaining 30 per cent in circling in thermals. The straight flight portion was divided into three parts with different mean flight speeds as follows: a) normal straight flight between thermals at 140 km/h (60 per cent), b) high-speed straight flight at 180 km/h (5 per cent) and c) flight at high altitude and at high speed at 200 km/h (e.g. under a cloud street) (5 per cent) These values are, of course, only representative, and may vary greatly depending on weather and piloting technique. As a result of the survey referred to above, cloud flying was completely omitted from the analysis. As in Ref. 12, one hour was chosen for the mean time of flight. This choice is on the conservative side with regard to the results of the survey, which gave 1.3 hours for the mean flight time. This is because the load spectrum becomes more severe, the shorter the flight time.

TURBULENCE INTENSITY PARAMETERS

The FAA proposal for the factors P_1, P_2, b_1, and b_2 in Eq. (1) is based on flight-record data for three large transport airplanes (Lockheed Constellation, Lockheed Electra, and Boeing 720B). As far as the authors are aware, no systematic investigations have been undertaken to determine the corresponding factors for sailplanes. Some measurements have been made in Hungary by Gedeon (Ref. 3), but it is difficult to use Gedeon's results directly in this context, since his method of analysis differs from that used in the present investigation.

Previous NASA tests have given values roughly 1 m/s and 2 m/s for the average gust velocity intensities of clear air turbulence and cumulus clouds, respectively (Ref. 6). In the light of these results, the average gust intensity of 1.4 m/s given by Gedeon (Ref. 3) for circling flight in thermals seems to be quite realistic. Thus, for the thermal circling portion of the flight profile, the value 1.4 m/s was used for b_1, P_1 being put equal to unity and P_2 equal to zero.

For other parts of the flight profile, values of P_1 etc. given by the FAA proposal were used (e.g. see Figs. 5-3 and 5-4 on pp. 34-35 of Ref. 4). Whether or not turbulence intensity parameters obtained for transport airplanes can be used for sailplanes is, of course, a matter for discussion. We hope that the systematic flight test program currently under preparation at the Laboratory of Light Structures of Helsinki University of Technology will cast more light upon this problem.

The turbulence intensity parameters used for different parts of the flight profile and the corresponding strain amplification factors and zero-crossing frequencies are summarized in Table 3.

Table 3 Turbulence parameters, zero-crossing frequencies, and strain-amplification factors for the PIK-20D flight profile

Profile segment	b_1 m/s	b_2 m/s	P_1	P_2	N_{0x} 1/s	$\bar{A}$ (‰)/(m/s)
a_1 Winch launching	1.14	2.32	0.665	0.00395	2.182	0.0716
a_2 Aero tow	1.14	2.32	0.665	0.00395	2.182	0.0716
b Start line	1.05	2.53	0.292	0.00204	2.655	0.1036
c Finish line	1.17	2.30	0.854	0.00465	2.710	0.1037
d Thermal flight	1.40	—	1.0	0.0	2.203	0.0572
e Normal cross-country	1.05	2.53	0.292	0.00204	2.233	0.0801
f Fast cross-country	1.05	2.60	0.236	0.00165	2.368	0.0933
g Flight in cloud streets	1.07	2.75	0.165	0.00110	2.466	0.0987

THE FATIGUE TEST

The fatigue spectrum was constructed by assuming an airframe life of 20 years and 200 hours of flight per year. The scatter factor was put equal to 4 in accordance with the FAA recommendation (Ref. 1). Thus, the final fatigue testing program corresponded to an airframe life of 80 years, or 16,000 hours of flight.

The fatigue testing program was divided into 40 blocks, each corresponding to 400 hours of flight (see Fig. 3). Each block was divided into 5 segments: a) a ground loads due to ground runs and takeoff runs, b) ground-air-ground load cycles due to liftoff and touch-down in aero-tow launching, c) ground-air-ground load cycles due to liftoff and touch-down in winch launching, d) gust loads in winch launching, and e) other gust loads due to atmospheric turbulence. Repetition of segments in this order made it possible to closely simulate the load sequence in actual flight. Parts d) and e), which together comprise 80 per cent of the whole program, were discussed in the previous three chapters. Only the mean load factor is different in the construction of parts d) and e). Part a) of the block was constructed using the load amplitude distribution proposed by Gedeon (Ref. 2) assuming an average of 0.5 bumps per meter and an average length of 100 m for takeoff and landing runs (Ref. 12). Parts b) and c) were constructed assuming that 50 per cent of launchings were by aero tow and 50 per cent by winch launching. These figures differ markedly from those obtained in the survey referred to above, but the fifty-fifty basis seems to be more reasonable because a large number of sailplanes use only winch launching, and because winch launching imposes more severe loads upon the airframe than aero tow launching. As the mean flight time was one hour, the number of load cycles for groups b) and c) was 200 for each.

The manufacturer wanted to test whether or not the strain level could be increased from that used in strctural calculations. For this reason all load factors of the actual airplane were finally multiplied by the factor 1.44. Thus the mean load factor in flight, for example, was taken to be 1.44 instead of 1.0.

In actual testing, the loads were applied to the wing using a hydraulic multipurpose loading machine. The loading machine was controlled by an instrument tape recorder using a preprogrammed magnetic tape. One 400 hour block could be run in 47 hours, and the whole test took 80 days to complete. During the test the deflection was measured continuously in

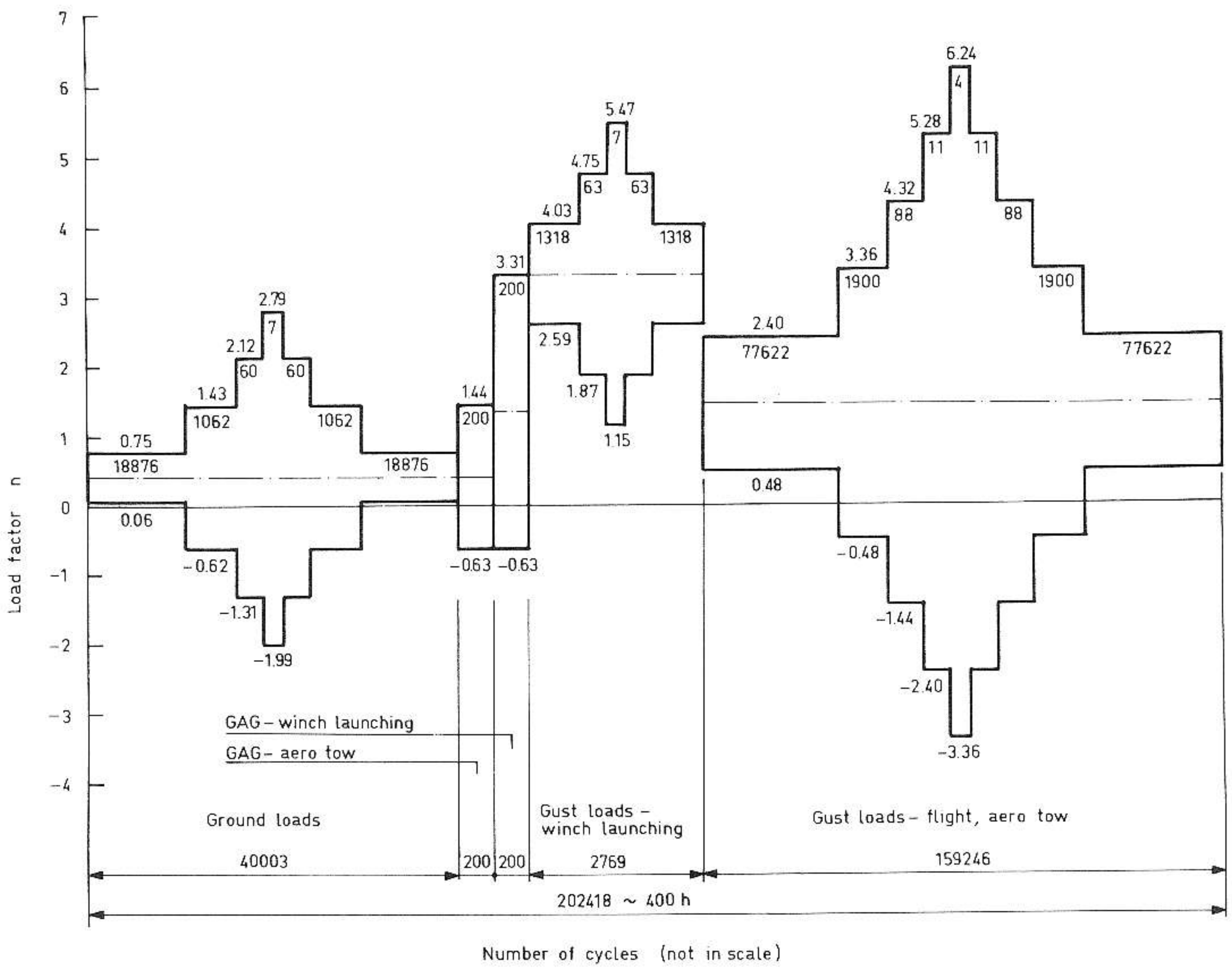

Figure 3. PIK-20D fatigue testing program (400 hours block)

order to detect eventual fatigue. A subsequent static test showed that the wing had adequate static strength. However, with respect to the increased strain level, the wing failed at a somewhat lower load than expected. Subsequent investigations revealed that the wing may have been partially fatigue damaged due to extensive static testing at the increased load level even before the actual fatigue test had begun.

CONCLUSIONS

Although there are still a number of problems to be solved in the present method, it is obvious that it can give a more realistic load spectrum for an elastic sailplane than the methods used previously for fatigue testing of sailplanes. The method also makes it easier to account for different flight conditions in different weather conditions.

Compared with a powered aircraft, a sailplane flies only for short times at speeds at which maximum load factors can occur. Thus, the loading program contains only very few high loads. To obtain a realistic result by the fatigue test the wing should be used as little as possible for static testing prior to the fatigue test so as to avoid premature fatigue damage.

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