Improvements in Fatigue Testing of Sailplanes

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Abstract

Combining data from the more detailed analysis of sailplane G records with some recently published theoretical results gives the possibility to calculate more exact load spectra taking into account some dynamical characteristics of the type in the design stage already.

In view of a life safety factor of at least 5 for safe-life designs dictated by the impossibility of making more than a sole full-scale complete fatigue test in most cases, the development of fail-safe structures is of prime economic importance. The possibility of developing fail-safe light metal sailplane wings has been proved by successful preliminary tests.

The relatively weakest part in fatigue testing is damage calculation. Limitations of the Palmgren-Miner theory applied so far by us are well understood, but several other formulas tried hitherto failed to come up to expectations. A series of two-stress level rotating bending and axial tensile fatigue tests were run to investigate the adaptability of some new ideas to dural type alloys.

Introduction

Safety and economic factors trend to give a steadily growing importance to fatigue testing in sailplane design and development. Work done in this domain at the Technical University, Budapest, Department for Aeronautics has been reported on at two previous OSTIV Congresses by Prof. Dr. Rácz and the author [1] and by Hatházi [2] respectively. Since then testing equipment and procedures have changed but little, nevertheless, improved theoretical understanding has led to some significant changes in the determination of load spectra, to work on fail-safe light metal sailplane wings and to research on possible improvements to the damage calculation. These aspects of our work are to be covered briefly in the present paper.

Notation

$a = \frac{dC_L}{d\alpha}$	airplane lift curve slope	rad^{-1}
b	'effective' rms intensity parameter	$m\ sec^{-1}$
c	mean aerodynamic chord of wing	m
g	acceleration of gravity	$m\ sec^{-2}$
1_0	sheat width of fatigue specimen	m
$\triangle 1$	length of crack propagation	m
$n = n_1 + n_2$	load factor	
n_1	mean load factor	
n_2	(stochastically) alternating load factor	
v	true flight speed	$m\ sec^{-1}$
w	vertical component of gust velocity	$m\ sec^{-1}$
A	ratio of rms response to gust velocity rms	
L_e	scale of load peak frequency	m
Λ	wawelength (power spectral analysis)	m
$M = \log e = 0.43429...$		
N	cumulative number of laod cycles less than or equal to n	h^{-1}
$\bar{N}$	cumulative number of load cycles greater than n	h^{-1}
N_0	total number of load peaks	h^{-1}
W/S	mean wing loading	$kp\ m^{-2}$
γ	exponent factor in load exceedence function	
η	spectral gust alleviation factor	
ϱ	air density	$kp\ sec\ m^{-4}$
μ	relative density of the sailplane	
$\Phi\ (n_1)$	probability density of mean load factor	
$\Phi \triangle n$	power spectral density function of C. G. normal acceleration	m
$\Psi\ (n_1, n_2)$	probability density function of load factor in circling flight	

1. Load Spectra

1.1 Statistical Determination of Load Spectra Constants

Nearly all of the air- and ground loads exerting a significant influence on the fatigue life of sailplanes are of stochastic character; winch launching, aerobatics and ground to air cycle being only exceptions to this rule. Raw material for the calculation of load spectra statistical constants can be obtained from flight test results only. Nevertheless, without intelligent sorting and fairing the amount of flying to be done for every new type would be obviously prohibitive or life prediction uncertainties of at least an order of magnitude were to be accepted.

Flight test data supported by practical experience showed the most significant differences in the number and severity of load peaks to be attributed to the kind of flying done. Consequently, as a first order approximation, G records were sorted into the following classes: start-landing, aero-tow, flight in calm air (e. g.: circuits with pupils), circling in thermals, flight between thermals and cloud flying. Statistical evaluation of flight records was done separately for each of these – let us say – flight modes. This meant practically dividing the record of each flight into corresponding phases, according to the flight log and controlled after the character of the section on the flight recorder film.

For air loads in straight flight a mean load factor of +1.0 has to be assumed and exceedence data may be faired by expressions of the form:

$$\bar{N} = N_0 e^{-\frac{\gamma}{M}(n-1)} = N_0 10^{-\gamma(n-1)} \quad [h^{-1}] \tag{1}$$

The corresponding probability density function being:

$$\frac{dN}{dn} = N_0 \frac{\gamma}{M} 10^{-\gamma(n-1)} \quad [h^{-1}] \tag{2}$$

In circling flight (circling in thermals and cloud flying) the mean load factor is changing, too. Best way of describing the resulting complex load factor distribution is straight by the probability density function:

$$\frac{\partial^2 N}{\partial n_1 \partial n_2} = \Psi(n_1, n_2) = N_0 \frac{\gamma}{M} \Phi(n_1) 10^{-\gamma n_2} \quad [h^{-1}] \tag{3}$$

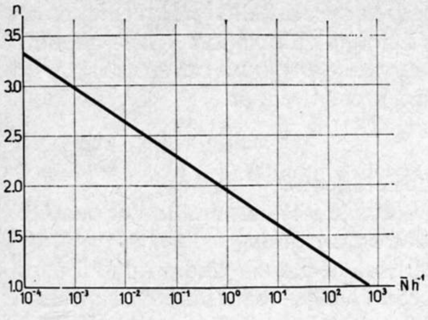

FIG 1

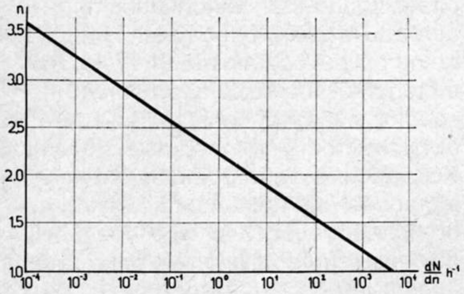

FIG 2

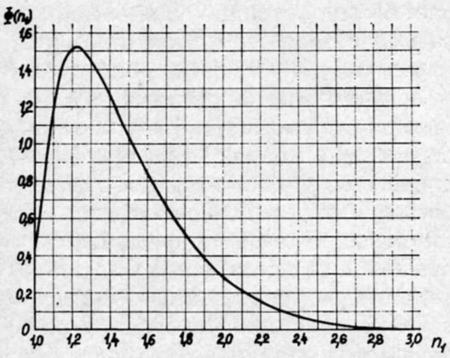

FIG 3

Thus for each flight mode two statistical parameters, N_0 and γ, have to be determined.
This was our state-of-the-art until 1968. Two serious deficiencies resulted from this oversimplification:

a) dynamical characteristics of the type concerned could not be made allowances for;

b) there was no possibility of drawing on the wealth of data compiled by and for the commercial and military aviation.

Number of severity of stochastic air loads are dependent on the magnitude of air turbulence and on piloting techniques. Differences between pilots may account for part of the data scatter but the average of flight test results for each of the flight modes, we are primarily interested in, may be attributed to air state and airplane dynamics only.
The velocity field of turbulent air is a function of place and time. Nevertheless, when sailplanes are going through the air at speeds they are capable for and compelled to, the influence of the variation in time of this velocity field on the total number of lead peaks is thought to be secondary to the influence of the flight speed. It was decided therefore to adapt as a second order approximation:

Table 1. Effective air turbulence parameters.

Flight mode	Aero tow	Flight in calm air	Glide between thermals	Circling in thermals	Cloud flying
L_o b m sec^{-1}	60 1.0	105 0.3	85 0.5	45 1.4	55 1.9

$$N_0 = 3{,}6.10^3 \cdot \frac{V}{L_e} \qquad [h^{-1}] \tag{4}$$

v has to be choosen according to the flight mode and to the characteristics of the type. Mean L_e values thought to be representative to different flight modes in our meteorological conditions* are to be found in table 1 at the end of this section.
Calculation of the exponent γ may be refined, too. As suggested by Taylor [3], the relative density of the sailplane may be computed as to be:

$$\mu = \frac{2}{\rho g} \frac{W}{S} \frac{1}{ca} \tag{5}$$

with ϱ corresponding to a mean flight level of say 1000 metres. The spectral gust alleviation factor may be expressed in first order approximation as in [3] by:

$$\eta = \frac{0{,}88\mu}{5{,}3+\mu} \tag{6}$$

The ratio of aircraft rms response to rms gust velocity can be expressed as recommended by Firebaugh [4]:

$$A = 1{,}15 \frac{\rho}{2} \frac{a n V}{W/S} \tag{7}$$

with the empirical factor 1.15 accounting for several minor omissions. Finally, as a last step of the calculation, modelled after [4] Eq. (1) we have:

$$\gamma = \frac{M}{bA} \tag{8}$$

In its present role b may be termed «effective» rms turbulence intensity including pilot-induced accelerations as well. Checking our own flight test results against published sailplane counting accelerometer data [5, 6, 7] and against some atmospheric turbulence measurements (e. g.: [4,8]) we have adapted and are using L_o and b values as in tab. 1.
Let the regional if not local character of these parameters be emphasized again.

* In determining L_e values the flight mode has a twofold influence:
a) certain phases of the flight are associated with certain mean air turbulence conditions (e.g.: cloud flying, thermalling, etc.);
b) the total number of load peaks is including those caused by pilot corrections too, so e.g. in aero tow there is a higher load peak frequency than when flying in normal straight glide under the same meteorological conditions.

1.2 Power Spectral Analysis

As advantages of power spectral methods over statistical evaluation the following may be specified:

a) about one order of magnitude less flight time is needed for the same accuracy;

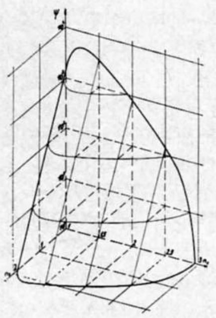

FIG 4

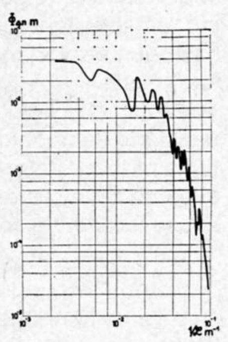

FIG 6

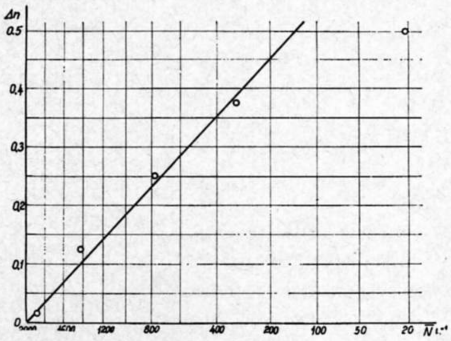

FIG 5

b) accounting for the effects of airplane dynamic parameters and flexibility is considerably facilitated.
These are decisive requirements for the adaptation of atmospheric turbulence data collected and published for meteorological and power plane use.
As far as it is known to the author, up to now the possibility of adapting this powerful research tool to sailplane use has been investigated only by Laudanski [9] and even he did not go beyond basic theoretical considerations.

Starting the work at first we felt some concern about the correct conversion procedure of power spectral density data in statistical exceedings data and vice-versa because Rice [10] had demonstrated it only for normal distributions whereas our load exceedence graphs for different flight modes showed a distinctive exponential character. But after flight records were split up into short sections, homogeneous by appearance, strong evidence was found of individual «turbulence cells» giving acceptable normal G exceedence distributions (fig. 5).
It remains now to collect enough flight data and practical experience to utilize the potentialities of power spectral methods and eventually to make a complete theoretical discussion practicable. As an exemple, the normal acceleration power density spectrum of a 255 second long thermal flight section is shown in fig. 6.

2. Fail-Safe Design

2.1. The Problem of Safety in Fatigue Design

In fatigue design and testing of sailplanes a practically zero probability of serious failures has to be provided for. For solving this intricate problem the real meaning of very low probabilities is to be considered.
There is, at first, the probability of exceeding a load of given magnitude. Our statistical load spectra are running formally, although with continually decreasing probability, until infinity. To decide whether these low probabilities have a real physical meaning or not, i. e. whether a sailplane may ever be subjected to them, is a question sometimes difficult to answer. Best way of guessing it is perhaps by the use of energy methods. There is also some experimental evidence of load exceedence graphs changing their character beyond a certain load level (see e. g.: [11] fig. 12). Low probability load maxima are to be considered only inasmuch as sufficient strength for eventual occurrence has to be provided for, damage in low cycle fatigue is usually negligible.
Fatigue lives, in test runs as well as in practice, are notorious for their scatter. Consequently, for the determination of a safe life limit of practically zero break probability it is mandatory either to run a considerable number of tests or to calculate with a generous life safety factor. No matter which one of the two ways had been followed the ill feeling of wasting about 80 % of the useful lives of the planes is accentuated by the possibility of perhaps still failing in providing for sufficient safety. Harmonizing of economic and safety requirements may be attained by way of fail-safe design principles only.

2.2. Tests on Fail-Safe Light Metal Sailplane Wing Specimens

The fundamental principle of fail-safe design is straightforward and clear: the ability of the structure to bear a sufficient high load in spite of incipient cracks and until the detection by routine inspection methods of the crack has to be demonstrated. Methods and ways of achieving this are known from power plane practice but do not seem to be readily adaptable to light sailplane structures of relatively low density, especially in metal.
A new metal sailplane wing construction method proposed by a design group and aimed at bypassing some outdated construction fashions was greeted therefore most enthusiastically. Proposal was made to have it tested according to fail-safe requirements.

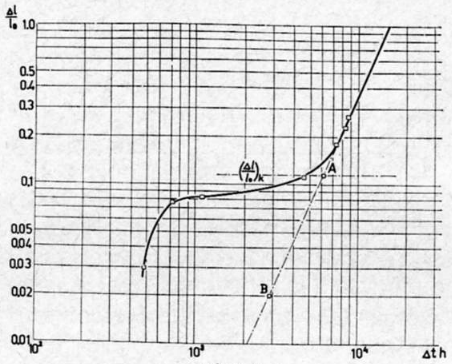

FIG 7

Results obtained so far on full-scale test specimens have been most encouraging. Fig. 7 shows results of a crack propagation test made after subjecting the wing specimen to the full fatigue life programme amounting to many times the normal service lift customary for sail-planes. As up to this time no fatigue cracks were visible, a crack was artificially introduced in order to measure the speed of crack propagation and the residual strength. Time since introduction of the crack is marked on the ordinate in equivalent flight hours. At first, crack propagation speed is varying; it is not yet known whether this is a peculiarity of the construction or due to the mode of cutting through the specimen. Anyhow, the fall of strength of the specimen begins at about $\triangle 1/1_0 = 0.115$ (point A), with still ample reserves, while a crack of $\triangle 1/1_0 = 0.02$ may be safely expected to be detected by simple visual inspection (point B). There seems to be therefore no objection against allowing this type of construction — other circumstances permitting — a practically unlimited flying time, up to the appearance of visible cracks or up to incipient rivet loosening.

3. Damage Calculation

It is impractical, if not impossible, to give fatigue test cells or specimens exactly the same treatment they are expected to receive in normal flight use. Some kind of damage conversion calculation is therefore inevitable in determining the flight time the test run has been representative for.
Damage calculation procedure used for this purpose are far from being perfect yet and utmost care is needed in their use to obtain reliable and consistent results.
Even using the simplest of them, the Palmgren-Miner linear damage theory, with correctly choosen load levels and a proper mixing of them in composing the runs from different blocks, our results showed a fair agreement with practical experience. But fig. 8 demonstrates this precaution to be

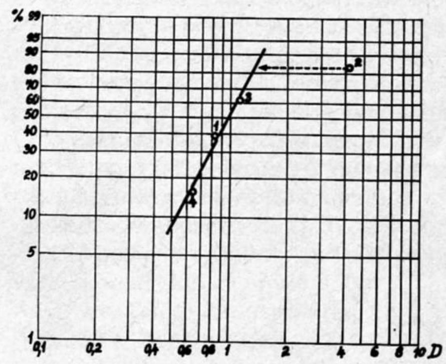

FIG 8

highly recommendable. While running a sequence of tests on 4 identical pieces the second piece was given a higher than specified and progressively increasing load level — in order to save time as the person in charge of running the tests explained. Time was saved indeed but results were suspicious to such a degree that for the remaining two pieces the original test programme was re-established. Uneven scatter does happen many times in fatigue testing, of course, but this one seems to have been avoidable. And what about No 2 being a single piece test run with the usual life safety factor of 5? Then No 4 could easily turn into a catastrophic in-flight failure with all its consequences.
A cumulative damage theory satisfactory for use in sailplane fatigue testing is permitted for:
a) damage differences when running programme blocks of sinusoidal loads in different time sequences;
b) conversion of stochastis loads into equivalent sinusoidal loads and vice versa.
In our search for finding a suitable damage calculation theory from the

abundance proposed in literature we have had as yet only partial success. So the theory of Freudenthal [12] or of Eugène [13] could not be put to a real test for want of sufficient basic data. The quick methods proposed for conversion of stochastic loads by Schütz [14] and in a different form by Fuller [15] and by Bussa and Der Hovanesian [16], respectively, have been tried but results seemed not too promising as regards to accurancy.

In a proposal by Manson and his co-workers for a double linear damage rule at least a workable compromise seemed to be found [17]. But their treatise and experiments covered some special high strength steels only and lacked any reference as to dural type alloys we were primarily interested in. This omission was suspected to be not unintentional and to be well founded. Nevertheless, it was thought worth-while to have a series of test runs on dural specimens following their way.

Manson's experiments consisted of making several series of two-stress level fatigue tests giving – in case of the assumption proving to be correct – a dual-life pattern as shown in fig. 9 (from Ref. [17]). Our results on dural

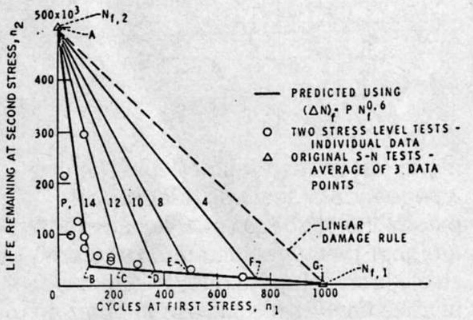

FIG 9

[FROM REF. 17]

specimens deviated substantially from it (fig. 10). It had been tried therefore to adapt a more universal damage definition but even this failed to account for all the differences.

Full numerical agreement between theory and test results may be expected perhaps by making allowances for the quality scatter inherent in engineering materials.

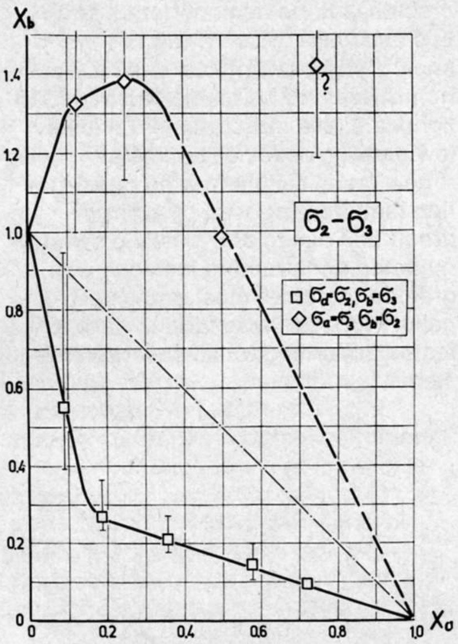

FIG 10

When all test runs and the evaluation have been finished a full report of the results is expected to be published in the not too far future.

Conclusions

Sailplane fatigue testing is a branch of engineering where labour capacity and financial possibilities are clearly unequal to the task to be solved. Acceptable compromises may be arrived at by keeping close watch on and drawing liberally from the developments in cognate but more wealthy branches, not forgetting to make the necessary flight and control tests as well.

This method has been applied successfully to a more exact determination of loads spectra and to the fail-safe design problem. When trying to adapt a double linear damage rule to dural alloys substantial difficulties have been met but hope exists of making some progress nevertheless.

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