STANDARDS FOR SAILPLANE FATIGUE TESTING LOAD PROGRAMS AND EVALUATION

by J. Gedeon, DSc., Technical University, Budapest, Hungary

Presented to OSTIV-SDP, Flin, Czech Republic, 1995

Fatigue design and testing isn't listed among the favorite activities of sailplane designers because of the basic problems and economic limitations to be dealt with. It requires official regulations for safety reasons but the Authority, too, has to be careful not to put unecessary burden on the manufacturers. For short, an everlasting subject of the debate for committees.

The present OSTIVAS fatigue cases are products of long years and they are still far from being frozen. At the 1994 Budapest meeting of the SDP two questions of detail have been raised and discussed at the 1995 January Omarama meeting. They are:

- when should full-scale fatigue testing be compulsory;
- what methods and procedures should be standardized for fatigue test programs and evaluation?

The present paper intends to be a contribution to this latter topic.

1. Aim and Possibilities of Standardization

Fatigue cases in sailplane Airworthiness Standards should give the owner/pilot:

- safety against sudden catastrophic fatigue failures in standard operation;
- economy in maintenance and in operation;
- the possibility to rank competitive designs in respect of fatigue performance and reliability.

At the same time they should give legal cover to the manufacturer and designer against unlimited claims from users as well as from the authorities.

Fatigue design and testing is an expensive and complicated process involving a number of highly nonlinear and stochastic relations. It is, therefore, not very tractable to strict standardization. It is highly desirable that sailplane fatigue tests should cover, as far as possible, the full range of standard exploitation and that service hours given for different types could be directly compared. Both of these requirements can be promoted by detailed and proper standardization. That is evident, but the problem is if it can be already done and if so, then how it could be done. The discussion is also about whether: a) we have already enough experience to freeze the development of test programming by standardization; b) test load program requirements should be given in terms of load-level exceedence statistics or otherwise.

As regards the timeliness of full standardization, I would not prefer to freeze everything in one step. Instead of this, new developments can be better introduced first in the form of designer's guides, data sheets, etc. for surmounting the gap between conference papers and full standards.

The aim of co-ordinating calculation or experimental methods is to get equivalent and directly comparable results or declarations. But on what conditions can two fatigue test load programs be declared to be equivalent?

2. Normal Fatigue Test Load Programs

Service loads are diverse and of stochastic character. A lot of experience and caution is needed for selecting a full and typical set from among them.

For a given type of sailplane or aeroplane, load levels can be characterized in terms of load factors or G's. This induced some authors to propose the same for fatigue test load program specification and standardization. Sorry to say, this seems not to be the right choice, because different types are subjected to different load levels in the same flying conditions.

Maneuver loads depend primarily on piloting, secondarily on some type characteristics. Gust loads depend on the intensity of atmospheric turbulence, air speed and type characteristics. Landing loads depend on piloting, landing speed, landing gear design and ground unevenness. And so on. It would be clearly wrong and unfair to fatigue test every type on the same load factor levels. Different types are subjected to different load factor levels while flying identical flight programs. Instead of this, the following line of thought can be recommended:

- typifying of the percentage and conditions of the respective flight tasks the type is intended for (i.e. standardization of the flying programs);
- typifying atmospheric turbulence and landing ground conditions;
- typifying characteristic speed points in terms of lift coefficients on the polar curve for the respective flight conditions (high-speed glide between thermals, circling in thermals, air tow, etc.).

Load collectives caused by the said flight conditions can then be determined by calculation, by flight tests or by both. Let us review these problems in some detail.

3. Flight Programs

The operation subjects the sailplane to continuously varying flying modes and load conditions. For calculation or simulation, we have to discretize, somehow, this continuous process. It is common sense to do this by specifying discrete flight tasks. Flying them is creating a number of – partly common, partly different – flying conditions (i.e. take off, landing, glide in different turbulence, circling, etc.). In terms of standardization, the flying conditions may be called dynamic load cases as well. Table 1 is showing a simple example for this. Flight programs for high-performance types, intended for competitions, may be covered by a single characteristic task while primary two-seaters require a number of different tasks.

Normal flight programs may be composed e.g. for the following sailplane classes: primary gliders, club class, high-performance class, acrobatic category. There is no need for more of them, two or three will be perhaps the best.

4. Service Load Assessment

Compilation of bulk statistics for hundreds of flying hours is relatively easy but not cheap. Moreover, such statistical data banks can hardly be converted to other types. Dynamic load assessment is best done for, and on, the respective flying conditions. Of course, the respective flight parameters, too, have then to be recorded and stored.

The next detail to be discussed here is the correct form of loading data storage. We intend to have such a form of data storage and standard requirements, that:

- they should give correct dynamic response and fatigue load levels for all types;
- they should be readily convertible to all types.

The elementary fatigue damage for a single harmonic load cycle

$$F(t) = F_1 + F_2 \sin\omega t \qquad (t = 0 - \frac{2\pi}{\omega}) \qquad (1)$$

depends on the load amplitude F_2 and on the mean load F_1. In other words, a perfect load history model has to conserve all significant local stress minima and maxima with their respective time sequence on every critical part of the structure.

Load level exceedence statistics are relatively simple but only a poor substitute for this because a given load

Table 1:
Flight Program for a Primary Two-Seater
(10000 landings/1750 hours)

Flight Task	Number of Starts	Flying Time	Winch Launch	Aero Tow	Flight in Smooth Air	Thermal-ling	Glide between Thermals	Number of Spins
Primary Flying by Winch Launch	7000	585	87	--	498	--	--	--
Soaring by Winch Launch	1500	500	19	--	51	228	202	--
Soaring by Aero Tow	350	345	--	35	35	146	128	--
Aero Towing Courses	800	200	--	107	93	--	--	--
Spinning	350	120	--	70	50	--	--	1400
Sum Total	10000*	1750	106	212	727	374	331	1400

* 8500 winch launches and 1500 aero tows

magnitude probability distribution can cover an unlimited number of quite different load histories. Furthermore, statistical distribution functions are of no use in dynamic calculations.

Direct records of atmospheric turbulence respective of landing ground unevenness are correct as regards the character and magnitude of fatigue loads but we have to add some statistical parameters in order to mark their class and magnitude and they require too much memory space for storage.

Stochastic dynamic response calculations on linear models are done by way of the input and output PSD functions. Nonlinear input-output problems, too, can be handled this way. It can be recommended to store and to standardize atmospheric turbulence and landing strip surface conditions in the form of power spectral density functions. Figure 1 is showing a typical atmospheric turbulence power spectrum calculated from a flight record measured at the DLR Institut für Physik der Atmosphäre, Oberpfaffenhofen.

Such spectra are storing all characteristics of the turbulence and require about a quarter of the memory space as compared to the respective original record. Of course, typical statistical parameters, too, have to be stored with them.

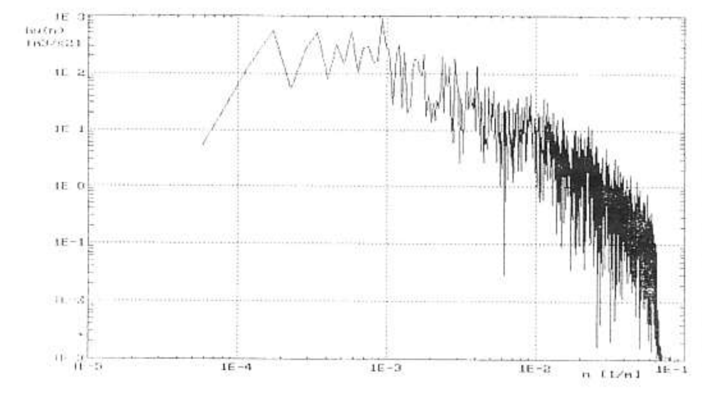

Figure 1. Atmospheric Turbulence PSD Function

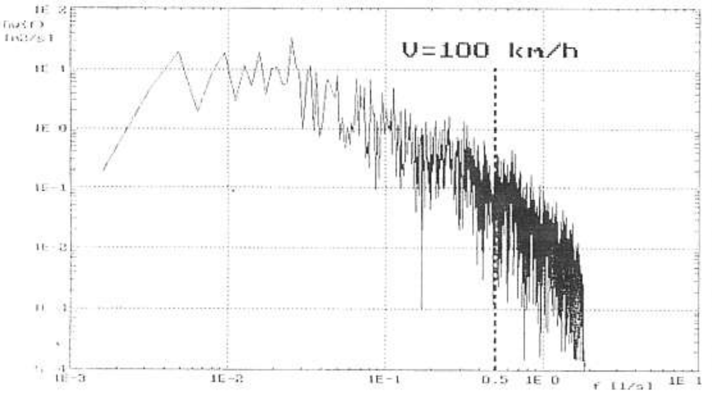

Figure 2. Turbulence Input Spectrum for V=100 km/h

5. The Influence of Airspeed on Service Loads

Flying speeds are substantially different according to wing loading and sailplane performance. Dynamic loads on a sailplane flying at an airspeed V through the turbulence can be calculated using the time-domain PSD function (see e.g.: Mai, 1976). Until recently only analytical PSD functions could be directly converted. Point by point conversion was possible only from the autocovariance function by Fourier transformation for each respective speed. An as yet unpublished work by the author has proven the possibility of a point by point direct conversion. It can be done as follows. A spatial power spectrum as on Figure 1

$$G_i(n_i) \quad (i = 1 \div m)$$

gives the input time domain PSD function

$$G_i(f_i) \quad (i = 1 \div m)$$

to an airplane flying at speed V. The conversion formula reads:

$$f_i = Vn_i \tag{2}$$

$$G_i(f_i) = \frac{G_i(n_i)}{V} \tag{3}$$

In this way the spatial PSD function on Figure 1 converts to Figure 2 for V = 100 km/h and to Figure 3 for V = 200 km/h, respectively. The significant part of the time spectra is that above say n = 0.5 Hz. In this zone intensities for a given frequency are growing markedly with the speed and the frequency boundary f_h is directly proportional to the speed. And last but not least, load increment due to a gust of amplitude Δw and frequency f is increasing directly with the speed. For short, fatigue program specifications are to be drawn up not in terms of load factors but in terms of turbulence spectra and flight speeds.

Instead of giving a very long sequence of spectrum points, turbulence intensity and character can be also specified by a set of the so-called natural parameters of a suitable analytical spectrum formula. An as yet unpublished analysis of four flight turbulence records measured at the DLR Institut für Physik der Atmosphäre, Oberpfaffenhofen, had shown the advantages of the following extended Kármán spectrum formula:

$$G_w(n) = 4\delta_w^2 L \frac{1 + A(CLn)^2}{\left[1 + \frac{(CLn)^2}{1 - \beta Ln}\right]^{\alpha}} \tag{4}$$

The standard deviation δ_W and the integral scale of turbulence L are standard turbulence parameters needing no further explanation. The exponent α and the peak coefficient A are constants in the original Kármán formula with

$$\alpha = \frac{11}{6} = 1.83333 \quad \text{and} \quad A = \frac{8}{3} = 2.66667$$

respectively. The cutoff ratio

$$ß = \frac{1}{Ln_h} \tag{5a}$$

is new in the formula made necessary by the high-frequency boundary of spectra as on Figure 1.

Space-time conversion of Equation (4) is straight and easy. It reads:

$$G_w(f) = 4\delta_w^2 T \frac{1 + A(CTf)^2}{\left[1 + \frac{(CTf)^2}{1 - ßTf}\right]^{\alpha}} \tag{6}$$

in which the time scale can be calculated as

$$T = \frac{L}{V} \tag{7}$$

The numerical value of the cutoff ratio remains unchanged but its formula reads now:

$$ß = \frac{1}{Tf_h} \tag{5b}$$

This type of conversion is to be seen on Figure 4. The growth of load components at higher frequencies, referred to when making the point by point conversion, is very noticeable indeed.

Taking all these into consideration, the best method for evaluation and standardization of turbulence conditions seems to be the following. A sufficient number of flight records giving PSD data as on Figure 1 are to be processed using the regression formula (4). This data bank will then serve to choose a suitable set of parameters for the different standard flight conditions.

The analysis of the four Oberpfaffenhofen flights has given the parameter ranges given on Table 2.

Taylor's scale λ doesn't figure in Equation (4). It is included in Table 2 because it is nevertheless a natural parameter of the turbulence. There is no room in the present paper to discuss all the problems of turbulence evaluation and modelling. The point is that a sufficient number of turbulence records is to be collected and processed representing different and characteristic atmospheric conditions.

A second level of analysis can indicate correlations between parameters – e.g between δ_W and L – if any. So a representative set of atmospheric conditions can be assembled for input load block calculations.

Taking all those into consideration the best choice seems to standardize turbulence conditions in the form of Equation (4). The theoretical values of the exponent

$$\alpha = \frac{11}{6} = 1.83333$$

and of the peak coefficient

$$A = \frac{8}{3} = 2.66667$$

seem to remain constant for all conditions. Measurements, analyse and than later specifications should cover the remaining parameters δ_W, L and n_h including possible correlations between them. This seems to be the best way for standardizing atmospheric turbulence conditions. Reference to specific flight speeds for each respective flight case – e.g. as the value of the lift coefficient c_L – will then complete the picture. Higher ones will be given for circling and lower ones for high-speed glides, etc.

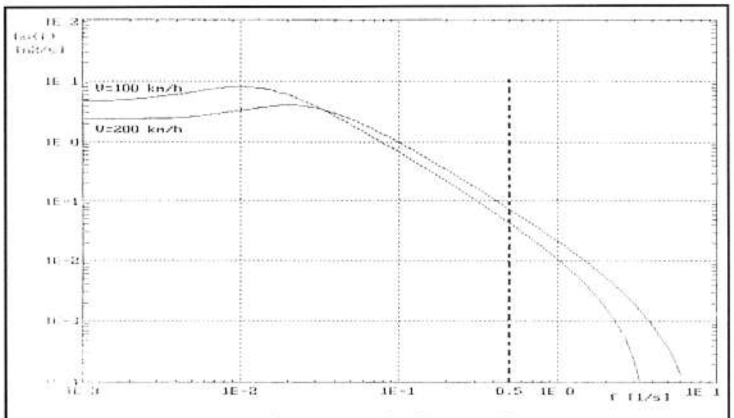

Figure 4. Comparison of the Smoothed Input Spectra

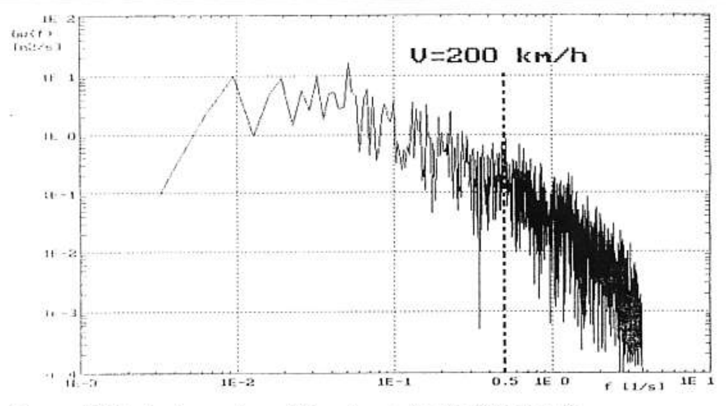

Figure 3. Turbulence Input Spectrum for V=200 km/h

Field unevenness spectra for inputs in take off and landing cases, too, can be specified in the form of Equation (4). Available data indicate that here the exponent

$$\alpha = 2$$

and perhaps the peak coefficient

$$A = 5$$

Table 2
Range of Parameters for the Four Flights

Notation:	Parameter:	Range:	Dim:
δω	Standard deviation	0.74 - 0.86	m/s
L	Integral scale	64.9 - 120.0	m
λ	Taylor's scale	29.2 - 33.2	m
α	Exponent	1.798 - 1.803	
A	Peak coefficient	1.423 - 2.124	
nh	Frequency boundary	0.09088 - 0.09091	1/m

can be supposed to be constant.

6. Load Program Structure

Fatigue test load programs are compiled of load blocks. The character of the load blocks depends strongly on the control system of the test equipment. Flight by flight stochastic load programing giving very good approximation to the real conditions is available on modern digital servo hydraulic machines. On the other hand, for want of better, even single step sinusoidal load blocks on maual-controlled old machines can give acceptable results if carefully programmed, run and assessed.

For particulars in the test programming, the numerous books and studies referring hereto can be consulted. A few of them are listed in the following references without a claim for completeness.

In all likelihood, this point of fatigue testing will be the last to be frozen and normed.

Summary

The aim of co-ordinating sailplane fatigue test calculation and experimental methods is to get equivalent and comparable results. The base of test load programs should be a normal flight program according to the sailplane category. Load blocks in the test program represent discrete flight conditions.

Flight load measurements and test load calculations can be sorted according to these flight conditions. Atmospheric turbulence conditions and ground unevenness data are best stored in the form of PSD functions or graphs. Requirements for turbulence conditions respective for ground profiles can then be drawn up using Equation (4).

Acknowledgement

The author wishes to express his thanks to the DLR Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany, particularly to Dr. Manfred E. Reinhardt and to Mr. Norbert Entstrasser for the LOTREX HIBE 89 atmospheric turbulence flight records.

References

1. J.S. Bendat, A.G. Piersol: Random Data: Analysis and Measurement Procedures (Wiley-Interscience, New York, 1971).
2. J. Gedeon, Gy. Kálmán: Service Life Extension Possibilities by Fatigue Tests on Used Sailplanes (OSTIV Publication XIV).
3. J. Gedeon: Some New Developments in Atmospheric Turbulence and Terrain Surface Description (OSTIV Publication XVII).
4. J. Gedeon: On the Fine Structure of Atmospheric Turbulence (*Technical Soaring*, Vol. XIV No. 3, July 1990; pp. 89-96).
5. J. Gedeon: Instationary Stochastic Modeling of Thermals (to be published in *Technical Soaring*).
6. Ch.W. Kensche: Influence of Composite Fatigue Properties on Lifetime Prediction of Sailplanes (*Technical Soaring*, Vol. 19 No. 3, July 1995; pp. 69-76).
7. H. Kossira, W. Reinke: Die Ermittlung von Kastkollektiven für die Bemessung von Segelflugzeugen (OSTIV Publication XVI).
8. H. Ulv Mai: Application of a Low-Frequency Aeroelastic Element Method to the Harmonic Gust Response Analysis of a Flexible Airplane (OSTIV Publication XV).
9. H. Nystrom: Fatigue Test on a Sailplane Wing (OSTIV Publication XV).
10. E. Rácz, J. Gedeon: Die Ermüdungsversuch eines Ganzmetall-Segelflugzeuges (OSTIV Publication IX).
11. M. Richie, A.O. Payne, N. Mileshkin: Fatigue Life Assessment of the IS28B2 Sailplane (*Technical Soaring*, Vol. 19 No. 2, April 1995; pp. 35-40).

Notation:

c_L	lift coefficient	
f	frequency	1/s
f_h	frequency boundary	1/s
n	wave number	1/m
n_h	wave number boundary	1/s
t	time	s
w	updraft in the turbulence	m/s
A	peak coefficient	
F	force	N
G( )	one sided PSD function	
L	integral scale of turbulence	m
T	time scale of turbulence	s
V	air speed	m/s
α	exponent	
ß	cutoff ratio	
λ	Taylor's scale of turbulence	m
δ_w	standard deviation of the turbulence	m/s
ω	circular frequency	rad/s