FATIGUE MONITORING AND OPERATIONAL SAFETY IMPROVEMENT OF SMALL SPORT PLANES

Tomas Marczi*, Milan Ruzicka, Svatomir Slavik***
***Department of Automotive and Aerospace Engineering, Division of Aerospace Engineering, Czech Technical University in Prague, Karlovo namesti 13, Prague, 121 35, Czech Republic, *tmarczi@yahoo.com*, phone: 00420 2 2435 7433, *slavik@fsik.cvut.cz*, phone: 00420 2 2435 7227, fax: 00420 224 920 594, **Department of Mechanics, Division of Strength of Materials, Czech Technical University in Prague, Technicka 4, Prague, 166 07, Czech Republic, *ruzicka@fsid.cvut.cz*, phone: 00420 224 352 512, fax: 00420 2 329 382**

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Abstract

To maintain the operational safety of increasing number of UL *Airplanes in use, the branch of Czech* AEROSPACE RESEARCH CENTER *at the Czech Technical University in Prague has established extensive research program. The research is focussed on the static strength of composite materials and parts of a plane structure, aeroelastic and frequency analysis (especially flutter) and investigation of the operational character and residual fatigue life prediction of the* UL *(Ultra-Light) Airplanes.*

Presented paper is focussed on the second part of the research dealing with the investigation of UL *planes operational character and fatigue life prediction.*

1 Introduction

In the Czech Republic, according to the Czech LIGHT AIRCRAFT ASSOCIATION, there are 1700 registered UL Airplanes, 400 Trikes (controlled by *'weightshift'*) and 100 Powered Parachutes. Next, there are 15 registered and certificated manufacturers of the UL airplanes and more than 15 manufacturers of UL Airplanes accessories and equipment.

At the present time, the main reasons of the UL Aircraft accidents are the pilot error, rarely poor maintenance and very rarely fundamental miscalculation of the airplane structure. It is obvious that in the future the structure fatigue damage and failure will not be negligible. Purpose of the presented project is to prevent fatigue accidents of UL airplanes.

Graph on *Fig. 1* represents the annual overview of UL Airplanes accidents in the *Czech Republic* during the year 2003.

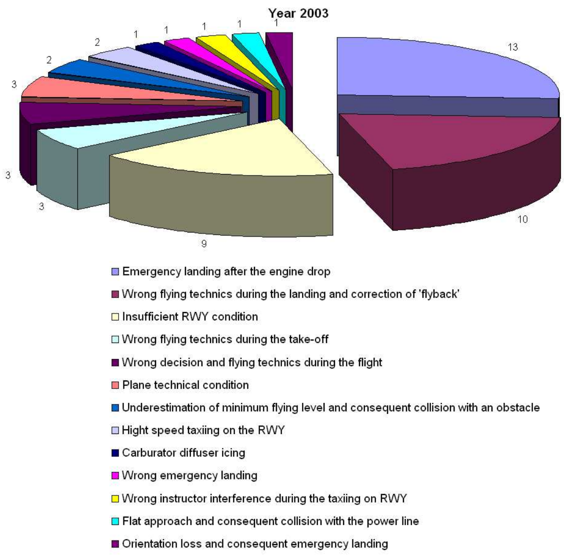

Fig. 1 Annual overview of UL Airplanes accidents in *Czech Republic* during the year 2003 [1]

One of the main *'input'* data to the fatigue calculation are operational spectra of particular plane categories. Operational spectra of the UL plane category are basically unknown. Therefore, *Aerospace Engineering Department at the Czech Technical University in Prague* has established an extensive research and operational spectra monitoring program of UL planes. Measured spectra are decomposed and consequently evaluated. Next part of the research is focused on the development of *in-time* plane fatigue evaluation methodology. Methodology itself will be implemented into the small data acquisition unit *(fatiguemeter)*. The mentioned fatiguemeter will monitor and immediately evaluate residual operational life drainage of particular plane structures.

2 UL Airplanes Involved in the Operation Monitoring

All actual measurements have been done on two UL Airplanes belonging to F-AIR flying school in the town *Benesov* southeast of Prague. The F-AIR's UL Airplanes serve as the school planes and also could be rented for the commercial flying. Hence, their service is combination of *'school flying'* and *'cross country flying'*.

The first plane on which the operation monitoring and data collection has been carried out is the TL-96 STAR *(Fig. 2)*.

Fig. 2 UL Airplane TL-96 STAR

The TL-96 STAR is all-composite low-wing UL Airplane, one of the best UL airplanes currently manufactured in Europe. Its performance is comparable with small sport aircrafts. The TL-96 STAR is the product of the *Czech* company TL ULTRALIGHTs.r.o.

The second plane is the Italian P-92 ECHO *(Fig. 3)* produced by the TECNAM company. It is an all-metal high-wing UL airplane. Especially the *high-wing* configuration of this plane provides a very comfortable plane control during the flight; therefore, it is widely used as the school or ab-initio training plane in flying schools.

Fig. 3 UL Airplane P-92 ECHO

3 Measuring Equipment

The *'g'* spectra have been measured by the fatiguemeter TL-3412_CVU [2] see *(Fig. 4)*. Measured *'g'* spectra are written in a *'two-parametric'* form. For the verification purpose, the supplementary *'in-time'* measurements of the *'g'* spectrum have been done. The *'in-time'* measurements have been carried out in the specified time intervals. For the *'in-time'* measurement the TL-3412_LNG/FST fatiguemeter has been used. Record from the *'in-time'* measurement have been evaluated by different methods (e.g. *rain-flow* method) and resulting data have been compared with the data obtained from the TL-3412_CVU. Both fatiguemeters TL-3412_CVU and TL-3412_LNG/FST are products of *Czech* company TL ELEKTRONIC. The fatiguemeter TL-3412_CVU was specially designed for the purpose of this project. The fatiguemeter TL-3412_CVU based on the microprocessor components [2], which electro-mechanically scans the vertical acceleration in the center of gravity of the UL Airplane. Then, the 12-bit A/D converter converts the analogue signal from the acceleration sensor to the digital signal. The resultant value of the vertical acceleration is saved in the memory of the type EEPROM. The data can be saved in the memory for the period of ten years without the power supply.

Fig. 4 Accelerometer TL-3412_CVU. *source:* [2]

4 Range of the UL Airplanes Operation Measurement

Monitoring of UL Airplanes Operation began in August 2001. Till 23th of May 2002 72.49 flight hours have been measured on the plane P-92 ECHO and till 10th of August 2002 130.22 flight hours have been measured on the plane TL-96 STAR. The operation of both planes has not been specially regulated. Hence, common air operation of both planes has been recorded. Part of the measurement has been done with *'filter'* set up on *'0.1g'*. The rest of the measurement has been done with filter set up on value *'0.3g'*. *'Filter'* represents limiting magnitude of *'g'* cycles taken into account during the measurement. Lower *'g'* cycles than the filter value have been omitted.

5 Measured Spectra Analysis

Used *'two-parametric'* method of *'g'* spectrum decomposition allowed the evaluation of two *'one-parametric' 'g'* spectrums.

The first one has been created by the evaluation of *'Ascending Half the Amplitudes'*, the second one by evaluation of *'Descending Half the Amplitudes'*. According to comparison of these two *'one-parametric'* spectra, it can be concluded that evaluation of *'Ascending and Descending Half the Amplitudes'* gives the same result *(the same 'one-parametric' spectrum, see Fig. 5)* [3]. Hence, it does not matter from which *'Half Amplitudes'* the *'one-parametric'* spectrum is evaluated. Number of *'Half Amplitudes'* is equal to the number of load cycles. In further calculation, the *'one-parametric' 'g'* spectrum has been evaluated form *Ascending Half the Amplitudes* only.

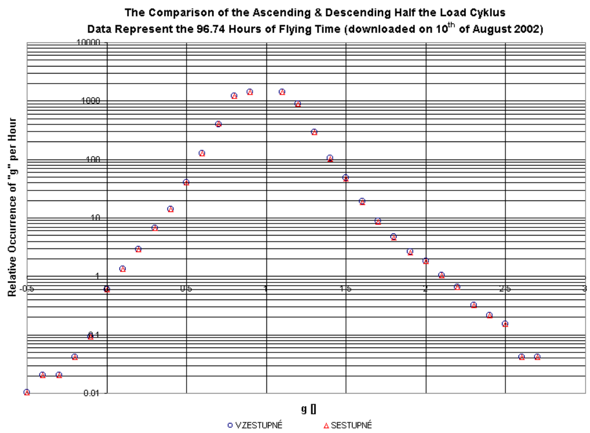

Fig. 5 Comparison of the *'one-parametric'* spectrums evaluated from the *Ascending and Descending Half the Amplitudes*

Let's emphasize that *'one-parametric' 'g'* spectra are independently created from the *Ascending or Descending Half the Amplitudes* and do not contain the information about the load sequence.

5.1 Partial and Safe 'g' Spectrum

The *Partial 'one-parametric' 'g'* spectra have been created as the subtraction of cumulative summary occurrences ('SUM f') of the *currently* downloaded *'g'* spectrum and the 'SUM f' of the previously downloaded spectrum. The length of the downloaded *'g'* spectra is variable. Measured spectrum lengths on the plane P-92 ECHO are: 21.06h, 17.32h, 1.82h, 8.79 and 23.5h. Measured spectrum lengths on plane TL-96 STAR are: 5.48h, 6.88h, 12.06h, 9.06h, 65.92h and 30.82h. All these spectra of both planes are depicted in *Fig. 6*.

Fig. 7 shows the spectra longer than 12 flight hours. It is clear that variance zone of the first graph *(Fig. 6)* is greater than in the second one *(Fig. 7)*. Hence, it could be advantageous to collect spectra approximately 15 - 20 hours long. Also to reset the fatiguemeter before a new data collection is recommended. Such measurement provides the homogenous data files according to which the spectrum stabilization can be evaluated. In addition, in the case of any problem, only the data of last *'relatively'* short record will be influenced by the error.

Fig. 8 shows the relation between the partial *'g'* spectrua, *'safe'* spectrum and the *'smoothed safe'* spectrum. Graph on *Fig. 8* is filled out by the mathematical models of the upper and lower branch of the *'safe'* spectrum.

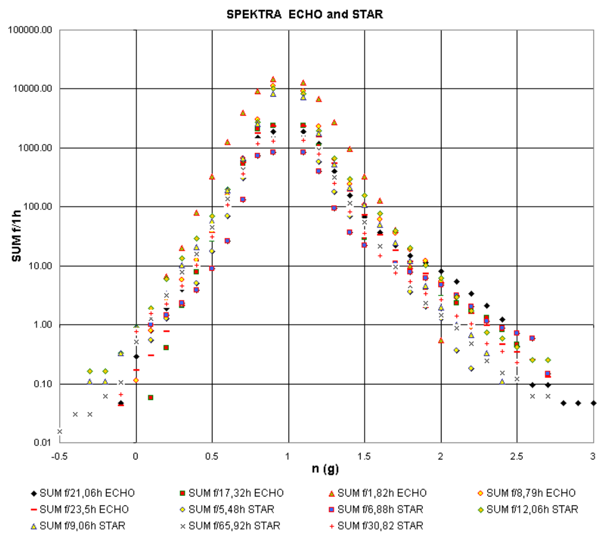

Fig. 6 The *'g'* spectrums of both plane TL-96 STAR and P-92 ECHO.

'Smoothed safe' spectrum has been the base from which the mathematical model *(Fig. 8)* of *'safe'* spectrum has been created [4]. From the *'smoothed safe'* spectrum the points representing

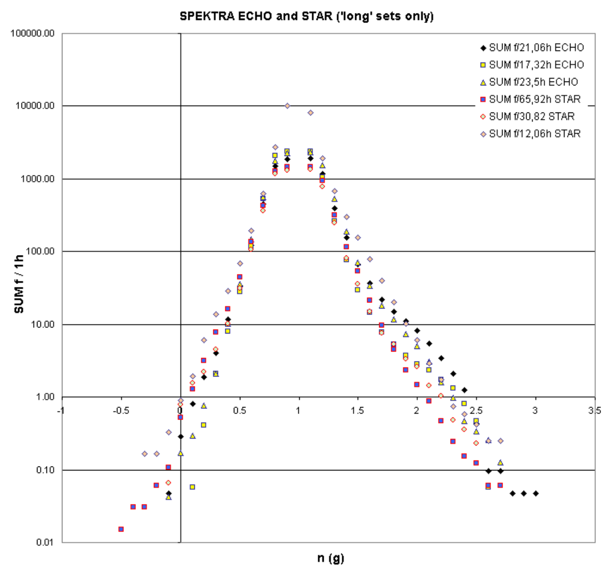

Fig. 7 The *'g'* spectrums of both plane TL-96 STAR and P-92 ECHO longer than 12 flight hours.

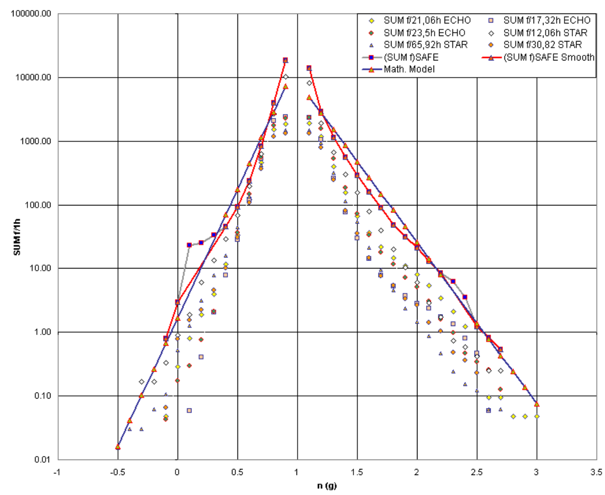

Fig. 8 The *'g'* spectrums of TL-96 STAR and P-92 ECHO longer than 12 flight hours.

the occurrences of 0.1g, 0.2g, 0.3g, 2.3g and 2.4g have been excluded. The differences in these points were greater than average value and the curve of the *'safe'* spectrum has diverted from the straight running. The remaining points of the *'safe'* spectrum have been used for the mathematical model evaluation.

As seen from *Fig. 8*, mathematical model describe the *'safe'* spectrum fairly well. The mathematical description of the *'safe'* spectrum in the further fatigue calculation provides the substantial simplification and saves time. The upper and lover branches of the mathematical model are expressed as follows:

equation of upper branch of *'safe'* spectrum:

$$\left(\frac{\text{SUM OCCURRENCE}}{\text{1h of flight}}\right)_{\text{SAFE}} = 3.10^{6} e^{(-5.83g)} \quad (1)$$

equation of lower branch of *'safe'* spectrum:

$$\left(\frac{\text{SUM OCCURRENCE}}{\text{1h of flight}}\right)_{\text{SAFE}} = 1.69 e^{(9.29g)} \quad (2)$$

The following two figures *(Fig. 9 and Fig. 10)* represent the summary occurrences (' $\frac{\text{SUM}\,f}{\text{1h of flight}}$ ') of the planes P-92 ECHO and TL-96 STAR distinguished according to measured flight times. From Figures *9 and 10* it can be clearly seen some spectrum development; however, the graphs on Figures *9 and 10* can not provide the explanation of the influence of *'measurement time'* on the spectrum stabilization. Despite this disability, figures *9 and 10* indicate the slightly different operation of these two planes.

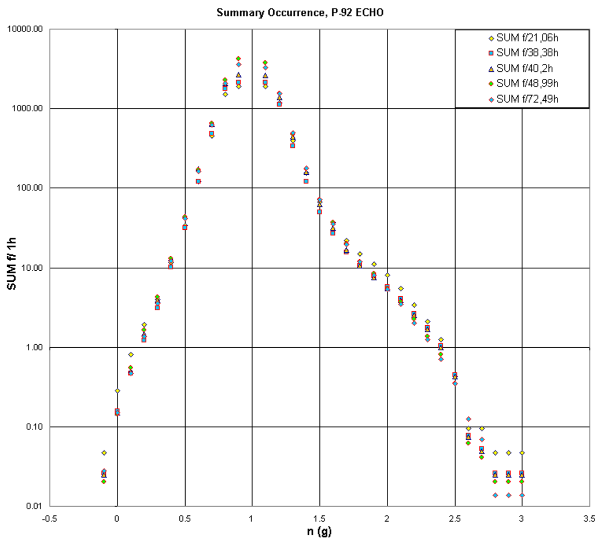

Fig. 9 The *'g'* spectrums of P-92 ECHO.

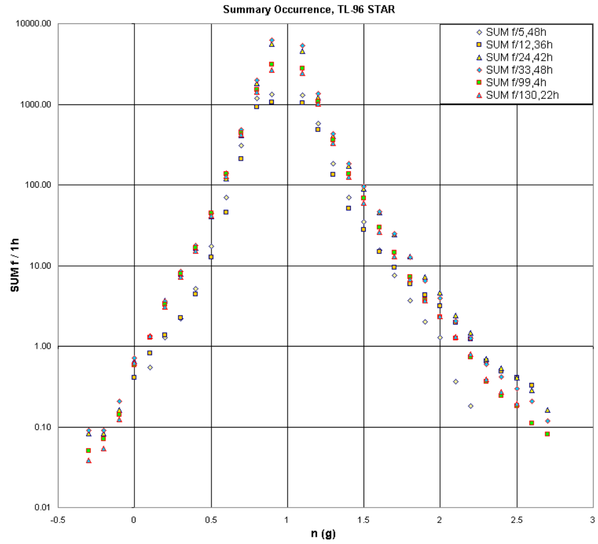

Fig. 10 The *'g'* spectrums TL-96 STAR.

Next graphs on *Fig. 11 and 12* show the development of summary occurrences on the both planes (P-92 ECHO and TL-96 STAR). From these figures (*11 and 12*) the spectrum stabilization can be seen approximately after 40 flight hours. Moreover, passed about 130 flight hours the spectrum does not change. It does not mean that the spectrum can not change by the future operation. However, it can be assumed that 150 flight hours can be representative enough for approximate description of the UL plane operation.

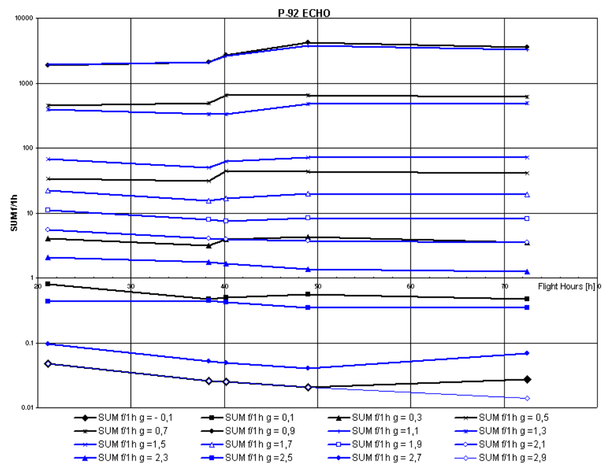

Fig. 11 Spectrum stabilization of P-92 ECHO.

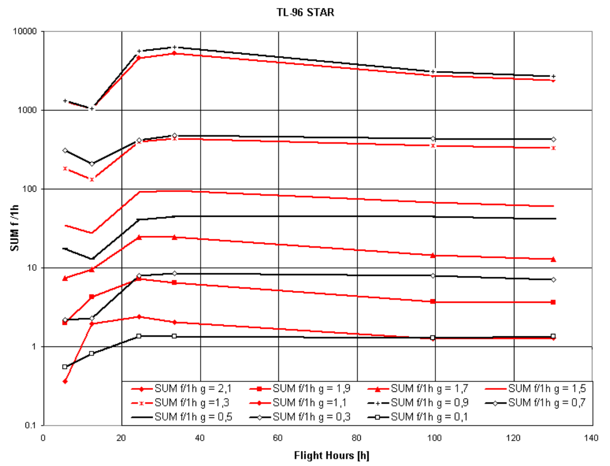

Fig. 12 Spectrum stabilization of TL-96 STAR.

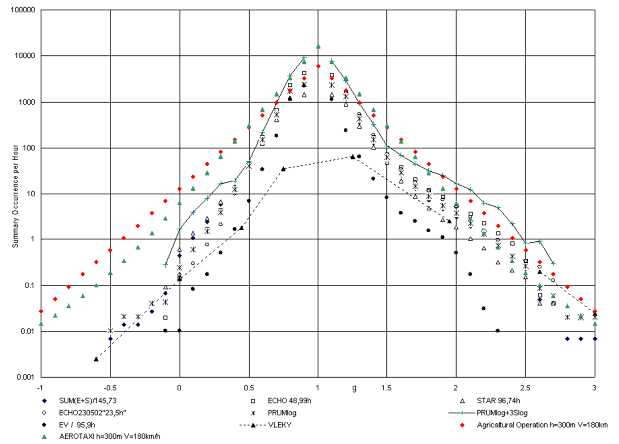

Fig. 13 TL-96 STAR and P-92 ECHO spectra comparison with spectra of *'Agricultural'* and *'Aerotaxi'* operation.

5.2 Spectra Comparison

Fig. 13 represents the comparison of both planes TL-96 STAR and P-92 ECHO operation with the spectra collected by other authors on various planes in the Czech Republic [4]. *'Agricultural'* and *'Aerotaxi'* spectra depicted in *Fig. 13* relate to the flight speed 180$km.h^{-1}$ and flight level 300m. Also the spectra from the glider tug are depicted in *Fig. 13*. For *'Agricultural'* operation the *Czech* airplanes *Z37* and *L60* have been used, for the *'Aerotaxi'* planes *Ae-45*, *Ae-145* and *L-200* MORAVA have been used. This planes have gross weight higher than 1200kg. All spectra in *Fig. 13* are depicted as cumulative summary occurrences (SUM f) per one flight hour.

- Gust spectra of the *'Agricultural'* and *'Aerotaxi'* operation are symmetrical about the *'g'*=1. *'Agricultural'* spectrum is above the value 1.5g and under the value 0.5g *'harder'* than spectra of *'Aerotaxi'*.

- Lower branch and the interval 1g to 1.5g of the upper branch of the spectra of both planes TL-96 STAR and P-92 ECHO are most likely built by gusts. However, higher values of *'g'* than 1.5 are influenced by manoeuvre load. This is the reason of spectrum deviation to the higher occurrences.

- Depicted spectrum EV/95.9h has been measured by the company EVEKTOR-AEROTECHNIC in the year 2000. As it can be seen, this spectrum is *'softer'* than the spectrum of planes TL-96 STAR and P-92 ECHO.

- Spectrum *'VLEKY'* represents the glider tug operation. Despite the fact that the spectrum *'VLEKY'* has been collected in relatively very turbulent area and during a bit *'dynamic'* flight within the approach to home airport and landing *(due to tug rope release)*, from *Fig. 13* is clear that Spectrum *'VLEKY'* is also *'softer'* than spectrums of TL-96 STAR and P-92 ECHO. Spectrum *'VLEKY'* has been measured on the *Czech* sport planes *Z226* and *Z326*. Gross weight of these planes is about 700kg.

- Despite the fact that *'Agricultural'*, *'Aerotaxi'* or GA sport planes can not be directly compared with the UL plane category, such comparison provides clear overview of the absolute magnitude of their operational load spectra. From *Fig. 13* it is clear that lower branches of the UL planes spectra are significantly *'softer'* than lower branches of *'Agricultural'* and *'Aerotaxi'* operation spectrum. Upper branches of mentioned operational spectrums roughly overlay each other about *'g'* value 2. At the interval *'g'*>2 the UL spectra are influenced by manoeuvre loading.

6 Plane Residual Life Monitoring

The second part of the presented project is focused on the *in-time* plane structure fatigue evaluation. The result of this part of the project is a small data acquisition unit also called *fatiguemeter* or *lifemeter*. Development of this *fatiguemeter* has been done in cooperation of TL-ELECTRONIK s.r.o. company with AEROSPACE ENGINEERING DEPARTMENT at CZECH TECHNICAL UNIVERSITY in PRAGUE, VANESSA AIR s.r.o. company and EVEKTOR-AIROTECHNIK s.r.o. company. Developed *fatiguemeter* is designated as TL-5824 *(Fig. 14)*.

Fig. 14 Developed Life Meter *('fatiguemeter')* TL-5824

Main features of TL-5824 are:

- Measured data are automatically sent to the research center via the GSM *(Groupe Spécial Mobile)* module which uses GPRS *(General Packet Radio Service)* function for data transfer.
- Plane fatigue life drainage monitoring
- Plane residual life calculation *(using by Rain-Flow method for spectra decomposition)*
- Flight data book, date of flight, time of flight, number of landings/take-off, record of g_{max} and g_{min}
- Maintenance book
- Display of short text messages sent by manufacturer or research center which monitors the particular plane.
- Option of remote control blockage of engine starter.
- Record of *'g'* spectra history from cca.150 flight hours.
- Record of the whole plane operation written in *two-parametric* form.
- Firmware update via the fatiguemeter's GSM module.
- Displaying of actual *'g'* value during the flight.
- Residual life calculation after each flight and display of the value of residual life in flight hours or in %.
- Ability to provide *'strain-gauge'* measurements and fatigue evaluation according the measured stress.

6.1 Residual Life Evaluation

Flow chart in the following figure *(Fig. 15)* represents the basic scheme of the fatigue life calculation.

Basically, input data are the load spectra and *S-N* curves of the critical places. The load spectra are very often expressed as the operational *'g'* spectra. Measured *'g'* spectrum is recalculated on the stress spectrum at the particular critical place[1].

According to known load spectra and fatigue behavior of the structure critical places, the fatigue calculation can be done. Calculation itself have been written as an independent program.

[1] Only if the correlation *'g'* vs. stress in the particular critical place is proved.

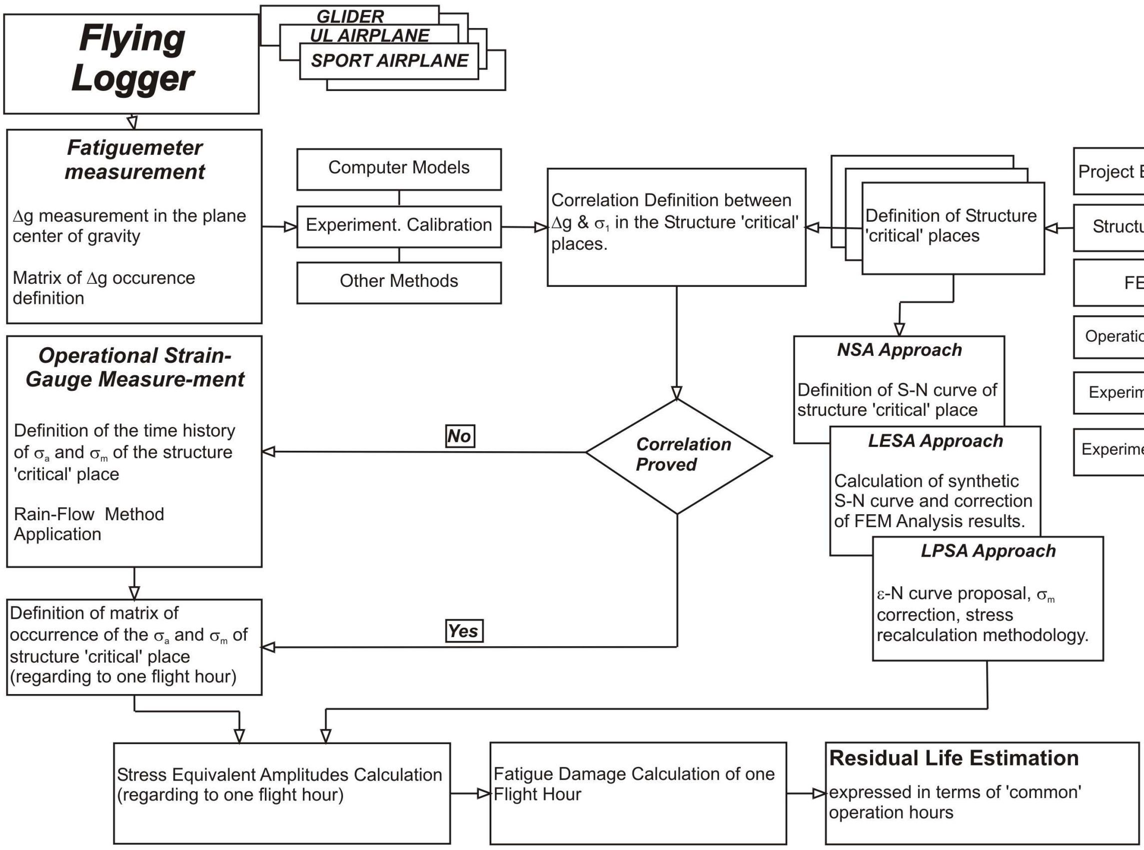

Fig. 15 Example of fatigue evaluation and residual life prediction. *source:* [5]

Then the program has been implemented to the *fatiguemeter's* microprocessor and *'fatiguemeter'* itself is accommodated in the plane center of gravity. The fatigue life drainage caused by plane operation is calculated immediately after landing. The value of residual life expressed in flight hours will be shown on the display of the cockpit's instrument board.

Development of residual life evaluation methodology has been done at the *Aerospace Engineering department of the Czech Technical University in Prague*. The hardware of the TL-5824 has been designed and manufactured by the *Czech* TL-ELECTRONIK s.r.o. company, supporting calculation and FEM model development of structure *'critical'* part have been done by the *Czech* company VANESSA AIR s.r.o. EVEKTOR-AIROTECHNIK s.r.o. company provided necessary design information of UL plane EV-97 VLA EUROSTAR - HARMONY *(Fig. 16)*.

EV-97 VLA EUROSTAR - HARMONY is all metal low wing configuration plane and it meets the JAR-VLA regulations. It is a new product of the *Czech* company EVEKTOR-AIROTECHNIK s.r.o.

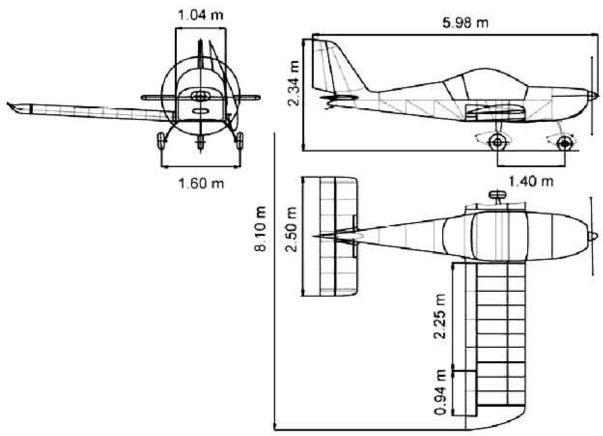

Fig. 16 UL Airplane EV-97 VLA EUROSTAR - HARMONY.

The plane HARMONY is a descendant of two successful planes EV-97 EUROSTAR and KOALA. The manufacturer of the plane HARMONY provided one plane for the *'fatiguemeter'* accommodation and flight tests.

6.2 FEM Model

The developed *'fatiguemeter'* and implemented *'Residual Life Calculation Method'* are capable to monitor cca. 20 structure *'critical'* places. In this project, wing attachment lugs have been selected as *'critical'* places of the EV-97 VLA EUROSTAR - HARMONY structure. Consideration of wing attachment lugs as common *'critical'* places of used plane structure leads to the development of the FEM model of the wing *(Fig. 17)*. This Fem model has been used for correlation investigation *'g'* vs. stress in the structure *'critical'* places.

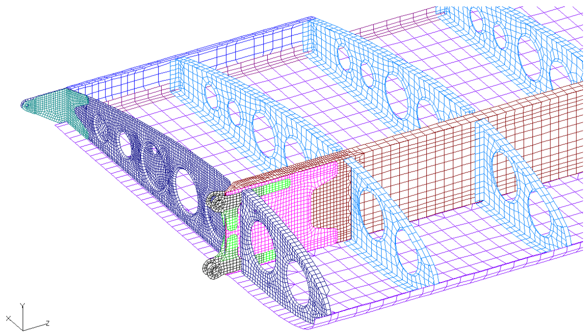

Fig. 17 FEM Model of the EV-97 VLA EUROSTAR - HARMONY wing attachments lugs. (source: [6])

The presented FEM Model has been verified by the test results of the EV-97 VLA EUROSTAR - HARMONY wing carried out by VUT BRNO [7]. Correlation investigation *'g'* vs. stress has been done after the FEM model deformations and stress verification.

Forces obtained from the FEM calculation have been used for nominal stress calculation at the cross sections of the wing attachment lugs (NSA method). The NSA *(Nominal Stress Approach)* method has been used for its simplicity, more advantageous but complex calculation methods such as LPSA *(Local Plastic Strain and Stress Approach)* method will be taken into account as the future work.

6.3 S-N Curve Definition

The common problem of a plane structure fatigue calculation is given by the unknown fatigue properties of particular structure *'critical'* places. However, in the literature there are number of *S-N* curves of the similar parts or plane structure details. With some accuracy they can be used for the fatigue evaluation of investigated *'critical'* places. Therefore, the collection of published steel lugs' *S-N* curves has been done and consequently one *'synthetic' S-N* curve has been estimated. Then, estimated *'synthetic' S-N* curve has been mathematically expressed and the equation used as an input data to the *fatiguemeter's* fatigue evaluation software.

7 Conclusion

7.1 UL Plane Operation Monitoring

From this part of the project, following conclusions can be made:

- According to statistical analysis, the *'safe one-parametric' 'g'* spectrum has been evaluated from the 202.7 flight hours of the both UL Airplanes (TL-96 STAR and P-92 ECHO). The accuracy of this *'safe' 'g'* spectrum is 99.865%.

- The *'safe'* spectrum has been consequently mathematically expressed. *Eq. 1* and *2* represent the upper an lower branch of the mathematical expression of the *'safe'*spectrum.

- It was found that during the first 50 flight hours the operational *'g'* spectra are very dynamically changing. By further measurement the spectra are stabilized. For example, in case of TL-96 STAR the stabilization occurred approximately after 130 flight hours. However, to prove that the spectra are stable, it is necessary to continue in the measurement. Moreover, further measurements can *'cover'* even the less frequent values of operational *'g'*.

- There was a slight difference between the upper branches of the operational *'g'* spectra of TL-96 STAR and P-92 ECHO. In the interval of 1.5g to 2.5g the spectrum of P-92 ECHO is slightly convex, whilst the spectrum of TL-96 STAR is slightly concave in the whole interval of its upper branch. The differences are not significant, therefore it was possible to express both spectra by the exponential equations *Eq. 1* and *Eq. 2*. The mathematical model of the spectrum almost perfectly correspond to the lower branches of measured spectra.

- The relative take-off frequency has been found 4 to 6 per flight hour. Hence, the average flight time of one flight is 10 to 15 minutes.

- It also can be concluded that measured operational *'g'* spectra of UL planes did not exceeded allowed values *(+4g; -2g)* defined by requirements for this plane category. However, two UL planes involved in this investigation are not representative enough for more general conclusions. Spectra measurements and their evaluation should continue on greater number of UL planes.

7.2 Development of the Residual Life Monitoring Methodology

The developed process of *'Structure Residual Life Monitoring'* provides direct evaluation of the *'Residual Life'* after each landing. In other words, it calculates fatigue damage caused by each flight. Such direct fatigue evaluation is unique in the UL or sport plane category and it can significantly increase operational safety of this plane categories. Calculation process is based mainly on measured *'g'* spectrum, *'correlation'* formulas *'g'* vs. stress and fatigue properties of the structure *'critical'* places.

Number of monitored structure *'critical'* places mainly depends on the *'fatiguemeter'* processor memory. The methodology itself is flexible enough to be used for all kinds of airplanes or plane operations. For every new type of plane it is necessary to input correct data represented by fatigue properties of the *'critical'* places and their correlation formulas *'g'* vs. stress.

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