Experimentální Analýza Napětí 2003

MEASUREMENT AND EVALUATION OF THE SMALL SPORT'S AIRCRAFT LOADING

MĚŘENÍ A VYHODNOCENÍ ZATÍŽENÍ MALÝCH SPORTOVNÍCH LETADEL

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***Abstract**: The presented paper provides the information about the experimental measurement and evaluation of the Acceleration Fatigue of the small sport's aircraft. The first part of the project is the long-term measurement of the load factor spectrum during the operational life of the Ultra Light Airplanes. The measurement is carrying out by the fatiguemeter specially designed for this research. The output of this fatiguemeter is two-parametric spectrum of the aircraft's operational load factor. The second part of the project tries to find the correlation between the operational load factor and the stress in the selected part of the airplane structure..*

Keywords

Measurement of Acceleration, Calibration Factor, Bending Moments, Correlation of stresses, Two-parametric Spectrum.

Měření zrychlení, Kalibrační koeficient, Ohybové momenty, Korelace napětí, Dvouparametrické spektrum zatížení

1 Introduction

The nineties of the last century are known by the great boom in the production of the small aircraft; known as Ultra Light [UL] or Micro Light [ML] airplanes. Their history is short; however, very dynamic. Nowadays, there are many planes, which differ in the manufacturing, used materials, traffic or maintenance. These planes are building at home (single-piece production) or in the professional workshops in the relatively big series. The common features of these airplanes are low maximum weight, wing surface load, operational speed, engine performance, relatively poor control instruments and usually are equipped by the pilot of boundless courage.

Nowadays, the service time of the UL Aircraft is still short. However, the operational time of some UL Airplanes is already several tens or hundreds hours. Despite this fact, the service of the UL Aircraft can be considered as inceptive. At the present time, the main reasons of the

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UL Aircraft accidents are the pilot error, poor maintenance or very rare fundamental miscalculation of the airplane structure. It is obvious that this time will pass to the time of structure fatigue damage and consequently failure. Therefore, it is very important to know the character of the UL Aircraft operation. Unfortunately, the character of the operation of the UL Aircrafts is still unknown. One of the main aims of the presented project is to describe the profile of the common operation of the UL Aircrafts.

1.1 Investigation of the UL aircraft air traffic

The investigation of the UL Airplanes air traffic is the firs part of the presented research. The process of the UL Aircraft air traffic investigation is explained on Figure 1. 1.

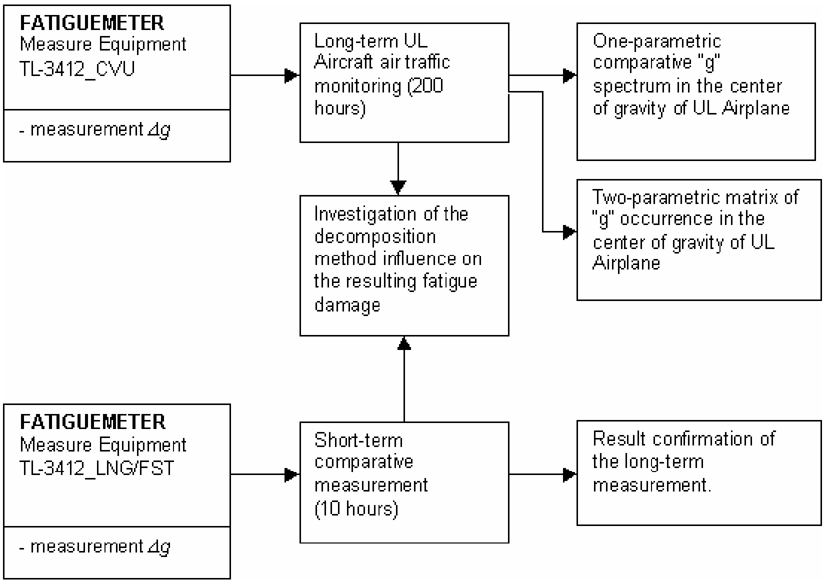


Figure 1. 1 - Flow Chart of the First Phase of the Project

The character of the flight can be described by the flying time and the spectrum of “g” achieved during the flight. The “g” spectrum is measured by the fatiguemeter TL-3412_CVU [1]. Measured “g” spectrum is written down in two-parametric form. For the purpose of verification the supplementary in-time measurement of the “g” spectrum is done. The in-time measurement is carrying out in the specified intervals. For the in-time measurement the TL-3412_LNG/FST fatiguemeter is used. Record from the in-time measurement is evaluated by the different method (e.g. rain-flow method) and resulting data are compared with the data obtained from TL-3412_CVU.

Both fatiguemeters TL-3412_CVU and TL-3412_LNG/FST are products of the Czech firm TL electronic. The fatiguemeter TL-3412_CVU was specially designed for this research. The fatiguemeter TL-3412_CVU base on the microprocessor components, which electro-mechanically scans the vertical acceleration in the center of gravity of the UL Airplane. Afterwards, 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 type EEPROM. The data can be saved in the memory for the period of ten years without the power supply. The technical data of the fatiguemeter TL-3412_CVU are written in the appendix.

The air traffic investigation is running on two UL Airplanes, which belong to flying school F-Air in town Benešov 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 fulfil the request of the combination of the operational character "school flying" and "cross country flying". The first plane on which the operation monitoring and data collection are carrying out is the TL-96 STAR (Figure 1. 2), all-composite low-wing UL Airplane. TL-96 STAR is one of the top UL Airplanes manufactured in Europe and its performance is comparable with the small sport aircrafts. The TL-96 STAR is product of the Czech firm "TL ultralight".

Figure 1. 2 - UL Airplane TL-96 STAR

Figure 1. 3- UL Airplane P-92 ECHO

The second one is Italian P-92 ECHO (Figure 1.3) maid by firm Tecnam. It is all-metal high-wing UL Airplane. Especially high-wing configuration of this airplane provide very comfortable plane control during the flight; therefore, it is widely used as the school or training plane in the flying schools.

Figure 1. 4 shows the accommodation of the fatiguemeter TL-3412_CVU in the structure of UL Airplane P-92 ECHO. The fatiguemeter is mounted on the metal spar behind the first pilot seat. Similarly as in the case of TL-96 STAR UL Airplane the two tightening strips fix the fatiguemeter on the spar of P-92 ECHO. For the purpose of separation of the aerodynamic load spectrum from the spectrum of the ground load, the both Airplanes TL-96 STAR and P-92 ECHO are equipped by the end switch mounted on the main landing gear.

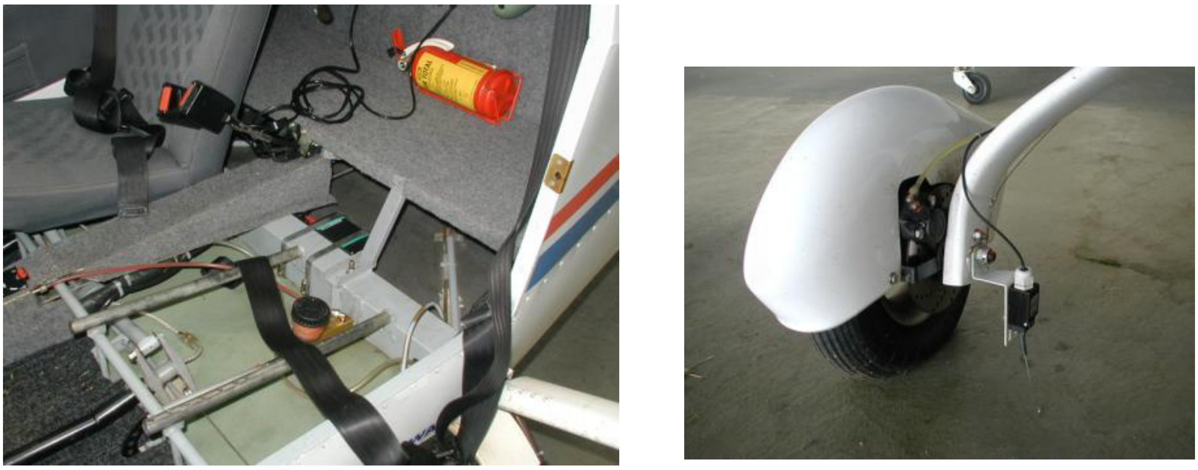


Figure 1. 4- Accommodation of the Fatiguemeter TL-3412_CVU in the P-92 ECHO and switch on the landing gear of TL-96 STAR.

2 Method of Acceleration Record and Evaluation

The fatiguemeter TL-3412_CVU uses two-parametric record of “g” spectrum. The record of “g” spectrum is written into two tables of ascending and descending half the cycles. According to the P.Kousal [2], meanwhile the two-parametric “g” spectrum is very advantageous entry to the direct calculation of the airplane service life; the one parametric “g” spectrum is still very helpful and convenient for description and comparison of airplane air traffic and operational load. The one parametric “g” spectrum can be very easily graphically presented, which allows very quick comparison of different spectrums. Moreover, one-parametric “g” spectrum can be easily obtained from the two-parametric “g” spectrum.

During this first phase of the project the 125 flight hours of the UL Airplane TL-96 STAR was recorded. This number of flight hours represents the period of one-year experimental measurement. Similarly, 90 hours of flight time for the same period of time was recorded on the UL Airplane P-92 ECHO.

2.1 One-parametric spectrums Evaluation

The data from UL Airplane P-92 ECHO were evaluated in two sets. First one represents the load spectrum of about 49 flying hours and second one 23.5 flying hours. The data from UL Airplane TL-96 STAR were evaluated in one set, which represents the 96.7 flying hours. From these three entry sets were calculated the “g” summary occurrences and their logarithmic standard deviations. Consequently, it allows estimate the resulting “*safe*” “g” spectrum of UL Airplanes (see Figure 2. 1).

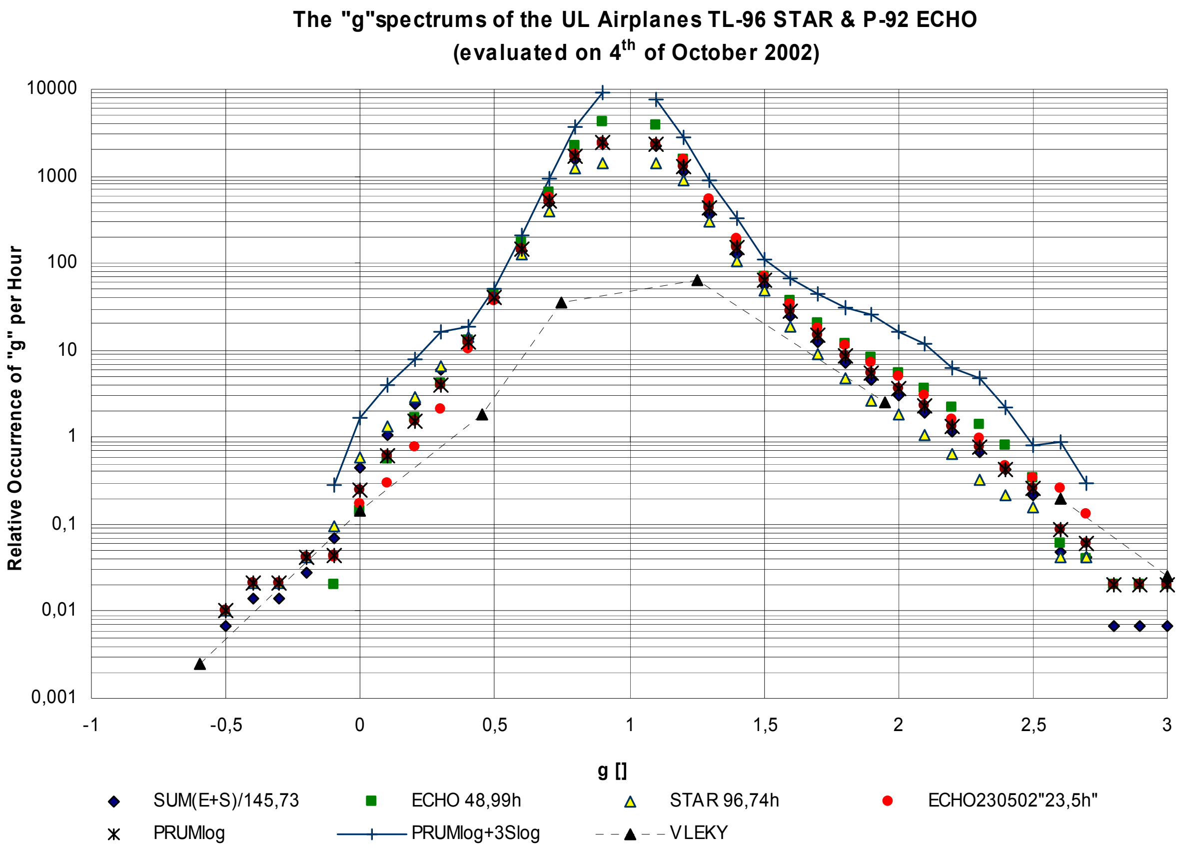


Figure 2. 1- Evaluation of One-parametric "g" Spectrums

The "*safe*" "g" spectrum shown on Figure 2. 1 is not smoothed yet. It was calculated as a sum of logarithmic mean value improved by three logarithmic standard deviations. The accuracy of estimated "*safe*" "g" spectrum is 99.86%. However, it has to be sad that this "*safe*" "g" spectrum presented in this paper covers the air traffic of two UL airplanes only.

From the presented results it can be concluded that the obtained load spectrum is relatively "hard". The previous conclusion is evident from comparison of spectrums "*ECHO*" and "*STAR*" with spectrum "*VLEKY*" (Figure 2. 1) [6]. Spectrum "*VLEKY*" represents the spectrum of glider tug. It was measured in the relatively turbulent area with high occurrence of air gusts. Here it can be note that during the approach on the home airport were registered higher values of "g" due to flatten out and tug-rope release. From Figure 2. 1 it is clearly seen that spectrums "*ECHO*" and "*STAR*" overlap the spectrum "*VLEKY*".

2.2 Correlation Investigation

The second part of the project tries to find the dependence or correlation between the operational vertical acceleration ("g") and stress in the selected "critical" part of the UL Airplane structure. The process of the investigation is basically explained on Figure 2. 2.

For the prediction of the Aircraft operational life according to vertical acceleration is necessary to know the correlation between the stress and "g". However, find such relation is quite difficult and the investigation is based on the experimental measurement "g" and stress in the selected critical place of the structure. There is the fundamental restriction for the application of "g" spectrum in the Airplane service life calculation. For the service life calculation the "g" spectrum can be used only if the correlation between the "g" and stress in the particular part of the airplane structure is known and experimentally proved. Hence, the vertical acceleration in the airplane center of gravity will with some appropriate accuracy provide information about the wing bending load; less accurate results will be obtained for the fuselage and for the tail wing calculation the "g" is practically useless.

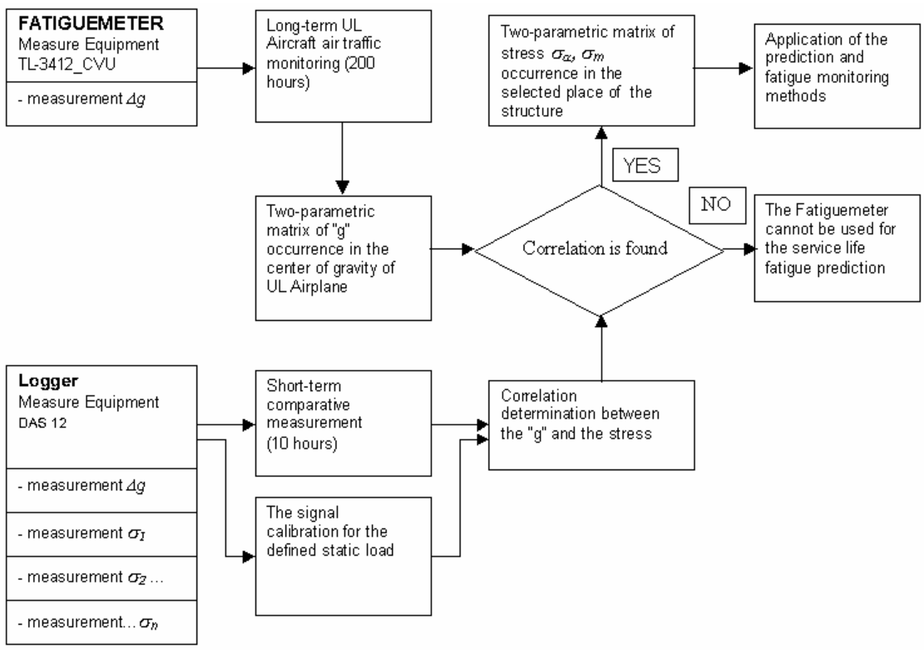
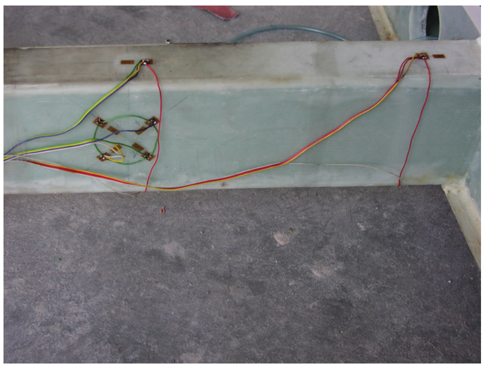


Figure 2. 2- Flow Chart of the Second Phase of the Project

According to Figure 2. 2 the two inputs are necessary for correlation investigation. The first one is two-parametric matrixes obtained from fatiguemeter TL-3412_CVU. The second input is from the special “flying” logger, which measure the in-time “g” spectrum and in-time load spectrum of the structure in the selected place. The in-time load spectrum is obtained using by the strain-gauges. This in-time “g” spectrum and Load spectrum measurement has been done in the cooperation with the Technical University in Brno, department of Aerospace Engineering. As the second independent measure equipment, their Logger “DAS 12” has been used.

The correlation between the “g” and structure load was investigated on the spars cantilevers (Figures 2. 3) of the wing of the TL-96 STAR and on the wing strut of the P-92 ECHO (Figure 2. 4). TL-96 STAR has two spars, one for each wing. The wing spars continue into the fuselage as cantilevers. For the purpose of correlation investigation the bending moment was measured on the three places of wing spar cantilevers of TL-96 STAR. Three independent half the strain-gauge bridges measured the resulting bending moment. Two half the strain-gauge bridges were placed on the right wing cantilever (see Figures 2. 3) and one on the left wing cantilever. The positions of half the strain-gauge bridges were measured from the airplane symmetric axis, which is defined by the wing spars connecting pivot (on Figures 2. 3 is clearly seen the hole for connecting pivot in the wing spar cantilever). The distances were 300mm and 625mm for the right wing cantilever and 300mm for the left wing cantilever. On the Figures 2. 3 can be seen the strain-gauge cross on the cantilever web. This strain-gauge cross measures the spars shear force.

On the UL Airplane P-92 ECHO the metal cover of the wing did not allow implementation of the strain gauges directly on the wing spar. Therefore, instead on the wing spar the two strain-gauge crosses were implemented on the wing strut Figure 2. 4.



Figures 2. 3- Half the Wing with Spar Cantilever End and Strain-gauge Bridges on the Right Wing Cantilever

The two strain-gauge crosses measure the tension force of the strut. The influence of the “g” on the load of wing strut is clear, which allows use the wing strut in the correlation investigation. From known force of the wing strut the load of the strut attachment and wing spar can be easily defined. Consequently, this load can be used in the investigation of correlation between the “g” and stress of the particular structure.

Figure 2. 4- The Strain-Gauge Crosses on the P-92 ECHO Wing Strut

2.3 The Strain-Gauge Signal Calibration

The strain-gauge signal calibration of the wing strut of the UL Airplane P-92 ECHO was relatively simple. The wing strut was dismount from the plane and hanged by one end. On the other (free) end the defined load (weight) were placed. According to particular weight used the strain-gauge signal was calibrated.

Meanwhile the process of the P-92 ECHO wing strut strain-gauge signal calibration was relatively simple the signal calibration of strain-gauge bridges of P-96 STAR wing was more difficult. Before the calibration itself the bending moment distribution on the wing spars has been calculated. The connecting pivot of the right and left wing cantilever defines the same rate of deformation. Therefore the left and right wing cannot be calculated separately. The shear force and bending moment distribution from action force acting at the tip of the wing is showed on Figure 2. 5. This Figure 2. 5shows the load distribution of asymmetrical wing load. The sizes of the bending moment in the positions of the strain-gauge bridges were calculated from the equations of equilibrium (2-1, 2-2, 2-4 and 2-5) and equation of the same rate of deformation in the position of the connecting pivot (2-3 and 2-6).

$$F_I - R_{AI} + T_I + R_{BI} = 0 \tag{2-1}$$

$$F_{II} + R_{AII} - T_{II} - R_{BII} = 0 \tag{2-2}$$

$$T_I = T_{II} \tag{2-3}$$

$$M_{AI} = F_I.L_s = R_{BI}.2.s + T_I.s \tag{2-4}$$

$$M_{BII} = F_{II}.L_s = -R_{AII}.2.s + T_{II}.s \tag{2-5}$$

$$EJy_I = \left(\frac{M_{AI} - M_L}{2} \cdot s\right) \cdot \frac{1}{3} \cdot \frac{s}{2} + (M_L.s) \cdot \frac{1}{2} \cdot \frac{s}{2} + \left(\frac{M_L.s}{2}\right) \cdot \frac{2}{3} \cdot \frac{s}{2}$$

$$EJy_{II} = \left(\frac{M_{BII} - M_P}{2} \cdot s\right) \cdot \frac{1}{3} \cdot \frac{s}{2} + (M_P.s) \cdot \frac{1}{2} \cdot \frac{s}{2} + \left(\frac{M_P.s}{2}\right) \cdot \frac{2}{3} \cdot \frac{s}{2} \cdot$$

$$y_I = y_{II} \tag{2-6}$$

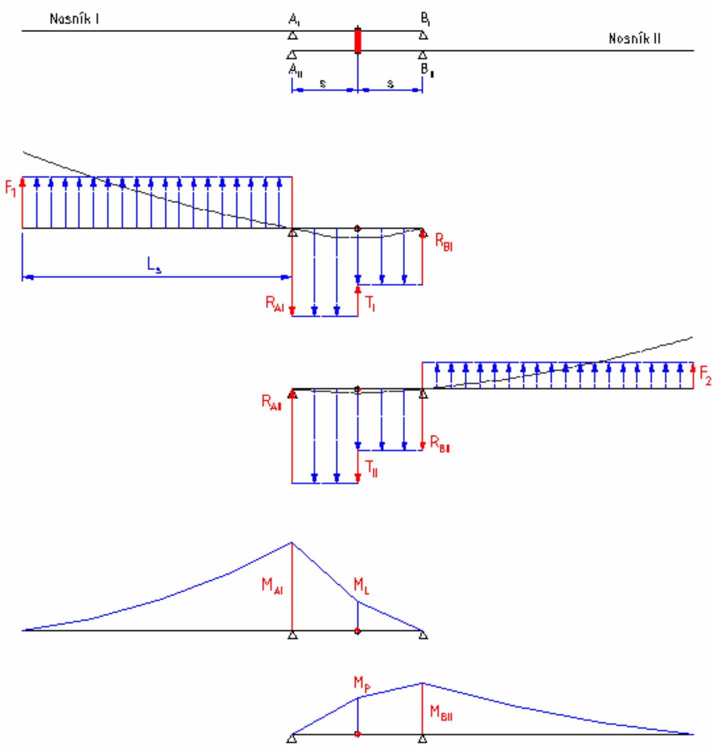


Figure 2. 5– (Asymmetrical) Load Distribution on the Wing of the TL-96 STAR

The whole process of calibration was done for several symmetrical and asymmetrical loads. The used calibration loads varied from the 500N up to the 1500N, which roughly represents the flight on the load factor equal to 1.53. The value of 1500N (150kg) is the wing structure limitation. It is due to the thin shell structure of the wing. The used fixture for the action load distribution is relatively narrow, which cause greater surface load on the wing in their contact place.

Figure 2. 6- The Fixture with Lifting Device and Scale

After the flight measurement the record from the Logger DAS 12 has been evaluated and the resulting in-time spectrum of the load factor and three bending moments are shown on Figure 2. 7 and 2.8.

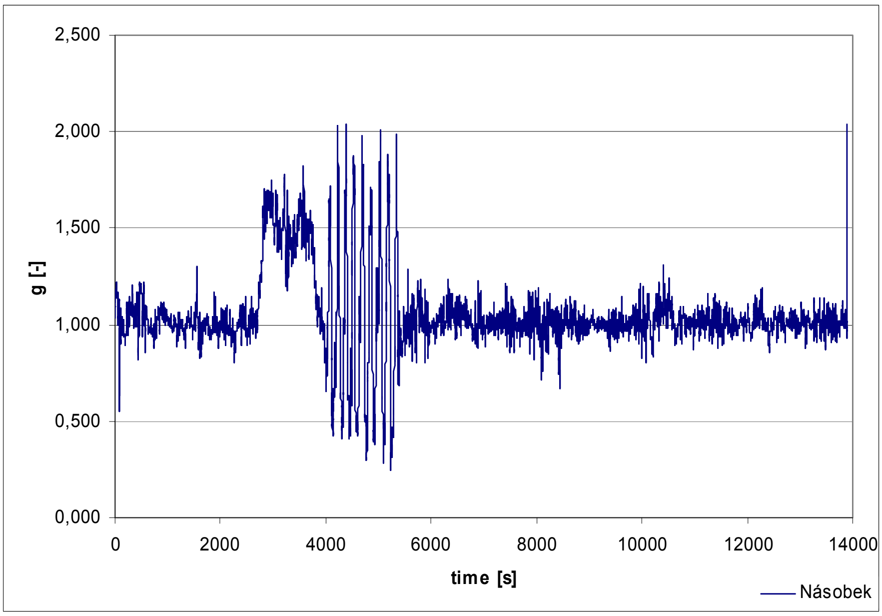


Figure 2. 7- The "g" in-time Spectrum obtained from Logger DAS 12

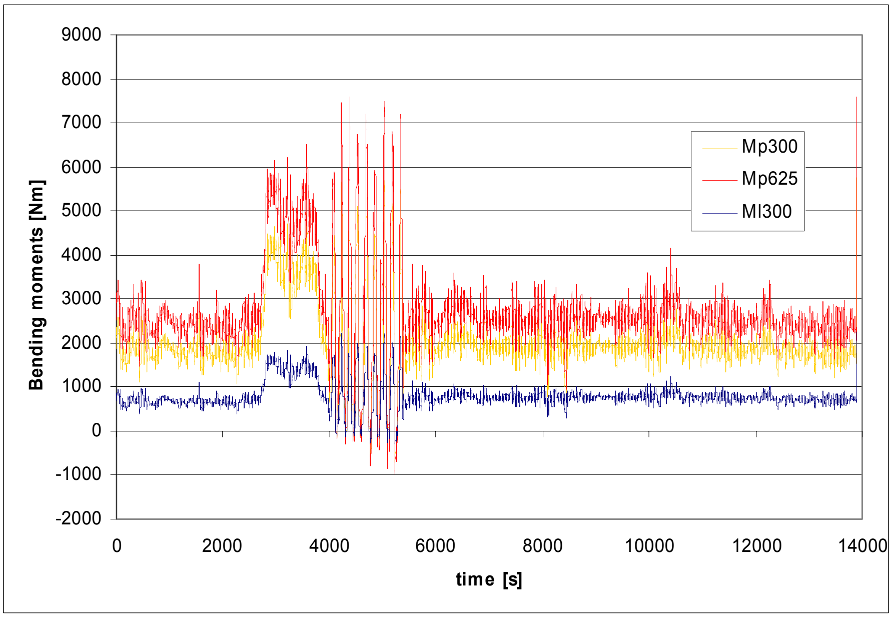


Figure 2. 8 - The Bending Moment in-time Spectrum obtained from Logger DAS 12

Figure 2. 7 represent approximately 13 minutes uninterrupted in-time record of "g" spectrum and three bending moments. Spectrums on the Figure 2. 8 were evaluated and have been used as the entry parameters for the investigation of the correlation between the vertical acceleration and load of the structure. Figure 2. 9 shows desired correlation. From Figure 2.9, linear character of relation "g" vs. bending moment is evident. Hence, the prediction of the fatigue damage and service life of the particular UL Airplanes structure can be calculated. Stresses calculation in critical cross sections of the composite *(fiberglass)* wing spar is not so simple, because of unknown composite material constants. These constants have to be evaluated or estimated before calculation itself. At the present time, there are very few information about the material constants of nowadays composites. For a stiffness matrix, and

stress/strain calculation of the composite beam, the new method described in [3] and [4] has been developed.

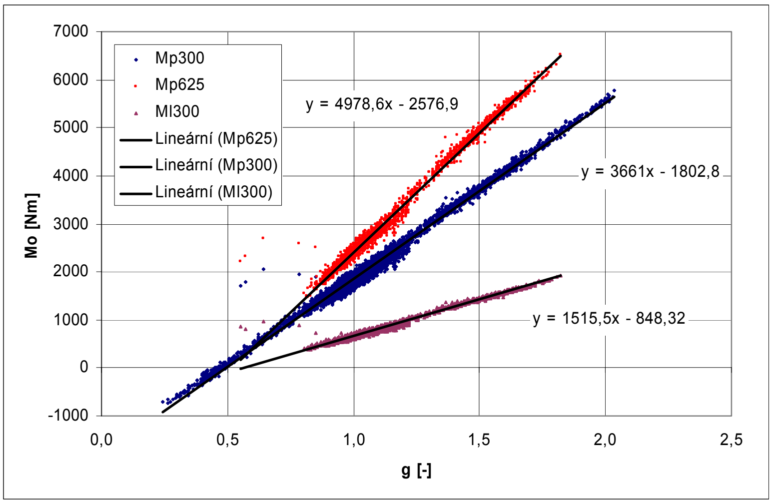


Figure 2. 9 The Correlation between the Vertical Acceleration and Load of the Structure

Once the correlation formula is defined, it can be used for structure *"critical"* place stress spectrum calculation. Consequently, this spectrum can be used for the calculation of fatigue damage cumulation in the investigated critical places. Cumulation *"speed"* of fatigue damage can be calculated according to the measured *"common"* spectrums of airplanes operational load. However, it is very suitable for fatigue calculation to substitute experimentally measured load spectrums by the mathematical model. Figure 2.10 shows one-parametric spectrum of UL Airplane TL-96 STAR overlayed by recalculated corresponding stress spectrum of the critical structure place.

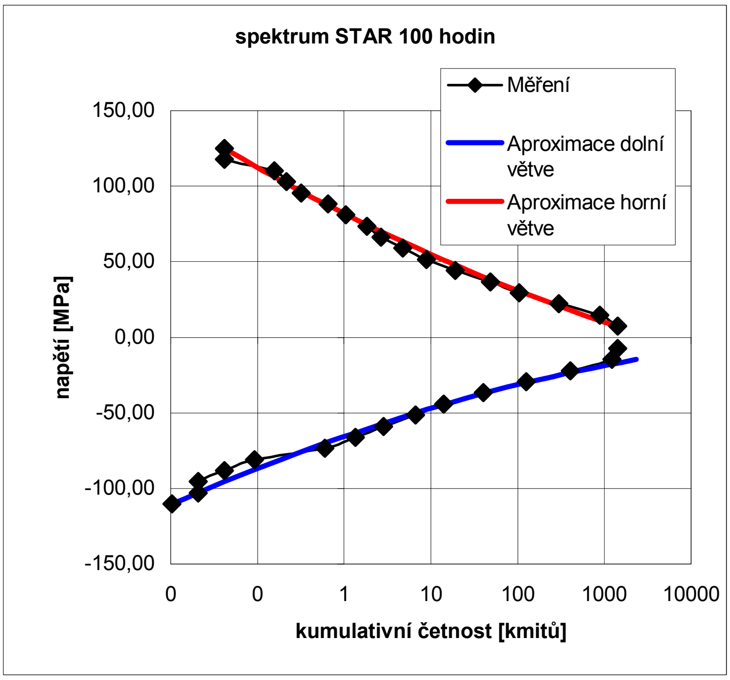


Figure 2. 10 - Aproximated stress strectrum of the 100 hours of operation

Following approximation formula for recalculation of upper and lower branch of the spectrum has been used:

$$h_i = h\left(\frac{h_p}{h}\right)^{\left(\frac{\sigma_{a,i}}{\sigma_{a,p}}\right)^s},$$

where $h = \sum_{i=1}^{p} n_i$ represents total count of cycles, h_p, $\sigma_{a,p}$ represents cumulative occurrence and magnitude of the stress in the biggest (p^{th}) rank of stress and $h_i = \sum_{k=1}^{i} n_k$ represents determined cumulative number of cycles for chosen stress amplitude $\sigma_{a,i}$. According to the magnitude of exponent [*s*], different frequency distribution can be obtained. In the case of s=1, the spectrum is linear, known as exponential occurrence discerption; s=2 provide "Normal" ("Gauss") occurrence discerption. The value of exponent s=0.36 provides the best approximation of the upper branch of the spectrum used in the example and s=0.55 is best for lower branch.

3 Fatigue life monitoring

Individual monitoring of every particular UL Airplanes operation can provide very precise information about the fatigue damage cumulation and allows plane residual life prediction. However, such wide spread UL Airplane operation monitoring cannot be done without the small operation registration unit permanently accommodated in the plane structure. More precisely, such registration unit is called *"fatiguemeter"*. Basically it is small computer which measure the operational *"g"* and measured *"g"* spectrum directly evaluate and calculate the fatigue residual life of structure. Described fatiguemeter and mathematical model of fatigue life calculation is third part of the presented project. Figure 3. 1 shows the scheme of the system for Airplane structure fatigue calculation. One of the main part of this mathematical model is description of the fatigue properties of Airplane structure, respectively its critical places. Due to the fact that in the UL Airplane category the fatigue tests or approval are not required by the nowadays regulations, there are very few information about the fatigue properties of UL Airplanes structures. One of the ways how to solve this problem is to collect and publish the catalogue of the known *S*-N curves used in the aerospace industry for small aircrafts. Those *S-N* curves describe the common critical parts of the Airplanes structure *(e.g. riveting, spar booms, wing joints…)*. Using by such catalogue, it will be possible with some appropriate accuracy at least estimate the fatigue behavior or *S-N* curve of particular UL Airplane structure.
"Local" or *"Nominal"* stresses of the structure critical place have to be defined using by complex FEM models and calculation. The result of the FEM calculation has to be consequently verified by strain-gauge measurement. Also the correlation formula of the relation *"g"* vs. stress has to be found according to this strain-gauge measurement. The fatigue damage calculation can be done according to several well known methods see [5] such as: Nominal Stress Approach (NSA), Local Elastic Stress Approach (LESA) or Local Elasto-Plastic Strain and Stress Approach (LPSA).

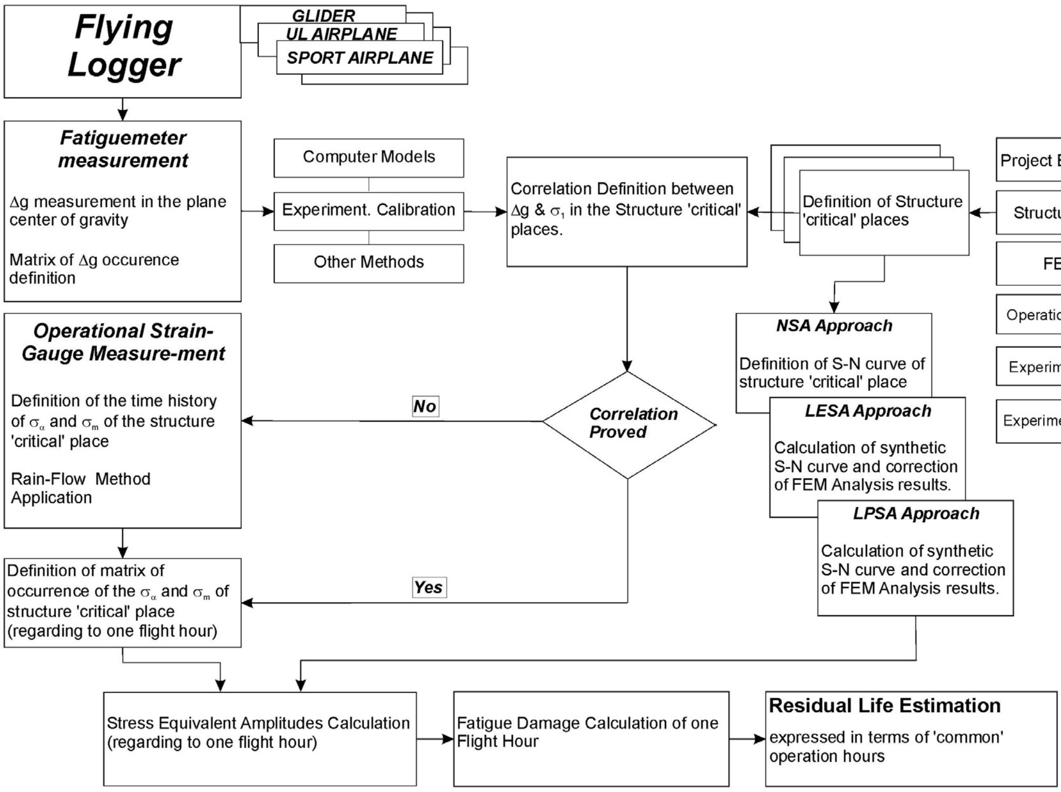


Figure 3. 1 Scheme of the in time life monitorin system

4 Conclusion

The project tries evaluate the character of UL Airplane Air Traffic with a relation to the load of the plane structure its fatigue damage. Whole project is divided in three parts. The first part is focused to the "g" spectrum measurement during the UL Airplane service. The character of the UL Airplane Air traffic is described and graphically presented by the one-parametric spectrum of operational load factor. This one parametric spectrum represents the occurrence of the particular load factor during the plane service. Till now, the 122.1 flight hours of the UL Airplane TL-96 STAR and 89.2 hours of flight time of the UL Airplane P-92 ECHO were recorded. These numbers of flight hours represents the period of one-year experimental measurement. The measurement will continue up to 200 flying hours for both airplanes. Unfortunately, the full evaluation and analysis of the obtained "g" spectrums was not done yet, it is the aim of the future work in this part of the project.

The second part of the project is focused to the correlation investigation between the operational load factor and structure load. The experimental measurements were partly, but successfully done and they will continue in the following period of time. The recorded data from the strain-gauge measurement were evaluated to the spectrum of structure load. According to them, the correlation investigation and the stress spectra in the critical points of the construction must be done.

The next step of the project solution is the development of fatigue life monitoring system of small sport planes. This will be the aim of the third part of the presented project.

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6 Appendix

6.1 TL-3412_CVU TECHNICAL DATA

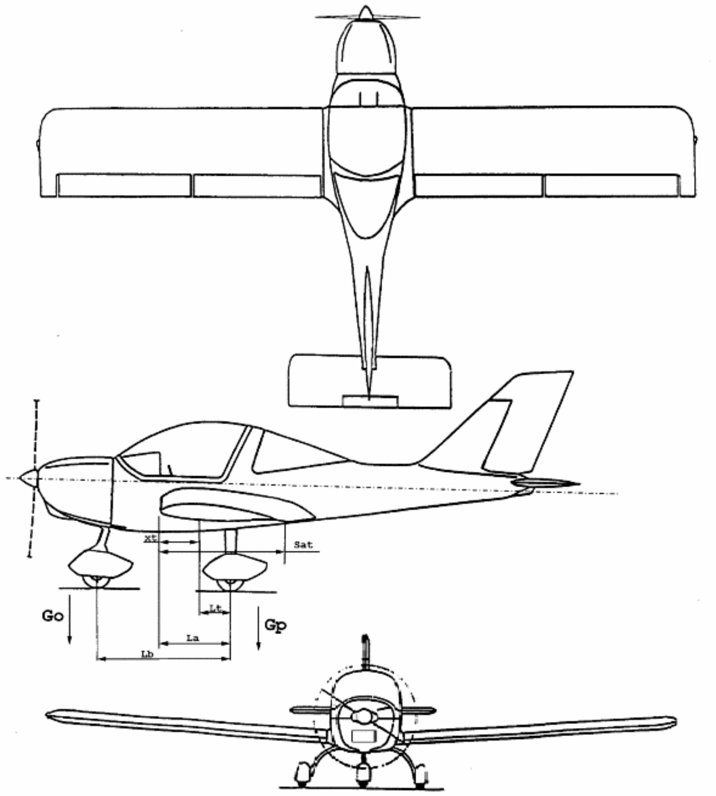
Figure 5. 1 Fatiguemeter TL-3412

Temperature Limit -20°C to 55°C
Supply Voltage 10.0 to 32.2V
Current Consumption 40mA
Max. Switch Signalization Current 30V, 100mA
Display Measuring Range ±20g
Measuring Accuracy ±0.1g[iv]
Permissible Overload ±25g
Permissible Vibration 5 to 500Hz
Weight 300 grams
Sample Speed 50ms
Filter Range 0.1 to 20.0g
Communication Speed 38400 bps
Saving Time after Landing max. 5 seconds
Memory Service Life 100 000 landings
Capacity 13 000 hours
Load Factor Memory Sample Speed 0.1g
Measurement Range for the Ascendant Half the cycles-1.5 to 4.6g
Measurement Range for the Descendant Half the cycles-1.5 to 4.6g
Memory Storage Time
form the Last Switch Off 10 years
PC Communication Serial port COM 1~4
Operating System Requirements Windows95, NT or better PC 486, 16MB RAM

[iv] Maximum is 0.3g in the low and high operational temperature.

6.2 The technical data of P-92 ECHO and TL-96 STAR

UL Airplane TL-96 STAR

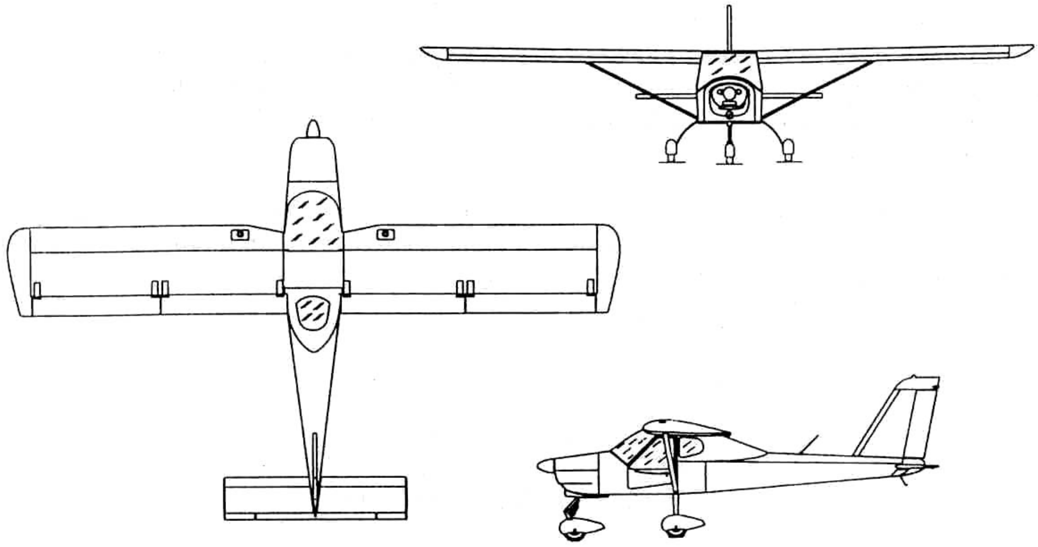


Wing span	9,2 m
Length	6,5 m
Height	2,15 m
Wing area	12,2 m2
Max. take-off weight	450 kg
Max. weight of baggage carried behind seats	8 kg

Speeds:

Take-Off	75 km/h
Climb	130 km/h
Cruise	180 to 220 km/h
Approach	120 km/h
Minimal with flaps down (stall speed)	63 km/h
Max. in level flight	200 to 255 km/h
Max. permitted speed	275 km/h
Rate of climb with ROTAX 912 engine	6 meters per second

UL Airplane P-92 ECHO



Wing span	9,3 m
Length	6,3 m
Height	2,5 m
Width Cabin	1.1 m
Wing area	13,2 m^2
Max. take-off Weight	450 kg
Empty Weight	281 kg

Speeds:

Rate of Climb	5,5 m/h
Cruise 75%	185 km/h
Minimal with flaps down (stall speed)	61 km/h
Max. in level flight	210 km/h