Modal analysis of sport aircraft

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Abstrakt
Příspěvek pojednává o funkci jednotlivých přístrojů v laboratoři, přípravě geometrie měřeného letounu. Dále je v příspěvku popsán průběh pozemní frekvenční zkoušky a vyhodnocení dat.

Abstract
This list deals with function of individual devices in laboratory, preparation of the measured geometry of the light sport aircraft. Further the paper describes the process of ground vibration test and evaluation of data.

Key words
Light sport aircraft, ground vibration test, fast Fourier transformation, averaging, measuring net, activator, accelerometer.

1. Reasons for doing modal analysis

Czech Republic is one of the largest manufacturer of light sport aircraft in Europe. To save weight (categories of LSA max weight is 650kg) are not-rigid aircraft. Result of a non-rigid construction may occur in flight to self-excited harmonic oscillation- called Flutter. Therefore aviation regulations FAR 23, an obligation to flutter resistance testing for airplanes that have V_d greater than 200Km/h. As sources for calculation of flutter resistance are measured data from GVT (ground vibration test).

2. Mobility laboratory for GVT

Mobility laboratory is consists of control panel, FFT analyzer, accelerometers, exciters, hand calibrator.

2.1. Accelerometers

The mobile laboratory used piezoelectric accelerometers, which works on the principle of a piezoelectric crystal that during the deformation generates an electric charge, which is proportional to the magnitude of the deformation. Thus obtained voltage is transmitting from accelerometers to FFT analyzer. Accelerometers are used to range of 14g and 71g. 14g accelerometers are used on solid surfaces as a fuselage, wings, stabilizer and keel. Accelerometers of 71g are used on control surfaces.

Installation of accelerometers is following. Construction at the desired location must be degreased. Mounting clips is glued by double cardboard. Into mounting clip is inserted accelerometer. Accelerometer should be calibrated before insertion into the mounting clip.

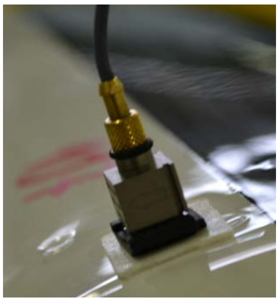

***Fig. 1-** One directional accelerometer*

2.2. FFT analyzer

To the FFT analyzer is getting analog signals from sensors (accelerometers and force transducers). Signals are discretized in FFT analyzer. FFT analyzer performs Fast Fourier Transformation of the signal. Signal dependence is changing from time to frequency dependence. Furthermore, the FFT analyzer calculates the frequency response function which sends via Ethernet cable to the control panel.

Frequency response function (*FRF*) is defined as:

$$H(\omega) = \frac{output}{input} = \frac{movement}{force} = \frac{response}{excitation} \tag{1}$$

$$H(\omega) = \frac{\tilde{X}}{F} = \frac{1}{k - \omega^2 m + i\omega b} \tag{2}$$

Or in nondimensional form of *FRF*:

$$H(\omega) = \frac{1/k}{1-(\omega/\omega_n)^2 + i2\zeta(\omega/\omega_n)} = \frac{1/k}{1-r^2+i2\zeta r} \text{ where } r = \frac{\omega}{\omega_n} \tag{3}$$

There are three basic types of response functions, depending on whether the parameter is the response displacement, velocity or acceleration. According to the shape of the response functions are called receptance, mobility, inertance.

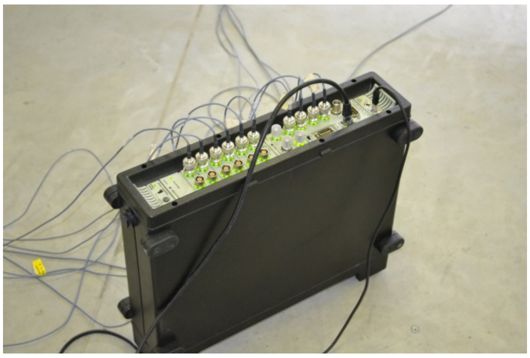

***Fig. 2-** FFT analyzer*

2.3. Control panel

Control panel is consist of two computers, two amplifiers and UPS

PC one on the left side (***Fig. 5-** Control panel*) is used to transmit the signal to the excitation amplifier. The amplifiers goes further signal to the electromagnetic exciters. Signal is used in the form of sine-sweep. Frequency of the signals goes from 2Hz to 102Hz, alternatively 5Hz to 105Hz. The time duration of one signal is 32 seconds. There are two types of signals. Signal for symmetric and antisymmetric excitation. Signals for symmetric excitation are both the same. Signals for antisymmetric excitation have the same amplitude at the one moment, but their displacements are opposite. Signal is generated by sound card.

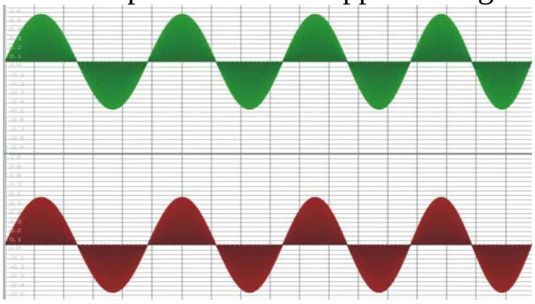

Fig. 3- *Signal for symmetric excitation*

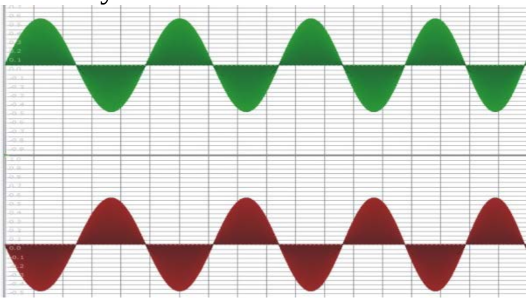

Fig. 4- *Signal for antisymmetric excitation*

PC two on the left side (***Fig. 5***- *Control panel*) is used to import geometry, setting the direction and position of exciters and accelerometers, setting measurement, making the calibration, accelerometers range setting, record *FRF*. Computer functions will be described in detail in chapter *3 Preparation of geometry*.
Uninterruptable power supply (*UPS*) provides input overvoltage protection. Devices connected to the *UPS* output are powered by filtered AC voltage from the public power grid. *UPS* batteries are recharged via an electronic circuit the battery charger. In violation of power (undervoltage, overvoltage), or sudden interruption in the supply of electricity from the public grid, ensuring its commutator switch an electrical circuit and the connected devices are directly powered from *UPS* battery.

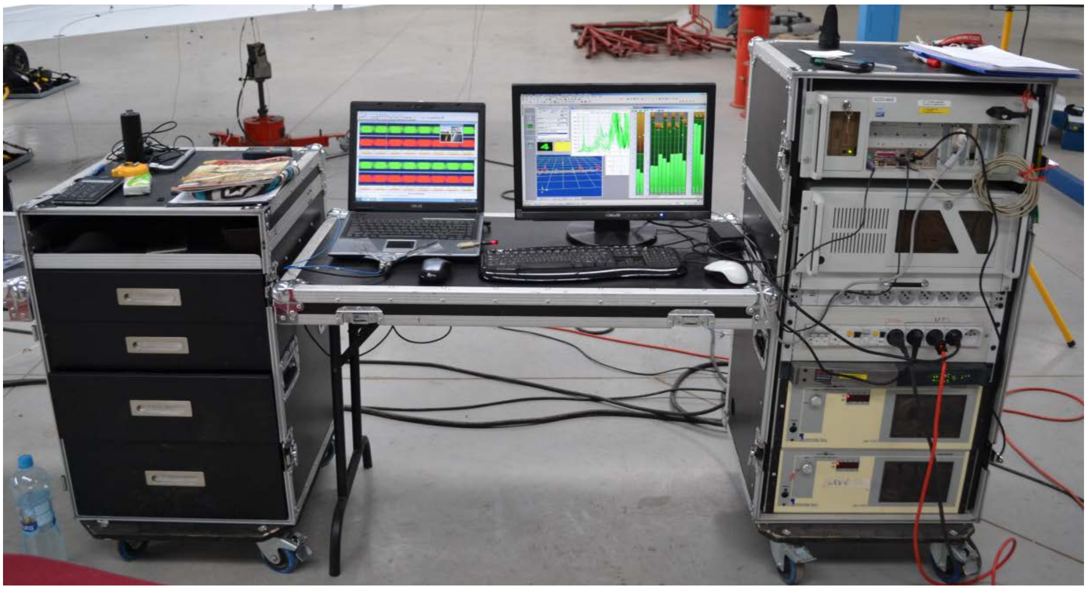

Fig. 5- *Control panel*

2.4. Exciters

Laboratory works with two electromagnetic exciters powered DC. Exciters are connected to the construction of the predetermined points. Using two excitations is due two reasons. In the method of excitation is adapted application of two drivers required for symmetric systems, which can have the same frequency at two different mode shapes (symmetric and antisymmetric. In the excitation spectrum is a reason to use more drivers in the design of energy dissipation and the effort to its better layout. Thus the mutual coherence in the whole spectrum is less than 1.

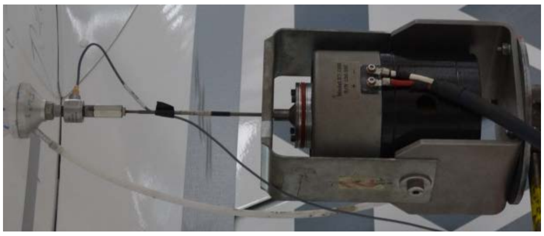

Fig. 6- *Connected exciter*

2.5. Hand calibration

All sensors and instruments must be periodically calibrated to meet given standards. Calibration is performed by authorized institution that issues the calibration protocols and declarations. In addition to these calibrations should be performed operative calibration. It is the calibration of measuring chains before each measurement. It is because of the connection of different capacity and impedance (cables, amplifiers, filters) between the calibrated sensor and calibrated analyzer. For this purpose accelerometers are used for operational hand calibrator.

Fig. 7- *Hand calibrator*

Fig. 8- *Hand calibrator with accelerometer*

3. Preparation of geometry

From the manufacturer require technical documentation airplane on which the test will be performed. We create a simplified two-dimensional model. The model neglects for example dihedral angle, if it is less than 5°. Neglect also, ending wings arches, curves are replaced by straight lines.

This simplified two-dimensional model is loaded into the pulse. From lines we make the triangular area in pulse. The next step is to set the type and serial number of accelerometers and load cells to be used in the test. These sensors are placed in the geometric model. Enter the position and direction. Thus, each measurement is created. Number of measurement depends on the density of the chosen network and the number of accelerometers. Each measurement is twice, symmetric and antisymmetric excitation.

Further setting it concerns the actual measurement, which selects the number of averaging, averaging type, overlap. For modal testing is chosen linear averaging, averaging depends on “smooth” FRF. The number is usually between 20 and 30 times, overlap is used 66,6%.

4. Description of GVT

4.1. Way of mounting airplane

Mounting is based on the purpose for which the modal test is performed, possibly stemming from the limitations of operating conditions. There are three ways to fit the measured structure:

- Free
- fix
- in situ

For GVT of LSA is used free fit. Free fit is the simplest way of fitting. Free fit is based in the fact that the airplane is hung on a special frame with very soft springs. This frame should theoretically have an order of magnitude lower than the natural frequency of the lowest natural frequency of the measured object.

Fig. 9- *Frame with very soft springs for sailplanes*

Fig. 10- *Frame with normal springs*

Another method to fit is to save the aircraft on airbags with underinflating tires. The airbags are underinflating too. For this way of fitting is needed air compressor, air hoses, valves, airbags, frames for airbags and straps.

Fig. 11- *Airbag with tire*

Fig. 12- *Valves with pressure gauges*

This method of fitting is to identify eigenmodes and eigenfrequencies of solid surfaces such as wings, tail, keel and fuselage. For testing the moving surfaces (rudders) fixes the airplane. Disallow any movement with solid surfaces. Solid surfaces are underpinned and loaded with bags of pellets. Thus, on one half wingspan disposed around 150-200kg. Solid surfaces are blocked due to the assumptions of the mathematical model. Model is used as the basis for flutter calculations. In tests it is sufficient if the movement of solid surface is at least an order of magnitude less than the movement of the rudder.

Fig. 13- *Fix of wing with bags of pellets and exciter*

4.2. Testing configurations

On sport airplanes is performed modal testing in several configurations. As the first configuration is the smallest weight according to flight manual. It is therefore an airplane without fuel but with one pilot, which simulates the bags of pellets. Furthermore, the test so called "heavy variant". This variant consists of filling the aircraft with fuel delivery and second pilot so that the weight of the aircraft was 450/472,5kg or 650kg. It depends on aircraft regulations (UL2 or CS-VLA).

For excitation rudders are two configurations. The first configuration is free control. Nothing prevents the rudder or the entire route management in motion. The second configuration is called "blocked control". The control lever and pedals are blocked in this configuration. So that, avoid movement routes control.

Measured configurations are chosen to describe the boundaries between which the aircraft normal moves. So that the normal operation of the airplane safe.

4.3. Connecting exciters and accelerometers

Exciters are connected to the measured structure through steel rods. Drivers have a high stiffness in the transverse direction. Rods are used to avoid drag forces and moments on the construction. This would be result in a secondary excitation At the end of rods are located force transducers. Furthermore connects preparations for connection structure. Construction requires an appropriate location of exciters. It is appropriate to know the approximate behavior of the structure. If the driver is placed in a "nodal point" mode would not be excitated and the results of the tests would not be complete. Position of exciters also determinates what modes we would like to excite. When the wing bending mode is excitation the excitation should be placed in the elastic axis. Location in the elastic axis is not always followed. Therefore, the exciter is placed either under the main beam or the rib. For generating torsion we haven't four exciters. Therefore, the exciters are placed farther away from elastic axis. Under the auxiliary beam.

Fig. 14*-Underpressure connecting*

Fig. 15*-Stirrup connecting*

Accelerometers are connected to the measure structure into measure points. Measuring network with points is based on the geometric model. The geometric model is transferred to the aircraft. It is usually that number of measuring points is greater than number of accelerometers and channels. Therefore, the accelerometers are placed in mounting clips. Mounting clips allow easy moving or rotating accelerometers. In the actual measurement must therefore be careful to change the location of the accelerometers and or their directions.

4.4. Main measuring

Excitation of the structure is via electromagnetic exciters. Earlier mentioned signal is coming into exciters. During the actual measurement only changes the voltage supplied to the exciters and ranges of sensed forces and acceleration. The voltage is adjusted by means of potentiometers in amplifiers. The voltage is adjusted so that the structure was excited by a suitable power. The force is usually between the excitation of solid surfaces around 30N. For rudder is then a little less.

During measurement is conducted such that the airplane at first is excitation by symmetrical signal. In the next step is location of accelerometers same, but the supplied signal changes to antisymmetric. Then the position or direction of accelerometers is change. Excitation is again initially by symmetrical and then antisymmetrical signal. In this way, all measured cases that were created in Pulze. From Pulze is then exported waveforms of required behavior of the structure for further evaluation.

5. Data evaluation

FRF are exported. Exported data is loaded into the program ME‘scope. The graphs are plotted ME’scope FRF magnitude, real and imaginary part of the FRF, Nyquist diagram, angles of displacement vectors. The display also includes animation behavior of the structure to identify the mode.

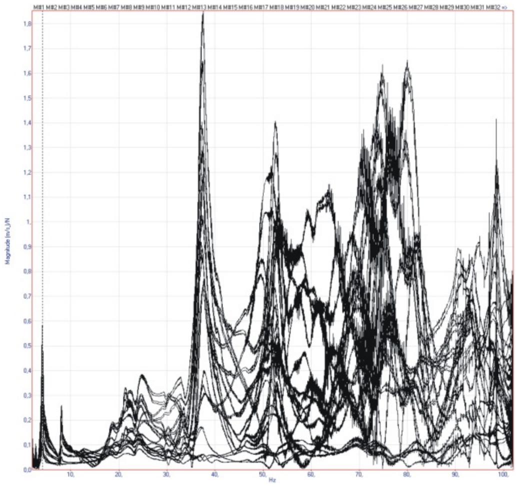

Fig. 16- *Chart of FRF*

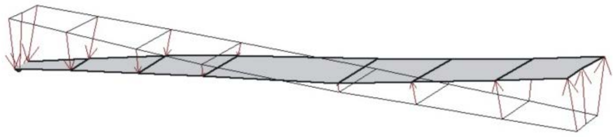

Fig. 17- *Movement of wing*

The natural frequency of the frame is visible on the first peak at a frequency of 4,06Hz. The figure shows (***Fig. 17-*** *Movement of wing*) that the wing is at a frequency of 4,06Hz behaves as absolutely rigid structure.

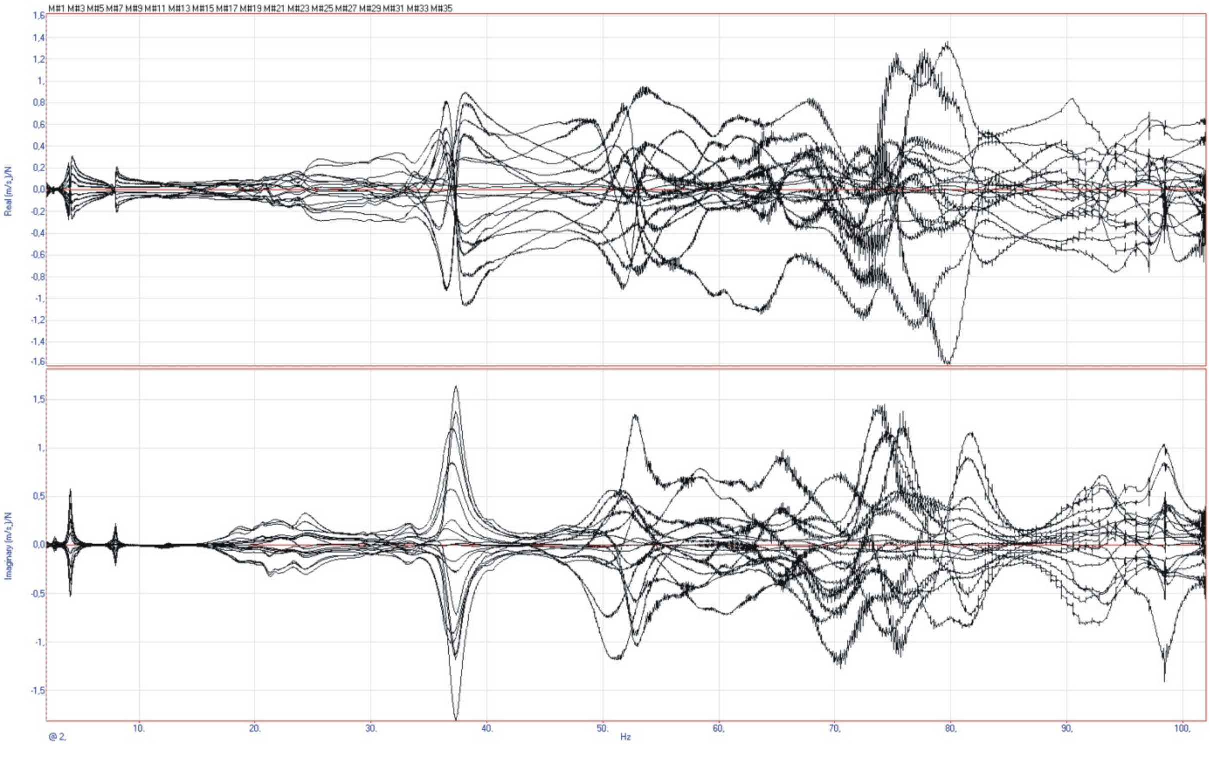

Fig. 18- *Real and imaginary part of FRF*

The damping system is evaluated using the half power point, or from real part of FRF. HPP method is deducted from the graph amplitude of FRF.

5.1. Half power point

The assumption of the method is such that the amplitude of the FRF graph is symmetrical around the resonance, and then apply:

$$\omega_1 = \Omega_0 - \delta \tag{4}$$

$$\omega_2 = \Omega_0 + \delta \tag{5}$$

Then following formula applies for damping:

$$g = 2\zeta = \frac{\omega_2 - \omega_1}{\Omega_0} \tag{6}$$

5.2. Damping from real part of FRF

$$\omega_1 = \Omega_0\sqrt{1 - 2\zeta} \tag{7}$$

$$\omega_2 = \Omega_0\sqrt{1 + 2\zeta} \tag{8}$$

Then following formula applies for damping:

$$g = 2\zeta = \frac{\left(\frac{\omega_2}{\omega_1}\right)^2 - 1}{\left(\frac{\omega_2}{\omega_1}\right)^2 + 1} \tag{9}$$

6. Conclusion

Modal analysis is performed on aircraft for the gathering data to calculate the flutter. In the article were discussed instruments and their functions in a mobile laboratory. Model creation process from the actual measurement and evaluation of results including damping

In the Czech Republic is able to perform modal analysis with the calculation of just a few organizations. CTU is one of these organizations. For several years evaluates the risk of developing flutter for manufacturers of small airplanes. Performed without flutter analysis and detected flutter resistance aircraft cannot be certified.

List of symbols

ζ	Proportional damping	*[-]*
ω	Circular frequency	*[1/rad]*
ω_n, Ω_o	Own circular frequency	*[1/rad]*
b	damping	*[kg/s]*
F	Force	*[N]*
FFT	Fast Fourier transformation	
g	Acceleration of gravity	$[m/s^2]$
g	Structural damping (complex damping)	*[-]*
$H(\omega)$	Frequency response function (FRF)	
i	Imaginary part	*[-]*
k	Toughness	*[N/m]*
LSA	Light sport aircraft	
m	Mass	*[kg]*
r	Tuning factor	*[-]*

V_d	Design velocity	*[km/h]*
$\tilde{X}$	Complex amplitude quantity	

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