Technology of Ground Vibration Testing and its application in light aircraft prototyping

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Abstract. The article describes the vibration measurement technology used for light aircraft and some results obtained during the prototyping process. The aim of researches was to determine the resonant frequencies and natural modes of an aircraft or its selected structural components. Ground Vibration Testing is an essential dynamic structural test necessary to carry out before the aircraft certification. This test should be performed on the aircraft example which is predicted to test in flight. The measuring system used in the Institute of Aviation Technology of the Military University of Technology consists of a multi-channel LMS SCADAS analyzer, a set of piezoelectric accelerometers, two vibration exciters equipped with impedance heads and a computer with the Test.Lab Software. The aim of the article is to present the methodology of performing GVT tests. Using the equipment applied to an aircraft or its airframe component, key vibration characteristics corresponding to resonant points can be determined. Not only completed aircraft can be tested, but also its isolated fragments (wings, stabilizers, tail units) or just empty airframe. Testing separately supported components allows to examine their aeroelastic properties at early stage of prototyping. As examples of the use of vibration measurements in various stages of the prototyping process, three examples are presented herein. The isolated strut-braced wing from of the light reconnaissance aircraft *OSA*, the airframe of a light jet *FLARIS LAR*, and the light drone *ATD JET-2* intended to be an aerial target for some anti-aircraft artillery sets. Some exemplary results obtained from testing these objects were presented. At the end, some observations and conclusions were noted in the context of usefulness of conducted researches.

1 Introduction

Aeroelastic phenomena may be divided according to the triangle scheme of aeroelasticity (Fig.1). The sides of the triangle represent the relationships among the particular pairs of forces representing specific areas of mechanics, including aeroelasticity, whereas the triangle's interior represents the interference of all three groups of forces typical for dynamic aeroelastic phenomena. Static aeroelastic phenomena that exclude inertial forces are characterized by the unidirectional deformation of the structure, whereas dynamic aeroelastic phenomena that include inertial forces are typical in their oscillatory property of structure deformation.
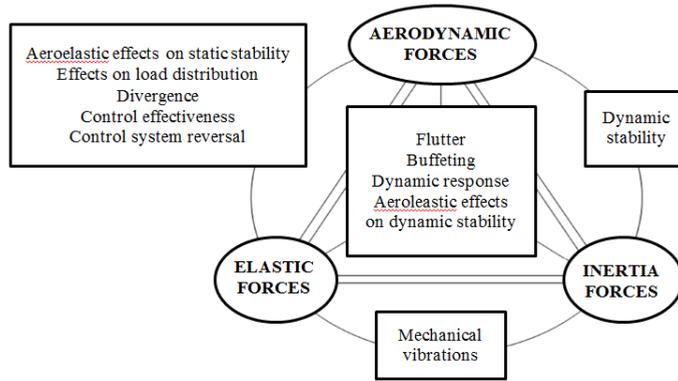
Fig. 1. The triangle of aeroelastic relationships – forces and resulting phenomena.

The main objective of a Ground Vibration Testing is to experimentally determine the low-frequency modes of the whole aircraft structure for validating and improving its structural dynamic model as part of the flutter clearance process [1]. A GVT are carried out in research phase, when we have almost ready product. Additional GVT are carried out when aircraft is operational or modified. Nowadays before first parts are manufactured, we have detailed virtual model. In fact we have a complete plane much earlier "in computer". So why we do not check flexibility of designed airplane at earlier stage of project, when corrections can be made at an early stage. When we have some already manufactured components we can check their dynamic properties. Also we can check the designed aeroelastic properties. Additionally in modern structures a big challenge is proper modeling of composite materials with correct properties and also proper flexibility.

Normal Modes Testing is essentially single sine excitation at the natural frequencies of the modes is used. By carefully selecting the shaker locations and the phase relation between the sine excitation signals, the aircraft is forced to act as a single degree of freedom system and the vibration response only contain a contribution from the mode of interest [2]. The mathematical model of vibrations of the examined object is known and assumed in advance. Assuming that the vibrations are characterized by small amplitudes and occur in the linear range, the object can be described by the following system of ordinary differential equations:

$$M\ddot{q} + C\dot{q} + Kq = Q \tag{1}$$

where M, C, K are diagonal matrices of inertia, damping, respectively and stiffness, q is the displacement vector, while Q is the external excitation vector. During the measurements the following characteristics and parameters are determined:
- adapted harmonic excitation force distribution corresponding to the tuned form,
- amplitude-frequency spectrum of sensor responses,
- matrix of spectral transition functions (Frequency Response Functions),
- resonant modes and frequencies of - determined according to the applied tuning criterion,
- coefficients of generalized mass, stiffness and damping coefficients.
Generalized coefficients refer to isolated resonance treated as vibrations of the model equivalent system with one degree of freedom. Individual degrees of freedom, which are subject to subsequent vibrations, are attributed to the so-called main coordinates q. Thus, each resonant state of the structure can be described by the specific equation transformed from the general equation (1), which in the case of any n-th characteristic mode takes the form:

$$\mu_n\ddot{q} + \beta_n\dot{q} + \chi_n q = Q_n \tag{2}$$

with the following generalized coefficients:

μ_n – the generalized mass factor of the n-th form,

β_n – generalized attenuation factor of the n-th form,

χ_n – generalized stiffness coefficient of the n-th form,

Q_n – main exciting force referring to the n-th form.

The dimensionless factor is taken as a measure of the damping of a given character:

$$\alpha_n = \frac{\beta_n}{2\mu_n\omega_{rn}} \tag{3}$$

where ω_{rn} is the resonance frequency of the n-th vibration mode. The resonance frequency determined by measurement clearly determines the ratio of stiffness and generalized mass according to the formula:

$$\omega_{rn} = \sqrt{\frac{\chi_n}{\mu_n}} \tag{4}$$

In turn, after substituting the special (harmonic) form of the solution into equation (2), the frequency domain is obtained with the amplitudes of displacement and forcing force, respectively: and: a and Q_{0n}:

$$\left(-\mu_n\omega_n{}^2 + \beta_n\omega_n + \chi_n\right)a = Q_{0n} \tag{5}$$

At resonance frequency $\omega_n = \omega_{rn}$ therefore equation (5) takes the simplified form:

$$\beta_n\omega_{rn}a = Q_{0n} \tag{6}$$

The determination of all three generalized coefficients additionally requires analysis of the system response in the range of resonance frequencies. It is then possible to establish an additional equation, which together with the relationships (4) and (6) will form a system of three equations with three unknowns: μ_n, β_n, χ_n mass, stiffness and generalized damping. The experimental determination of at least one of the coefficients: therefore, guarantees the calculation of the other two.

2 Measurement equipment and methodology

Elements of the system applied in described investigations are the following: analyzer LMS SCADAS Lab (244 channels), analyzer LMS SCADAS III (48 channels), modal shakers TMS2100E11, impedance heads ICP 288D01,amplifiers 2100E18/RMX 2450, accelerometers PCB T356A15 and computer with LMS Test.Lab software.

Fig. 2. Modal analyzer LMS SCADAS Lab with wires connecting piezoelectric sensors.

The first stage of measurements is the initial identification of resonance frequencies [3, 4]. The *MIMO Sine Sweep & Stepped Sine Testing* module of the Test.Lab software is used for this [5]. Excitation with a specified frequency is carried out twice. During the first pass,

the inductors operate in compatible phases, while the second pass with 180° phase shift. This is dictated by the necessity to force all possible forms of the tested element and allows control of the amplitude and phase at a later stage. As a result, frequency characteristics for each measuring channel are obtained. The *PolyMAX* application creates aggregated amplitude-frequency characteristics [6]. An additional characteristic in the context of resonance location is the course of the IMIF (Inverse Mode Indicator Function), which means a decrease in the excitation force amplitude during the increase of the collective response amplitude. At the resonance state the applied force decreases, therefore the decrease of the IMIF coefficient towards zero and the jump of the amplitude run give a clear signal that there should be resonance around this point. Then a stabilization diagram is created for the narrowed frequency range. For resonant forms, stable poles marked S are important, which in a given peak should occur several times and approximately form a straight line. Selected points of the obtained characteristic are converted, and identified characters displayed in the form of animations. On its basis, you can determine the form of vibrations, define the points of greatest amplitude, determine the nature of displacements and assign it to a specific frequency. Additionally, approximate attenuation is determined, which is needed when tuning to the frequency in the *Normal Modes Testing* module. In this way, a number of points are obtained with a characteristic amplitude gain, which should then be subjected to the process of verification and precise tuning.
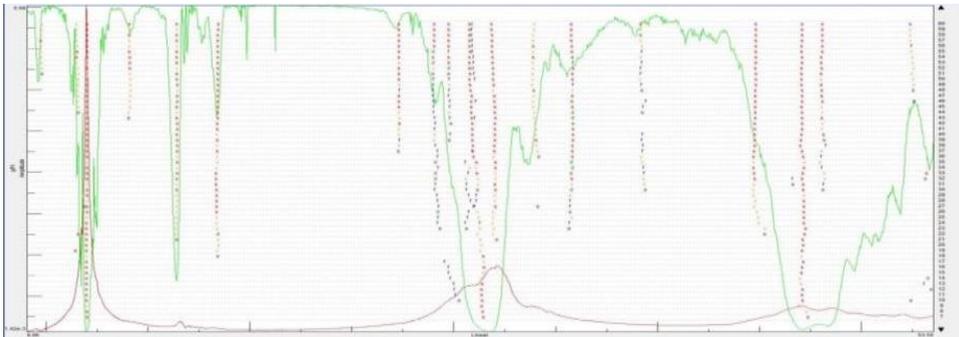

Fig. 3. Stabilization diagram from the *PolyMAX* application (LMS Test.Lab v.14) – collective amplitude-phase spectrum generated from all measuring channel responses and the IMIF graph.
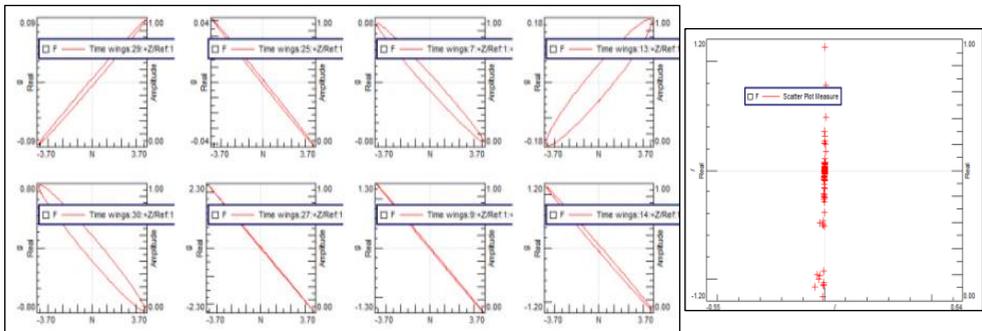

Fig. 4. Graphs illustrating phase shift between response and excitation signals in resonant point: a) views of Lissajous curves for some specified measuring channels (graphs after transformation enabling the view of seemingly superimposed signals, when in reality they are shifted by π/2), b) complex plane indicator with amplitude and phase for measuring channels.

After the initial sweep, several points are obtained, where there is a characteristic amplification gain. Physically, this involves placing the inductors at the appropriate points. The apparatus used is characterized by repeatability of results. Due to this, similar initial

conditions and forcing forces can be used on various elements. The relocation of inductors involves the necessity to repeat the sweep with a sinusoidal signal in order to obtain response characteristics (FRF) for their given location. The tuning process consists in determining whether there is resonance around the frequency being tested, and then determining the resonance frequency and generalized coefficients [2]. There are several criteria for determining the resonance point. In the LMS Test.Lab program, the module used to identify natural vibrations is called Normal Modes Testing. The first criterion displays two types of visualization of dynamic structure deformations. The right geometry illustrates the share of the real part of the displacement, while the left shows the imaginary part. In the case of perfect tuning, there should be a disappearance of the movement of the real form, while the maximum oscillations in the image of the imaginary part. The second assessment criterion is the Lissajous curve waveforms, observed for sensors showing the highest levels of displacement. In this case, resonance occurs when the curve is approximately straight. The third criterion is based on a phasor diagram illustrating the distribution of amplitudes of response signals from individual sensors relative to the real axis and the imaginary axis. In the case of resonance, the vectors of the response from the vibrating element should be close to the vertical axis, and the vectors from the force sensors close to the horizontal axis. After tuning, the procedure for determining generalized parameters is started [7]. The estimation of generalized parameters corresponding to resonance points was carried out based on the Complex Power Method. The method is based on the balance of total power of measured oscillations in relation to the power of the signal consistent with the excitation and the signal shifted in phase. The total power balanced in the vibration cycle around the tuned frequency is therefore a complex quantity and is given by the formula:

$$P = \sum_{i=1}^{n} \frac{\bar{F}_i V_i}{2} \tag{7}$$

where:
$F_i = F_i{}' + jF_i{}''$ - complex force at the i-th point of the structure, $V_i = V_i{}' + jV_i{}''$- complex speed at the i-th point, $P = P' + jP''$- complex power at the i-th point, n – number of response points.

Plotting the real part (active power) is realized as a curve of the frequency function, reaching the maximum at resonance. The graph of the imaginary part of the power passes from positive to negative, passing through zero value at resonance. In addition, the characteristic should maintain a linear character around the resonance. This relationship is illustrated by the mathematical notation:

$$\left[\frac{dP'}{d\omega}\right]_{\omega_k} = 0 \tag{8}$$

and

$$P''(\omega_k) = 0 \tag{9}$$

One can show that:

$$P'(\omega_k) = \zeta_k \omega_k k_k \tag{10}$$

and finally:

$$\left[\frac{dP''}{d\omega}\right]_{\omega_k} = -k_k = -m_k \omega_k^2 \tag{11}$$

where:
ω_k – pulsation at the k-th frequency, m_k – generalized mass at the k-th frequency, k_k – generalized stiffness at the k-th frequency, ζ_k – damping factor at the k-th frequency.

3 Examples

3.1 Military fighter MiG-29

Our first experience was vibration testing of military jet MiG-29. A virtual model of this airplane was made earlier, so main aim of these tests was to compare measured vibrations with FEM. Because our first system has only a few accelerometers we decide to measure components of aircraft. We prepare grid where each component included all available accelerometers. Shakers stay in one position and excitation parameters were still the same, but accelerometers were moved from one component to another. Thus obtained vibration shapes of all elements of aircraft and in software all elements were connect in whole plane.
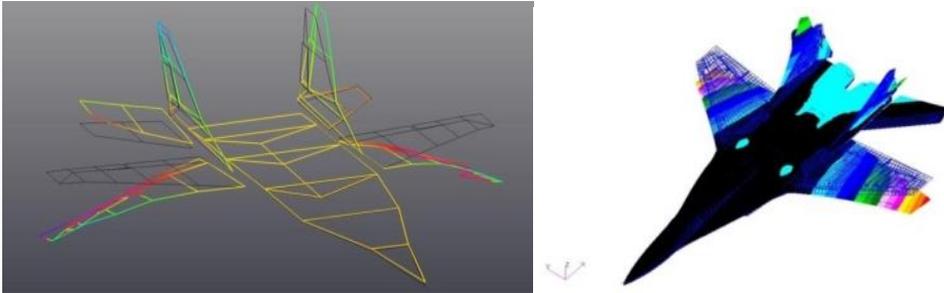
Fig. 5. Visualization of the 1st natural mode for MiG-29 – symmetrical wing bending: a) simplified "wire" model with measured displacements, b) 1st mode simulation from FEM analysis.

3.2 Isolated strut-braced wing of the VLA airplane

Our Institute develops a VLA reconnaissance airplane Osa (eng: Wasp). Because fuselage was still under development, our institute got only a left wing of prototype to static tests. To accelerate research a vibration test of isolated wing was performed. As a fastening a beam system imitating the real attachment to the airplane during static tests was used.

Fig. 6. Isolated wing of the VLA Osa: a) wing in real stand, b) FEM model of wing and stand.

3.3 Aerial Target Drone (ATD) Jet-2

For GVT we received aerial target drone without equipment. A drone is made of composite and it is powered by two small jet engines. Example for tests had no engines, parachute, accumulator and some electronics devices. According to the mass data we prepare equivalent masses for each component. The aircraft was tested in max take-off weight. Additionally servos were powered from an external power supply to reflect the rigidity of control systems.
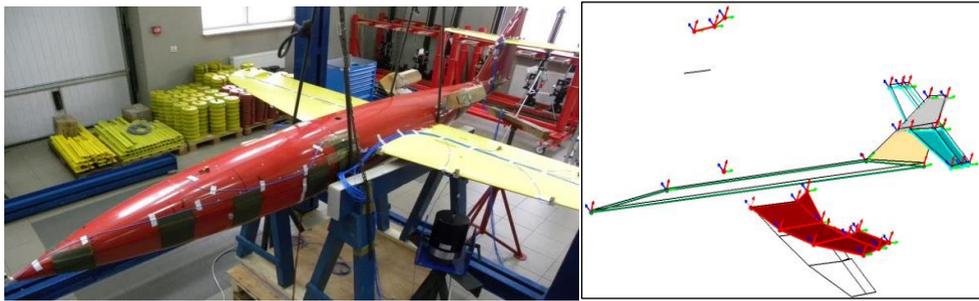
Fig. 7. ATD JET-2: a) on test stand, b) visualization of wing bending from test.

3.4 Very Light Jet Flaris LAR-1

FLARIS LAR-1 is a single-engine jet aircraft with a very lightweight, full-composite construction. Because of not enough number of accelerometers to create dense measuring grid the accelerometers were glued only on a wing skins. The main aim was to determine shapes and frequencies of wings, ailerons and flaps main resonant vibrations for numerical analyzes. A test was performed on airplane hang in free-free conditions. A fuselage was incomplete – only empty airframe and instead of the engine a substitute mass was attached.

Fig. 8. View on bottom side of right wing during test on Flaris Lar-1.
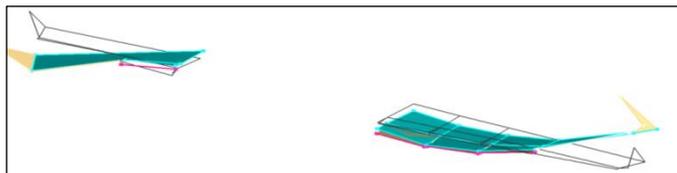
Fig. 9. Asymmetrical wing bending measured on Flaris Lar-1.

3.5 A mini-UAV Rybitwa (eng: Tern Bird)

Mini-UAV Rybitwa is a miniature reconnaissance aircraft. The drone has a classic aerodynamic layout with a T-tail and it is made of composite. It is designed to support the activities of the Police and Fire Service during emergencies. Version witch training video-head mounted to the front tip of under-fuselage pod was chosen for the test. Due to the very low weight, aircraft is very difficult to measure. Aircraft weights about 8 kg and one accelerometer 10,5 gm. First grid includes 70 measurement points, so it means, that we add almost 10% of weight. Keep in mind that the most mass is in fuselage – camera, electronics devices accumulators. Additionally it is impossible to put these accelerometers at tips of light control surfaces like ailerons or flaps. Final grid had only 27 points, mainly located on wings, one on each control surface to see the direction of swing and only a few at fuselage.
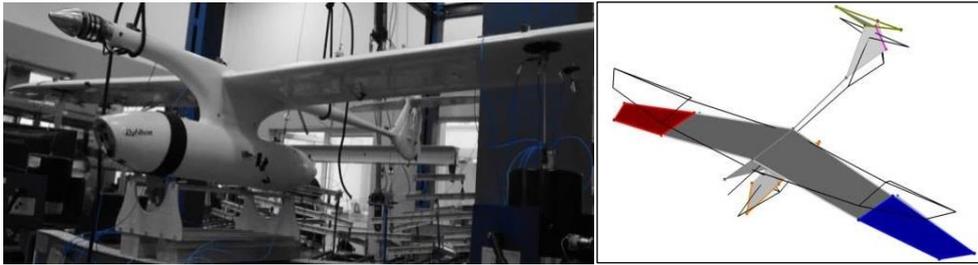
Fig. 10. Mini-UAV Rybitwa: a) mini-airplane suspended, b) visualization of wing-bending mode.

4 Final Remarks

Measured modes were explicit, clearly visible in software visualizations. The characters received are generally consistent with the expected forms. Such tests give very important information if designed structure has designed parameters or if numerical model or material is properly modeled. When project is stalling or there are delays and we have some ready components, the GVT test can be very useful and give possibility to checking already measured elements. All presented tests are completed successfully and collected data will be used for further works.

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