Identification of resonant vibrations of the miniature unmanned airplane with contact and non-contact measuring techniques

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Abstract. The paper describes application of two different vibration measurement methods for identification of natural modes of the miniature UAV. The aim of this research was to determine resonant frequencies and modes of mini-airplane within specified range of frequency values. Special measuring equipment was used including both contact and non-contact techniques. The measuring systems on equipment of the Institute of Aviation Technology in the Faculty of Mechatronics, Armament and Aerospace of Military University of Technology (Warsaw, PL) were used to conduct measurements. In traditional GVT methods a large number of sensors can be attached to the aircraft. The weight of sensors and cables is negligible in relation to the mass of the large aircraft. But for small and lightweight unmanned aerial vehicles, this could bring a significant mass component in relation to the total mass of the tested object. In this paper the methodology of GVT was presented. Two different measuring methods were applied, i.e. the contact method and the non-contact method. Using the dedicated apparatus in relation to mini-airplane, properly prepared in terms of mass distribution, rudders deflection stiffness and proper support, some resonant characteristics can be determined. The contact measuring system consists of a multi-channel analyzer, piezoelectric accelerometers, electrodynamic exciters, amplifiers, impedance heads and a computer with the Test.Lab Software. As the non-contact method a laser scanning vibrometer was used. The principle of its operation is based on the separation of the emitted laser beam. The returning beam reflected from a vibrating object is captured by the camera and compared to the reference beam. Dedicated software analyses collected data and on the basis of it creates animations of structural vibrational shapes and spectral plots within investigated frequency range. Object used for research is the mini-UAV Rybitwa – composite mini-plane with a classic aerodynamic layout manufactured in IAT MUT. In the work both measurement methods and some sample results were presented. Results referenced to dynamic properties of the mini-UAV can be applied in the future to FE model tuning.

1. Introduction
The aeroelastic phenomena are specified according to the triangle scheme of aeroelasticity (Fig.1). The sides of the triangle represent the relationships among the particular types of mechanical forces, whereas the triangle’s interior represents the interference of all load types. Static aeroelastic phenomena are effects of only aerodynamic load and structural elastic reactions, whereas dynamic aeroelastic phenomena include aerodynamic, elastic and inertial forces.
Figure 1. The Collar’s triangle of aeroelastic relationships – forces and resulting phenomena.

The main objective of a Ground Vibration Testing (GVT) is to determine experimentally the low-frequency modes of the whole aircraft structure for validating and tuning its structural dynamic model as a part of the numerical flutter calculations 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. Single or multiple sine excitation is introduced within the range of natural frequencies of interest. By carefully selecting the shaker locations and the phase relation between the sine excitation signals, the aircraft is excited and its structure is introduced into vibrational state; some specific criteria applied to identify resonant states at which structural dynamic deformations are the strongest at natural oscillation modes [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:

\[ M\ddot{q} + C\dot{q} + Kq = Q \]  

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.

2. Investigated object

Mini-UAV Rybitwa is a miniature unmanned airplane with the wingspan of 3450 mm and the take-off weight of about 11 kg. The electric 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. It is our original project, which is used for various tests. There was a need for vibration tests. Version with training video-head mounted to the front tip of under-fuselage pod was chosen for the test.

Figure 2. Mini-UAV Rybitwa suspended. 
Figure 3. Components of UAV
3. Contact method
The contact method includes accelerometers on the tested structure. They are connected to a multi-channel analyzer. 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]. 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. 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.

![Figure 4](image4.png)

**Figure 4.** 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.

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 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.

Due to the very low weight, aircraft is very difficult to measure. Full equipped airframe weights 8 kg and one accelerometer 10,5 gm. First plan includes 70 measurement points, so it means, that we add almost 9% of extra 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.

4. Non-contact method and equipment

The most popular method of non-contact testing is the use of laser. This method needs visual access to the surface of detail. The principle of operation of the laser vibrometer is based on the comparison of the laser beam reflected from the tested object and reaching the photodetector with a known reference signal. The POLYTEC PSV-400-3D laser vibrometer was used to perform the test. This is a device that enables the analysis and visualization of all kinds of structural vibrations. The principle of operation is based on the separation of the laser beam inside the head. One part remains inside and is the reference beam, while the other part goes to the vibrating object. The returning beam is captured by the camera and compared with the reference one. On this basis, the apparatus determines the displacements on the element and adjusts it to the frequency set on the generator.

Optical interference can be observed as an effect of convergence of two separate coherent light beams. The resulting intensity identified by a photodetector, varies with the phase difference \( \varphi \) between the two beams according to the equation:

\[
I(\varphi) = \frac{I_{\text{max}}}{2} \cdot (1 + \cos \varphi)
\]  

(2)

The phase difference \( \varphi \) is a function of the path difference \( L \) between the two beams, according to expression:

\[
\varphi = \frac{L}{\lambda} \cdot 2\pi
\]  

(3)

where \( \lambda \) is the laser wavelength. If one of the two beams is scattered back from a moving object (the object beam), the path difference becomes a time function \( L(t) \). The interference fringe pattern moves on the detector and the displacement of the object can be determined by directionally sensitive of the passing fringe pattern.

The component of the velocity in the direction of the object beam is a function of the path difference \( L \) according to:

\[
\frac{dL(t)}{dt} = v(t) \cdot 2\pi
\]  

(4)

For a constant movement \( V \) there is a relation:

\[
\left| \frac{dL(t)}{dt} \right| = \frac{\lambda}{2\pi} \cdot \left| \frac{d\varphi}{dt} \right| = f_D \cdot \lambda = |v| \cdot 2
\]  

(5)

from which the following expression could be obtained:

\[
f_D = \frac{|v|}{\lambda} \cdot 2
\]  

(6)

Thus, the movement of the object causes a frequency shift at the object beam, which is called the Doppler shift \( f_D \). Superimposing object beam and internal reference beam, i.e. two electromagnetic waves with slightly different frequencies generate a beat frequency at the detector which is equal to the Doppler shift. The relation 16 is used to describe the velocity, however independent of its sign. The velocity direction can be determined by introducing an additional fixed frequency shift \( f_B \) in the interferometer to which the Doppler shift is added with the correct sign. Thus the resulting frequency at the detector \( f_{\text{mod}} \) is given by formula:
\[ f_{\text{mod}} = f_B + \frac{v}{\lambda} \cdot 2 \]  

This type of interferometer, which are directionally sensitive is described as a heterodyne.

![Figure 5. Components of Polytec PSV-3D system: 3 scanning optical heads and junction box.](image)

### 5. Non-contact measurement of UAV

Inside the under-fuselage container, there are ultimately batteries, avionics equipment and a rescue system. Instead of them some substitute mass was inserted into the interior to achieve the take-off weight. Then, it was balanced and the equilibrium was obtained through the appropriate location of the equivalent load inside the pod. Since, during measurement of a vibrometer you are required visibility of the test surface, it was necessary to position the plane so that the wing surface was set in front of the lens. The plane was placed in a vertical position with the engine up and the top surface facing the lens. In this way, the plane was able to free dislocations and sprains in the desired directions.

![Figure 6. Right shaker with impedance head](image)  

![Figure 7. Suspension method](image)

At the beginning, the measurement was performed using the 1D mode and with the use a single head. An electrodynamic exciter with an amplifier was used for excitation. Inductor gave a signal structure via a rigid rod (stinger). A duralumin U-profile was mounted on the threaded end of the stinger, which was then rigidly attached to the tail beam. The forcing signal was a modulated damped waveform of the Periodic Chirp type. It is a broadband modulated signal in which the carrier wave is additionally modulated over a wide frequency range and transmitted during the pulse duration. The measuring head was distant from the tested object by about 4.5 meters. The 1D measurement is characterized by the fact that displacement measurements are performed in only one axis. In order to obtain good-quality displacement shapes, it was necessary to create a dense measurement grid composed of 127 control points. The surface turned out to be the real problem during the test. Very
low reflectivity resulted in the creation of overload status points. This resulted in uncorrelated displacements of single points in relation to the vibrating element. Due to the large distance between the vibrating object and the head, it was very difficult to read the measurement points on the curves. 19 vibration modes were identified from 1D measurements with the use of a single head.

Figure 8. 1D measurement sequence with marked spectral ranges with peaks

The 3D mode allows you to measure vibrations in all axes. Three independent heads measure the displacement vectors, and the software converts the components into resultant displacements. Measuring with three heads is much more difficult because three separate laser heads have to be properly adjusted and calibrated. They should be placed approximately in the corners of an equilateral triangle inside which the tested object is located. It should be remembered that larger distances between the heads give better displacement vectors, but they cause a shift in the area of the laser beam movement. Therefore, when measuring with three heads, it was necessary to increase the distance from the measured surfaces to a value of over 5 meters. 2D alignment is performed for each of the heads separately. The primary purpose of 2D and 3D alignment is to align the three laser beams. Due to the distance and its size, the object practically guarantees the propagation of laser beams. To minimize this adverse impact, create as many points on different elements as possible in the 2D alignment mode. The 3D alignment mode allows three laser beams to focus together. It is necessary to align the spots as accurately as possible to obtain accuracy below 1-2 mm, it is very difficult and requires high precision. To improve accuracy, add points in the 2D alignment and rerun the 3D alignment. Ultimately, the accuracy of 0.8 mm was achieved for all heads (the TOP head as a reference has an accuracy of 0.0). When measuring with 1D, it was possible to position the head in such a way to obtain sufficient visibility (signal level) for all grid points. When three heads were used, it became practically impossible to achieve. The distance from the element and its curvature made it impossible to perform measurements without distortions. Always at some point a head did not have a sufficient signal level. Consequently, several ways have been tried to increase reflectivity. The pieces of reflective material worked best. At the points of the mesh, pieces of reflective material were glued with double-sided tape. In problematic curves, the sections had a larger surface area to accommodate slight shifts or divergence of the beams. The input was applied to the underside of the wingtips using two shakers, as in the 1D measurement. The forcing signal was periodic chirp with an amplitude of 0.4 V. The forcing signal was supplied from one generator output and split between both shakers. The reference signal was the force signal (N) from the impedance head mounted at the end of the stinger and attached directly to the aircraft structure.

Due to the measurement with three heads, it was not necessary to create such a dense mesh as in the 1D mode. The measurement grid consisted of 73 points. 24 forms of vibration were obtained. All marked peaks were clear. For each selected point, the visualizations contain displacements in all axes.
6. Comparison of methods
Using both the contact and non-contact methods, a number of clear vibration shapes were obtained. The frequencies from the sensor equipment were obtained from the tuning process, while the frequencies from the vibrometer were obtained from the collective characteristic at the end of the measurement. In comparing the vibration modes from both apparatuses, most of them coincided. The difference between the frequencies is less than 6% and mostly less than 3%, except in one case being 14% - the last mode at the end of the measuring range. In the range of 10-20 Hz, more frequencies were identified by the laser vibrometer, while in the range of 30-40 Hz, more were identified with the use of the LMS modal system. Figures 11-16 below show the visualization for the three basic normal modes.
Figure 13. 2\textsuperscript{nd} vibration mode: LMS – 8.70 Hz
Figure 14. 2\textsuperscript{nd} vibration mode: Polytec – 8.47 Hz

Figure 15. 3\textsuperscript{rd} vibration mode: LMS – 10.37 Hz
Figure 16. 3\textsuperscript{rd} vibration mode: Polytec – 9.78 Hz

7. Final Remarks
The main difference was the measurement method. Apparatus using sensors collects at the same time signals from all accelerometers simultaneously. This allows for a later resonance tuning process. However, in this case it is necessary to limit the number of sensors, which is associated with a decrease in the points from which responses are obtained. As a result, it was impossible to determine the type of vibration of the control surfaces and the identification of complicated shapes of vibration was difficult. In measuring with a vibrometer, the measurement is performed separately for each point of the grid, which makes the process itself longer and very sensitive. It also makes the tuning process impossible, as continuous measurement is required for this. Polytec PSV-400 allows you to measure frequencies up to 80 kHz, and the minimum measuring range is 100 Hz. To obtain an accuracy of 0.001 Hz, maximum sampling concentration is necessary. The fact that it placed no weight on the plane allows to build a very dense mesh. An additional reason to compact the meshes is the interpolation of unmeasured points in relation to the neighboring ones. At the edges, one of the spots often misses the object, which led to distortion and the need to move the mesh away from the roundnesses. Often the laser beams dived at the tips of the wings or at the tips of the tail.

Concluding, the accelerometer measurement is the most appropriate and gives the best results for aircraft vibration measurements. However, in the case of difficulty in measurement, such as a very light construction, in this case, the measurement using the laser vibrometer may be used. Also, it may be used as the initial measurement and later tune with the use of only a few sensors.

References
[1] W. Heylen, S. Lammens, P. Sas, Modal Analysis Theory and Testing, Katholieke Universiteit Leuven, Faculty of Engineering, Department of Mechanical Engineering, Division of Production Engineering, Machine Design and Automation (1998).
[2] W. Wiśniowski, Resonance testing of flying objects - methods and analysis of results. Transactions on Aerospace Research, 7/2010 (209).
[3] B. J. Schwarz, M. H. Richardson: Experimental Modal Analysis. Fifth Edition, Butterworth-Heinemann. CSI Reliability Week, Orlando, FL, (October 1999).
[4] B. Özkök, U. Weltin, Aeroelastic analysis for the CH601XL and the CH601 with a maximum take-off mass of 600 kg. Hamburg University of Technology. Hamburg, (2009)
[5] LMS Test.Lab MIMO Sweep & Stepped Sine Testing 14. Copyright Siemens Industries Software NV
[6] B. Peeters, H. Climent, R. De Diego, J. De Alba, J. R. Ahlquist, J. M. Carreño, W. Hendrickx, A. Rega, G. García, J. Deweer, J. Debille, Modern solutions for ground vibration testing of large aircraft. 26th Conference and Exposition on Structural Dynamics 2008, IMAC-XXVI.
[7] LMS Test.Lab MIMO Normal Modes Testing 14. Copyright Siemens Industries Software NV.