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Ground vibration tests of an unmanned aerial vehicle using multi-channel equipment

We developed a combined computational and experimental technique for determining modal characteristics using specialised *Prodera* equipment for the unmanned aerial vehicle class under consideration. We analysed the functioning of the specialised *Prodera* software and hardware, created according to the algorithms developed by the French national aerospace research centre, *ONERA*. Testing the technique using real-world examples ensures that we obtain data for calculations preventing dangerous self-oscillations during flight, taking into account the specifics of the unmanned aerial vehicles we consider.

Keywords: vibration tests, flexible unmanned aerial vehicle, modal characteristics, *Prodera* multi-channel equipment.

Problem statement

Experimental acquisition of data for natural oscillations of an unmanned aerial vehicle (UAV) is the only basis for as-built (final) calculations of elastic oscillations during flight. The most important of them include solutions to dynamic aero-elasticity tasks [1]: flutter calculations and analysis of "elastic UAV – AP/FD flight control system" loop stability. Such self-oscillations can lead to destruction of the UAV or failures in the UAV equipment operation.

Calculations of elastic oscillations based on design documents show that their results are not accurate enough and can only be used as preliminary estimates. The conclusion about the UAV flight safety shall be made using as-built calculations, corrected based on results of ground resonance tests [1, 2]. The most important components of the developed testing methods are development and application of *Prodera* equipment [3], which is available in some domestic enterprises. Unfortunately, in most cases, only excitation devices included in the equipment are used, which affects the experimental procedure and the quality of the performed tests.

Modal tests

In relation to tests with controlled artificial excitation of oscillations for the UAV structure, the terms "experimental modal analysis" and "modal tests" imply the natural frequencies and eigenmode analysis. One of the most important options of the experimental modal analysis can be described as tests with multipoint excitation of oscillations and selection of forces, or an experimental phase resonance technique. This technique helps to evaluate the ground resonance tests under consideration, carried out to experimentally identify the specifics of eigenmodes of the UAV with outside the flow. These eigenmodes are required to update the computational dynamic design of the structure.

The distinguishing qualities of natural oscillations include 10–20 natural frequencies and the most important eigenmodes, logarithmic decrements of oscillations, generalized weights, as well as estimates of the non-linearity of characteristics. The latter are determined using the dependence of natural frequencies on the amplitude of oscillations and the dependence of the amplitude of oscillations on the excitation level.

Those characteristics that are less critical for calculating the mode flutter do not require precise measurement, since they are not associated with selection of the excitation forces.

Let us consider a UAV of cross-shaped design with surfaces of small or ultra-low aspect ratio, in subsonic and supersonic modes of controlled flight, with electrical drives on each control surface.

Fundamental theory of modal testing

Let us briefly describe the fundamental theory of modal testing to determine the experimental procedure. The computational dynamic design of the UAV uses a linear model; structural damping is replaced with equivalent viscous friction. In normal (master) coordinates [4], forced oscillations during ground resonance tests can be represented as

$$\boldsymbol{M}^0\ddot{\boldsymbol{q}} + \boldsymbol{H}^0\dot{\boldsymbol{q}} + \boldsymbol{K}^0\boldsymbol{q} = \boldsymbol{F}^0 \cos pt, \qquad (1)$$

$$\boldsymbol{M}^0 = (\boldsymbol{Y}^0)^T \boldsymbol{M}\boldsymbol{Y}^0, \;\; \boldsymbol{H}^0 = (\boldsymbol{Y}^0)^T \boldsymbol{H}\boldsymbol{Y}^0,$$

$$\boldsymbol{K}^0 = (\boldsymbol{Y}^0)^T \boldsymbol{K}\boldsymbol{Y}^0, \;\; \boldsymbol{F}^0 = (\boldsymbol{Y}^0)^T \boldsymbol{F},$$

$$\boldsymbol{y} = \boldsymbol{Y}^0\boldsymbol{q},$$

where $\boldsymbol{M}$ and $\boldsymbol{M}^0$, $\boldsymbol{H}$ and $\boldsymbol{H}^0$, $\boldsymbol{K}$ and $\boldsymbol{K}^0$ – matrices of physical and generalised masses, damping and stiffness;

$\boldsymbol{F}$ and $\boldsymbol{F}^0$ – vectors of physical and generalised excitation forces;

$\boldsymbol{Y}^0$ – modal matrix with its columns representing eigenmode shapes;

$\boldsymbol{y}$ and $\boldsymbol{q}$ – vectors of physical and generalised coordinates, respectively.

Matrices $\boldsymbol{M}$, $\boldsymbol{K}^0$ are diagonal due to the orthogonality of eigenvectors [4, 5], matrix $\boldsymbol{H}^0$ is diagonal if the viscous friction force is proportional to inertial and elastic forces or their combination (in practice, it can be assumed to be diagonal).

Then the system of equations (1) splits into independent, homograde equations with constants $m_j^0, h_j^0, k_j^0, q_j, F_j^0, y_{kj}^0, F_k$, representing the elements of homonymous matrices and vectors:

$$m_j^0\ddot{q}_j + h_j^0\dot{q}_j + k_j^0 q_j = F_j^0 \cos pt,$$

$$F_j^0 = \sum y_{kj}^0 F_k, \qquad (2)$$

where j – eigenmode number;

k – excitation force number.

With special distribution of excitation forces that differ in the sign of the phase shifts, oscillations of only one mode are excited on the natural frequency ω_j. In this case, the damping is compensated by the excitation forces

$$\left(-p^2 m_j^0 + k_j^0\right) q_j = 0,$$

$$h_j^0 \dot{q}_j = F_j^0 \cos pt, \quad p = \omega_j, \qquad (3)$$

and the generalised forces differ from zero only for the resonant j-th mode, the phase shifts of displacements of all UAV points are $\pm\pi/2$ relative to the excitation forces.

The natural frequency is determined by the ratio of the generalised stiffness and mass $k_j^0 / m_j^0 = \omega_j^2$, therefore, finding only one of these values is sufficient for the experiment. The eigenmode shape is determined by a range of $\boldsymbol{y}$ values at the measurement points on the natural frequency.

In domestic aviation practice, the viscous friction is assessed using a dimensionless value, i.e. the logarithmic decrement of oscillations θ_j, which is determined at steady-state oscillations with the width $\Delta\omega$ of the resonance dependence at the level $y_{\max}(\omega)/\sqrt{2}$:

$$\theta_j \approx \pi\Delta\omega / \omega_j. \qquad (4)$$

Independently, the logarithmic decrement is traditionally determined by l periods of damped oscillations:

$$\theta_j = (1/l)\ln(y_0 / y_l). \qquad (5)$$

The generalised mass m_j^0 is determined using the integrated power method [3, 5] by the slope of the dependence of the action of forces at the points of excitation (or power) on the frequency in small neighbourhood of resonance.

The most accurate method requiring no information on calibration of sensors and exciters, is mechanical additional loading using light loads Δm_k. The measurements are carried out at several additional loading values, with averaging using the least-squares method, in order to reduce the influence of the random error. If the frequency of the additionally loaded structure is denoted as ω_Δ, then the reduced weight $m_j^{п}$ is determined as

$$m_j^{\text{п}} = \sum \Delta m_j (\xi - 1) / \sum (\xi - 1)^2, \;\; \xi = (\omega_j / \omega_\Delta)^2,$$

$$\Delta m_j = \sum \Delta m_k (\operatorname{Im} y_k)^2 / (\operatorname{Im} y^{\text{п}})^2. \qquad (6)$$

In this case, the calculation uses the oscillation amplitudes only at the additional loading points, which refer to this or that reference point.

Testing procedure

The experimental procedure involves, firstly, an approximated general measurement of frequency characteristics in a wide frequency range with different excitation options; secondly, the sequential excitation of each eigenmode, its measurement and registration of the necessary parameters. The mode of steady-state harmonic excitation is mostly used with transient processes recorded additionally.

Conventionally, the technique can be presented as the following main stages:

1) preliminary calculations of the structure, development of the test program, "workplace" preparation, elastic jacking of the UAV, installation of exciters and sensors;

2) general measurements and determination of non-linear dependences;

3) excitation of a separate mode and carrying out of measurements;

4) in-line processing and analysis of data;

5) inspection check of excitation and measurement devices.

The second and third steps repeat cyclically immediately after measurements for each mode. Partial repetition of measurements may be required depending on the results of in-line data processing.

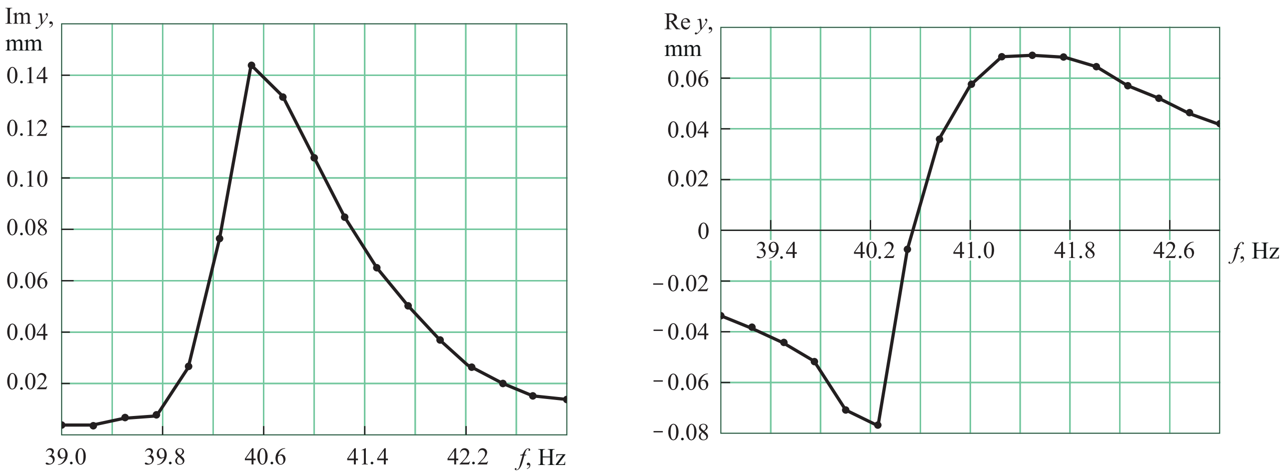
Below we will take a closer look at particular stages of the developed methods.

Preliminary calculations providing an initial idea of natural frequencies and eigenmode shapes are made at the first testing stage. The calculation results are essential in development of the test program and selection of equipment, preparation of options for boundary conditions long before the UAV manufacturing. The workplace is also prepared at this stage, including calibration of excitation and measurement devices, elastic jacking of UAV, placement of sensors, force exciters, control of all systems functioning.

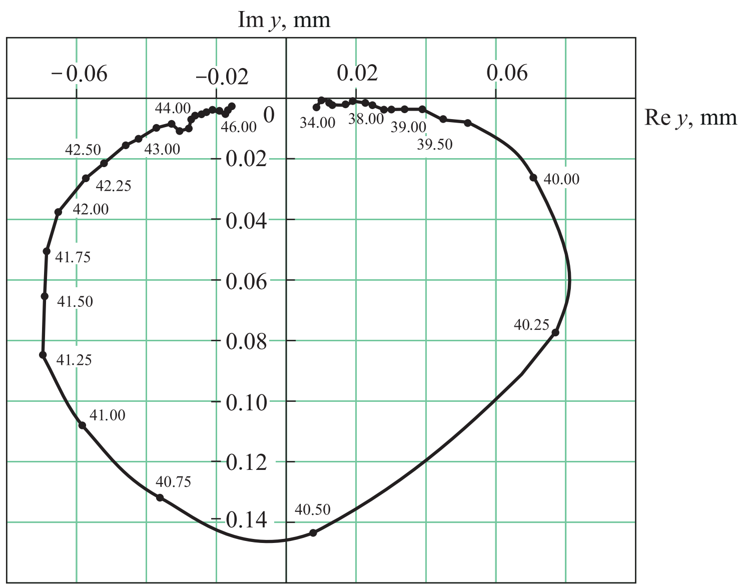
The second stage (beginning of measurements) involves software input of the basic information on force exciters, sensors and their connections with one another, UAV coordinates, filling in of the software-based test report, frequency intervals and excitation levels, overload limiting thresholds (at selected points). The control software is launched on the equipment: general measurements (with symmetric and antisymmetric excitation) of resonance curves with observation over oscillations of typical points (Fig. 1). The tests include assessment of resonance frequencies and the corresponding excitation options, visual observation of vibrations and check of equipment operation.

The second stage also involves determination of non-linear characteristics of the structure: the dependence of the resonance frequency on the amplitude and the dependence of the amplitude on the excitation force (Fig. 2). This allows for selection of the required oscillation levels for the next step and for adjustment of the measurement point coordinates. The measurements duration can be reduced during the automatic search for the resonance frequency and measuring its dependence on the amplitude.

The third stage includes all valid measurements. The resonance frequency is specified by the phase shift at the measurement reference point, the excitation forces are selected (with specialized software or manually). Adjustments are made towards obtaining the minimum phase shifts at the measurement points. The condition for resonance is a zero phase shift between force and velocity at the reference point, another option is the minimum value of the average phase shift $\varphi_{\text{ср}}$ at the most important measurement points for the specified mode, or the mode indicator function (MIF), which is generated by the software (Fig. 3).



a



b

Fig. 1. Experimental frequency characteristics:
a – resonance curves of body oscillations; b – frequency locus

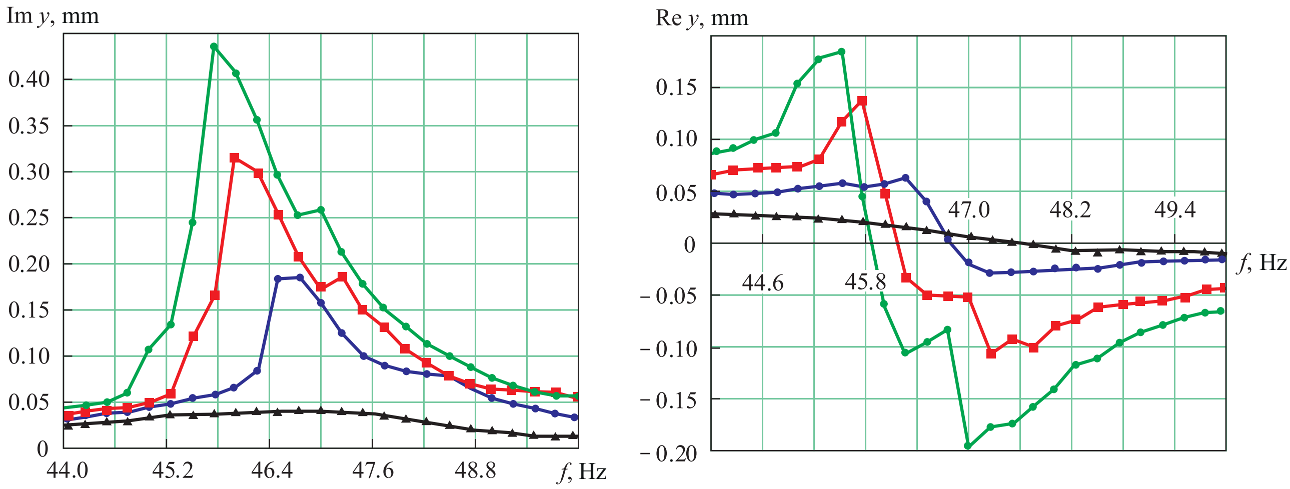
A sharper (in contrast to MIF) variation in φ_{cp} from frequency gives a better idea of the mode identification quality (in practice, the condition $\varphi_{cp} < 3°$ must be fulfilled for satisfactory identification of the first eigenmode).

Visual inspection during selection of the excitation forces is carried out by the Lissajous figures (plane $F, \dot{y}$) and/or a beam of vectors $\boldsymbol{y}_k$ on the plane $(\mathrm{Re}\, y, \mathrm{Im}\, y)$. In the first case, the ellipse on the screen straightens into a line when approaching the resonance; in the second case, the lines of the accelerometer signal vectors rotate and approach vertical axis $\mathrm{Im}\, y$.

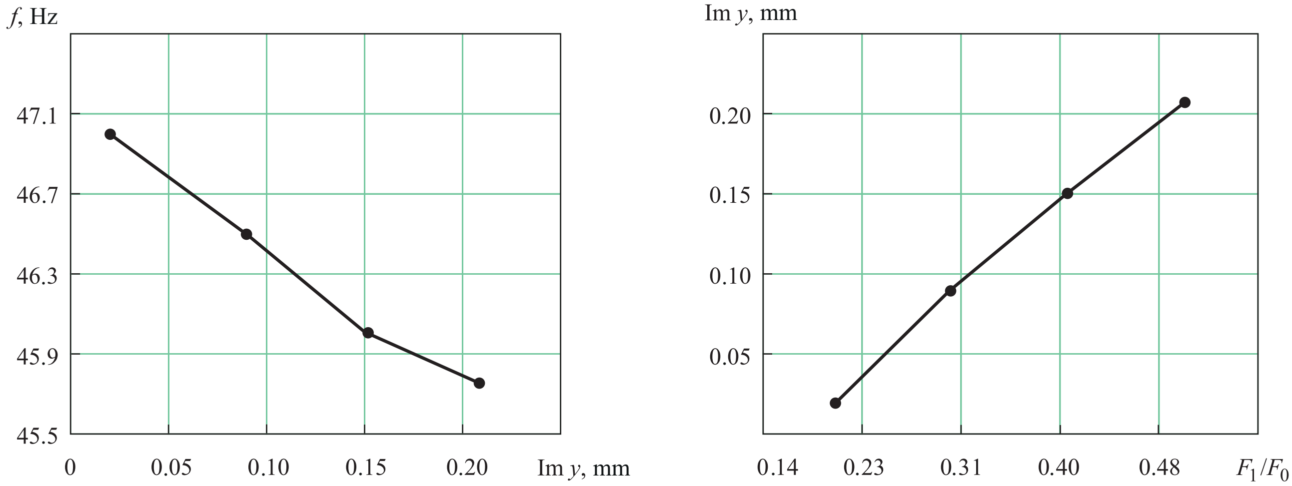
Animation of oscillation modes in real time also plays an important role: this helps to understand the behaviour of the structure and enables to control of proper operation of the measurement and excitation system.

In some cases, measurements of the third stage are carried out on-line using an automatic resonance search program.

Having completed selection of forces, measurement of the resonance curves (with the constant magnitude of the excitation forces) are made in such a neighbourhood of the frequency that includes the oscillation amplitudes $y_{max} / \sqrt{2}$.



a



b

Fig. 2. Non-linear dependences for body:
a – resonance curves at different excitation levels for F_1/F_0 equal to 0.2 (▲▲▲), 0.3 (●●●), 0.4 (■■■) and 0.5 (●●●);
b – dependence of resonance frequency on amplitude and dependence of amplitude on force

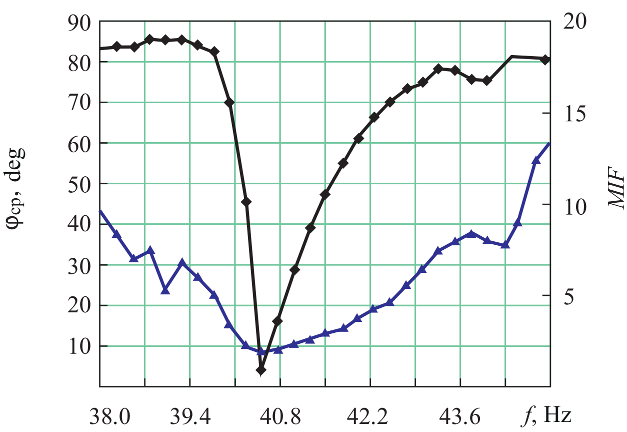


Fig. 3. Frequency dependences φ_{av} (◆◆◆) and *MIF* (▲▲▲)

Therefore, the data required for automatic determination of the decrement and the reduced mass by the energy method are recorded. At least 6–8 points are used for both characteristics. These points approximate the work or power of the generalized forces, depending on the frequency. Check measurements of the reduced weight are carried out by mechanical loading.

The eigenmode is observed and recorded according to the signals from all sensors (generally, 10–30 accelerometers are required to determine it) on the resonance frequency. After processing, it is represented either by deflection lines or nodal

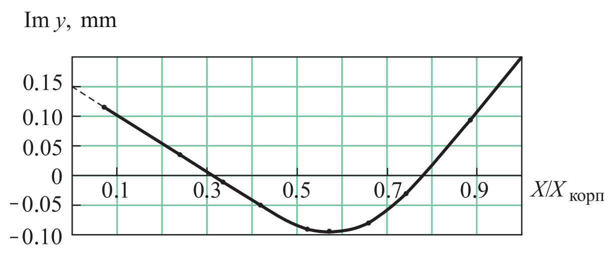


Fig. 4. Normal shape of the body first bending mode

lines and corresponding diagrams. Fig. 4 shows the body bending mode, and the coordinates of the reference points of dimension X are referred here to its length $X_{корп}$.

The transient process is recorded at the end of the third stage. It represents an oscillogram of damped oscillations at the reference point after switching off the excitation forces on the resonance frequency.

On-line processing and analysis of data related to the fourth stage are carried out after each series of measurements. The completeness of the measured values is analysed at this stage, and, if necessary, the test program is corrected.

The fifth stage, the last one, involves control measurements of the excitation device characteristics and measurements upon completion of the tests. This stage is important for comparing the condition of the entire measurement and computational complex before and after the tests, thereby also for confirmation of the results reliability.

In some cases, not all points of the resonance curve in the resonance neighbourhood can be measured due to a spike in the amplitude upon approaching the resonance. In this case, the natural frequency is determined approximately on the maximum amplitude.

Survey tool

Prodera multichannel equipment is used in this study. It enables carrying out sequential identification of harmonic oscillations of one mode and measurements in the neighbourhood of the natural frequency. Frequency spectra are determined additionally for harmonic and non-harmonic excitations.

The certified multichannel *Prodera* equipment includes oscillations excitation and measurement hardware controlled by special *P-WinModal* software package. This equipment provides for the following:

• controlled harmonic excitation of oscillations;

• measurement and animation of oscillations;

• data acquisition, filtration and computations;

• on-line computations and data indication during measurements;

• presentation of results in tabular and graphical forms suitable for express documents.

Fig. 5 shows the experiment block diagram.

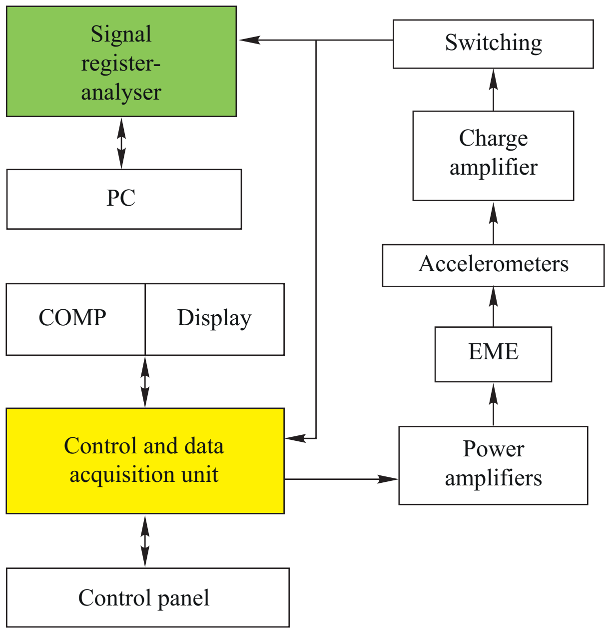


Fig. 5. The block diagram of the experiment: EME – an electromechanical oscillation exciter

The excitation system contains the following:

• a controlled precision (harmonic or pulse) voltage source with digital-to-analogue converter (DAC) modules, where the phase shifts of the output voltages are 0, π, and the voltage levels, ranges and frequency sweep velocity, as well as delays for the oscillations stabilisation time are input based on the software means;

• power amplifiers or current generators (modal) that convert the DAC output voltages into the proportional exciter current;

• electromechanical exciters (modal), in which the force applied to their moving system is proportional to the current and does not depend on the frequency and oscillations of the excitation point within the operating frequencies (up to 300 Hz) and displacements (up to 40 mm), to excite the body oscillations by 200–1000 N, or by 10–50 N for controls;

• initial settings for the automated excitation program, set by the operator using the keyboard in the dialogue mode.

The measurement system includes the following:

• sensors, which are piezoelectric accelerometers and piezo-transducers of force (with the standard total number of channels of 64 and more);

• preamplifiers, the voltages of which are fed to the inputs of the analogue-to-digital converter with high-speed signals switching.

Special software *P-WinModal* can be for clarity divided into three parts, intended for tests preparation, measurements and on-line data processing.

The first part is an interface for filling out the experimental conditions (date, time, aircraft, equipment included, measurement channel), the type of the measured characteristics (resonance dependence, eigenmode, etc.), coordinates of excitation and measurement points, data on exciters (type, number, calibration, orientation) and the same data for sensors. The software channels for excitation and measurement are created in other windows.

Following the preparation stage, the measurement window is filled in, mainly with a set of frequency interval boundaries and options for their application (frequency step, the number of oscillations stabilisation periods and their measurements) with indication of the measurement time, interval number and transmission ratio; besides, the excitation levels are set.

The second part controls the measurements with indication of the current results in tabular and graphical forms and enables to adjust the excitation level, the frequency or amplitude increment value, the number of averaging periods. The instantaneous voltage values $u\cos(pt+\varphi)$ of each sensor are converted using the excitation reference signals $1\cos(pt)$ and $1\sin(pt)$ to obtain the values of component $\mathrm{Re}\,u$ co-phased with excitation and quadrature component $\mathrm{Im}\,u$ (displaced by $\pi / 2$):

$$\mathrm{Re}\,u = \frac{2}{nT}\int_0^{nT} u\cos(pt+\varphi)\cos(pt)\mathrm{d}t,$$

$$\mathrm{Im}\,u = \frac{2}{nT}\int_0^{nT} u\cos(pt+\varphi)\sin(pt)\mathrm{d}t, \qquad (7)$$

where n – number of averaging periods;

T – current measured period.

Further, these values are used to calculate displacement components $\mathrm{Re}\,y$ and $\mathrm{Im}\,y$ or moduli and phase shifts [3, 5] (Fig. 6).

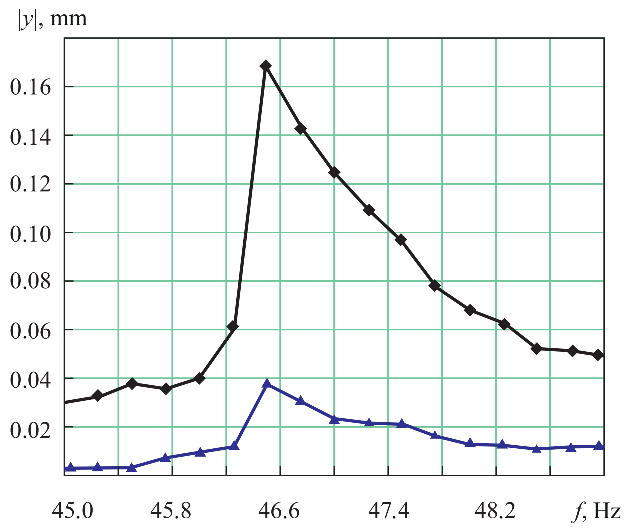


Fig. 6. Amplitude-frequency response of the body oscillations in Oxy (◆◆◆) and Oxz (▲▲▲) planes

At the same time, one can observe the Lissajous figures on a separate screen, as well as vectors of all sensors in coordinates $\mathrm{Re}\,y$ and $\mathrm{Im}\,y$, and, in addition to this, animation of the eigenmodes.

The third part is on-line display of the results immediately after the measurement completion; the results are displayed in the form of tables and graphs with the necessary comment enabling to print them.

Analysis of the results

Resonance tests with multichannel *Prodera* equipment are performed primarily with harmonic multipoint excitation of the body and surface oscillations. The excitation control is exercised in the software with setting the frequency variation limits, oscillations stabilisation time and the number of averaging periods. Limits for the maximum phase shift of the oscillation acceleration signals are set in the automatic resonance search mode. Measurements are made by means of piezoelectric accelerometers, their transmission ratios and filter frequencies are changed remotely, the signals and their phase shifts are observed on the Lissajous figures, vector components and animated eigenmodes. The results are presented in a tabular form by the pairs of components from the first harmonic of the sensor signals. The experiment controls, data acquisition and on-line processing are supplemented by specially developed *P-WinModal* software.

Conclusion

Multichannel *Prodera* equipment was tested during the study and used to develop the experimental procedure. The equipment ensures successful modal testing of the specified UAVs.

Application of the developed technique enabled to speed up the testing, which is essential for preparation of documents permitting the beginning of flight tests. The test results are included in the complex of computational and experimental surveys of the UAV safety during flight.

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Наземные резонансные испытания беспилотного летательного аппарата с применением многоканального оборудования

Разработана расчетно-экспериментальная методика определения модальных характеристик с использованием специального оборудования *Prodera* для рассматриваемого класса беспилотных летательных аппаратов. Проведен анализ функционирования специального программного обеспечения и оборудования *Prodera*, созданного по алгоритмам Французского национального центра аэрокосмических исследований, *ONERA*. Апробация методики на реальных примерах обеспечивает получение данных для расчетов по предотвращению опасных автоколебаний в полете с учетом особенностей рассматриваемых беспилотных летательных аппаратов.

Ключевые слова: резонансные испытания, упругий беспилотный летательный аппарат, модальные характеристики, многоканальное оборудование *Prodera*.

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