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Development of Computational and Experimental Methods for Determining Dynamic Characteristics of Aircraft Landing Gear

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Abstract
Experimental methods for determining dynamic characteristics of landing gears are considered. The main dynamic characteristics of landing gears are resonant frequencies, damping coefficients and resonant oscillation shapes.
• Features of ground vibration testing for landing gears
• Methods for determining main normal modes
• Processing algorithms
• Application of impact method
• Influence of hydraulic rams on landing gear dynamic characteristic

1. Introduction

The methodology of aircraft shimmy of wheels research is based on calculation research and experimental methods for determining dynamic characteristics of landing gears. Numerical research of wheels shimmy is the main method of analysis at all stages of creating an aircraft. However, to obtain reliable shimmy characteristics, determining parameters of mathematical models must be identified from experimental data. Such data are the experimental dynamic characteristics of landing gears — resonant frequencies, damping coefficients and resonant vibration shapes. Experimental methods for determining dynamic characteristics are: vibration tests, laboratory tests and aerodrome tests. Currently most reliable method for determining dynamic characteristics of landing gears is ground vibration testing of landing gears. Ground vibration tests(GVT) of landing gears (LG) of airplanes consist of vibration excitations of a structure and measuring its response at various levels of exciting forces and loads from weight of aircraft.

Obtaining data for correction of mathematical models of shimmy is the main purpose of LG GVT. In addition, when conducting GVT of nose landing gear, influence of operation of nose landing gear wheels control system on characteristics obtained is investigated, backlashes and structural defects can be detected, and quality of assembly is checked. The figure 1 shows location of landing gears GVT in entire structure of establishing safety of the aircraft from shimmy.

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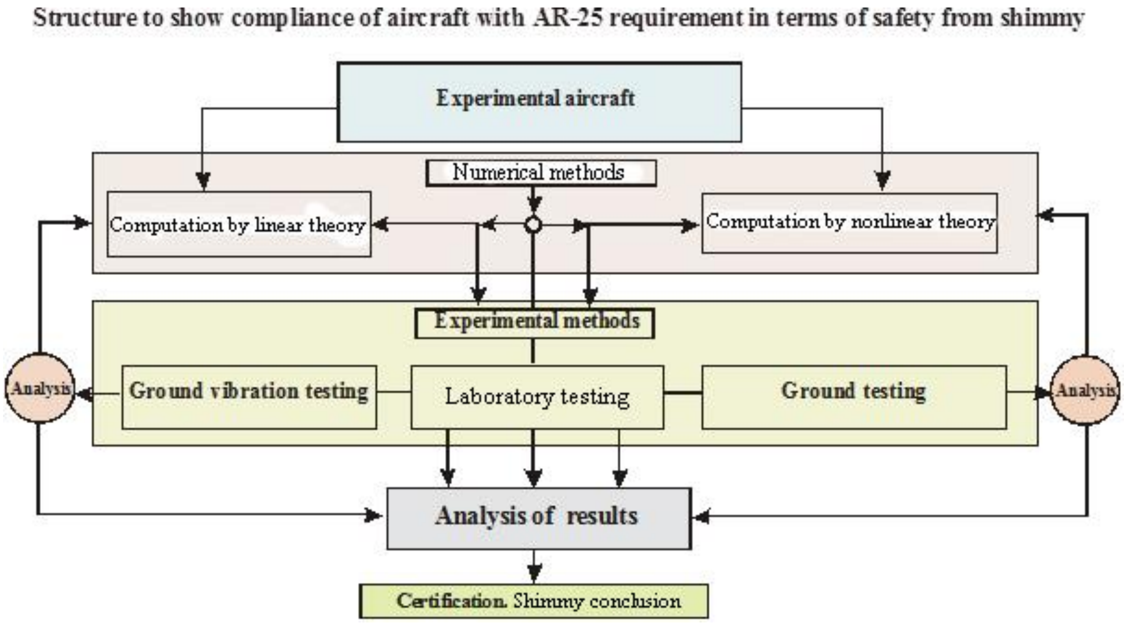

Figure 1: Structure of the research methodology of the wheels shimmy of aircraft landing gear.

2. Features of GVT of LG

Landing gears are a complex spatial structurally variable substantially nonlinear dynamical system. As a result, landing gears are investigated under various vertical loads on support (travel of the damper rod). In this case, dynamic characteristics can vary significantly. In some cases, mode shapes of LG can be changed in principle.

A landing gear is a highly damped non-linear system. The main non-linearities appear due to backlashes in the joints, dry friction in the sealing cuffs, non-linearities in the control system module and in tire. During GVT characteristics of at least 3 lower modes of landing gear vibrations are investigated. The test procedure for landing gears GVT is similar to the GVT procedure for a whole aircraft. However, it has a number of significant distinctive features:

- the need to measure vibrations of landing gear in three mutually perpendicular planes;
- measurement of frequency response functions and determination of resonance characteristics should be carried out at different operating modes of wheel control system (in the “control” and “free orientation” modes);
- measurement of frequency response functions and determination of resonance characteristics should be carried out at different levels of vibration excitation to research non-linear dependencies in the design of supports.

The above features of LG GVT significantly complicate research. Thus algorithms for the operational processing of experimental results play a large role.

3. Methods of carrying out LG GVT

LG GVT are carry out on a fully assembled aircraft with a prepared wheel steering control system. Aircraft must be operated from external sources of pressure in the hydraulic system and power supply.

Before starting the tests and at the end, level of shock absorbers and the pressure in the tires of wheels are checked.

In the process of testing an aircraft is installed on the standard hydraulic rams which are used to establish a required compression of a shock absorber rod. LG is mounted on a set of wooden shields with the help of which the alignment of wheels axis with the rods of electrodynamic exciters is achieved. Between tires and wooden shields enclosed sheets of drawing paper, designed to produce prints of tire contact spots with the supporting surface. The weight force of vibration exciters is transmitted to landing gear using special elastic rods that connect exciter with the axis of wheels. Exciters are set on special loaded carriages. A general view of LG GVT with measurement of tire contact spots with a supporting surface is presented in figure 2.

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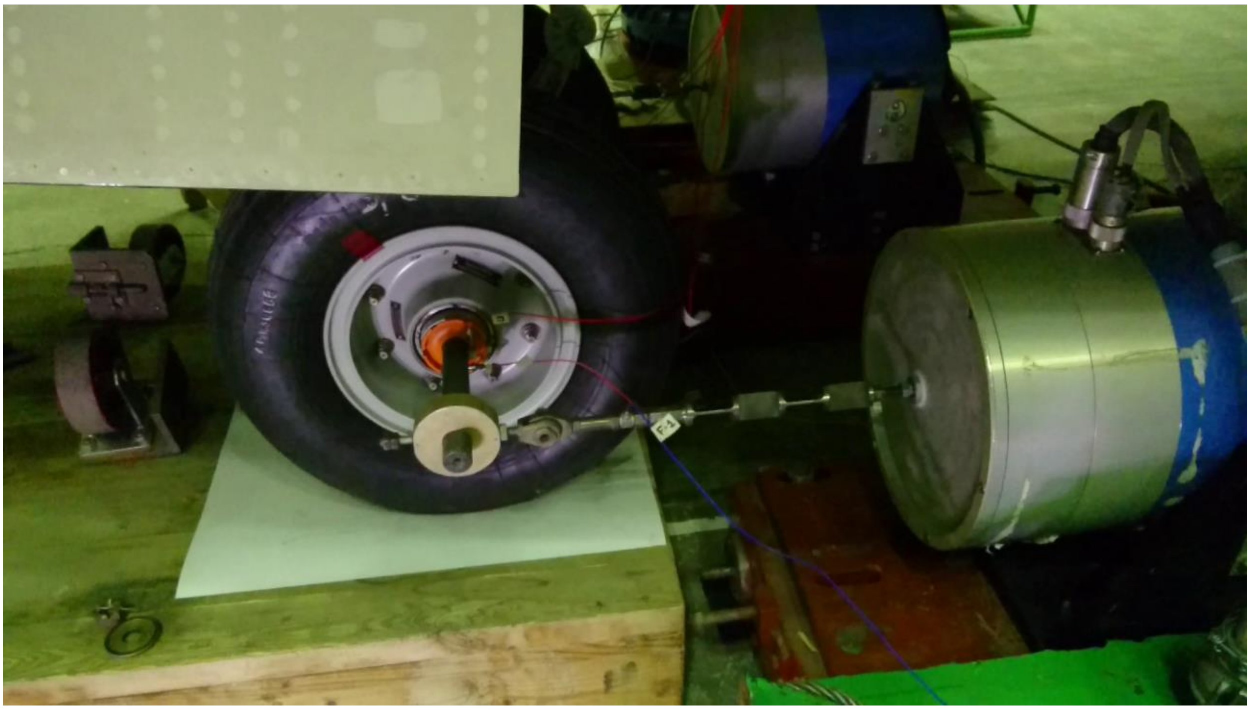

Figure 2: LG GVT as a part of an aircraft. Measurement of tire contact spots during tests.

4. Contact spots

In order to control loading conditions of supports, when carrying out LG GVT with the aid of paper sheets, imprints of tire contact spots with the supporting surface are obtained, their geometrical parameters are determined. The results of the pattern processing of spots make it possible to establish a connection between the response of a shock absorber rod and the given amortization characteristics. An example of tire contact spots of nose landing gear is shown in figure 3.

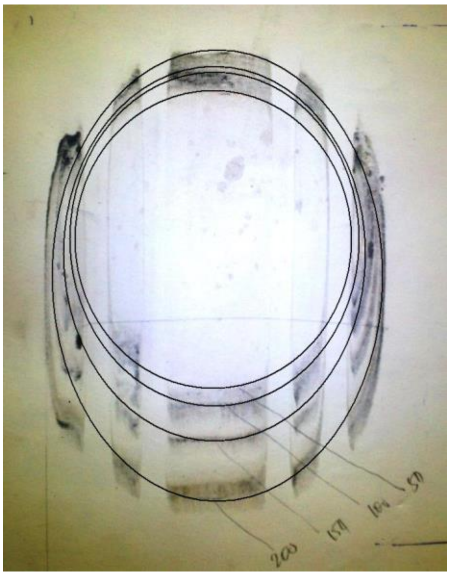

Figure 3: Tire contact spot

5. Excitation and measurement of vibration

Characteristics of at least 3 lower modes of vibration of landing gears are researches during GVT. For a symmetrical rack these are:

• lateral bending vibrations;
• longitudinal bending vibrations;

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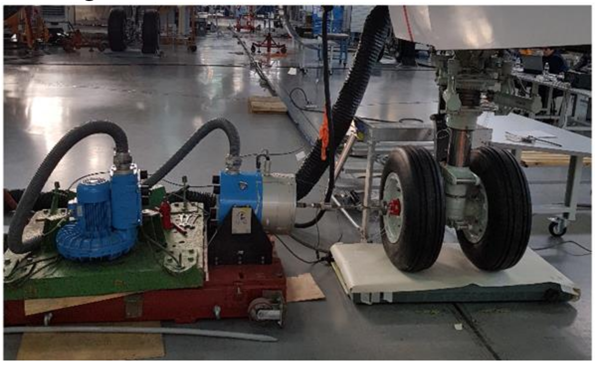
• torsional vibrations around the vertical axis.

To obtain frequency characteristics of the structure, excitation method with a sinusoidal signal with step-by-step frequency changes is used.

Vibrations are excited by electrodynamic exciters, which are set perpendicular to the axis of movement of the aircraft (figure 4a) for mode of lateral bending vibrations or along the axis of movement of the aircraft (figure 4b) to research longitudinal and torsional modes.


a)

b)

Figure 4: Location of exciters with lateral or longitudinal excitation of NLG in composition of aircraft.

In cases of asymmetric LG strut to obtain mode of the vertical bending of wheel axis relative to axis of the strut, exciter is mounted in a vertical plane (figure 5).

Figure 5: Vertical excitation of an asymmetrical landing gear.

Vibration measurements are carried out using piezoelectric accelerometers mounted on test landing gears. Testing experience has shown that it is enough to install 2 accelerometers in the longitudinal and vertical planes on wheels axes and 1 accelerometer in the lateral direction. In sections of the fixed part of a strut, 2 sensors are installed in the lateral direction and 1 in the longitudinal direction. Such arrangement allows to determine vibration mode during recording of responses. Sensors to determine backlashes in the hinge nodes of an LG are also always installed - as close as possible to strut and fuselage. Sensors on the fuselage or on the wing are installed in order to identify and evaluate the effect of aircraft modes in frequency range under research. In figures 6 and 7 the layouts of accelerometers used in LG GVT of a passenger aircraft are shown.

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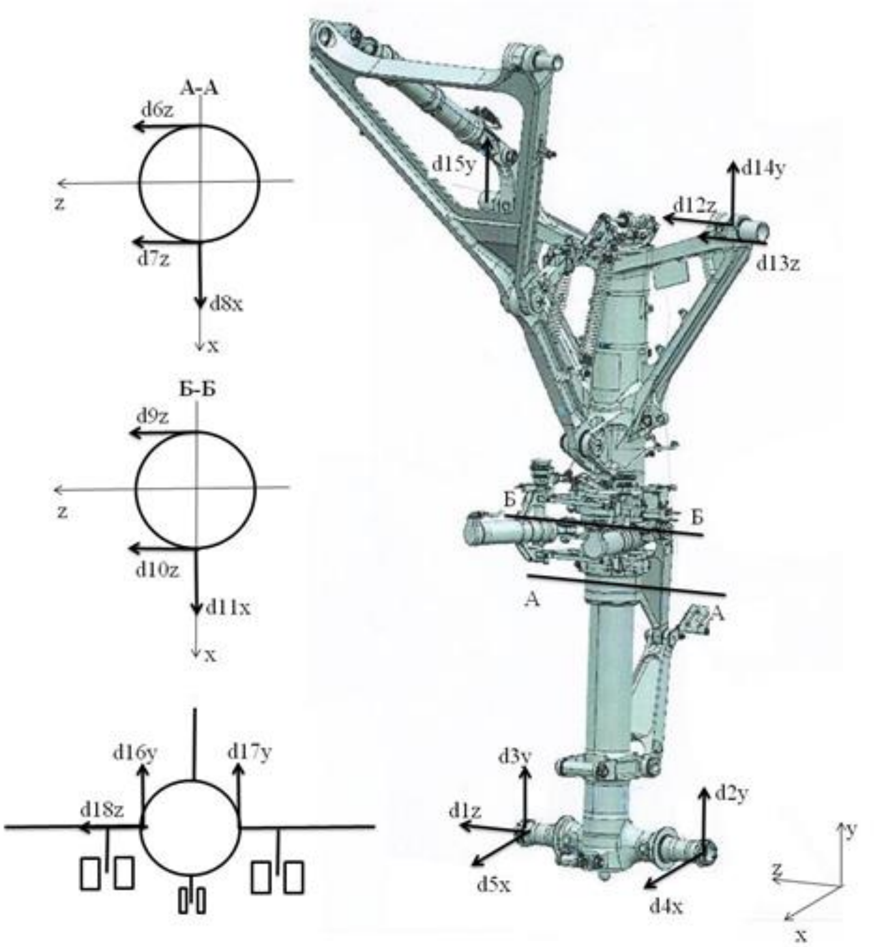

Figure 6: An example of accelerometers layout on nose landing gear.

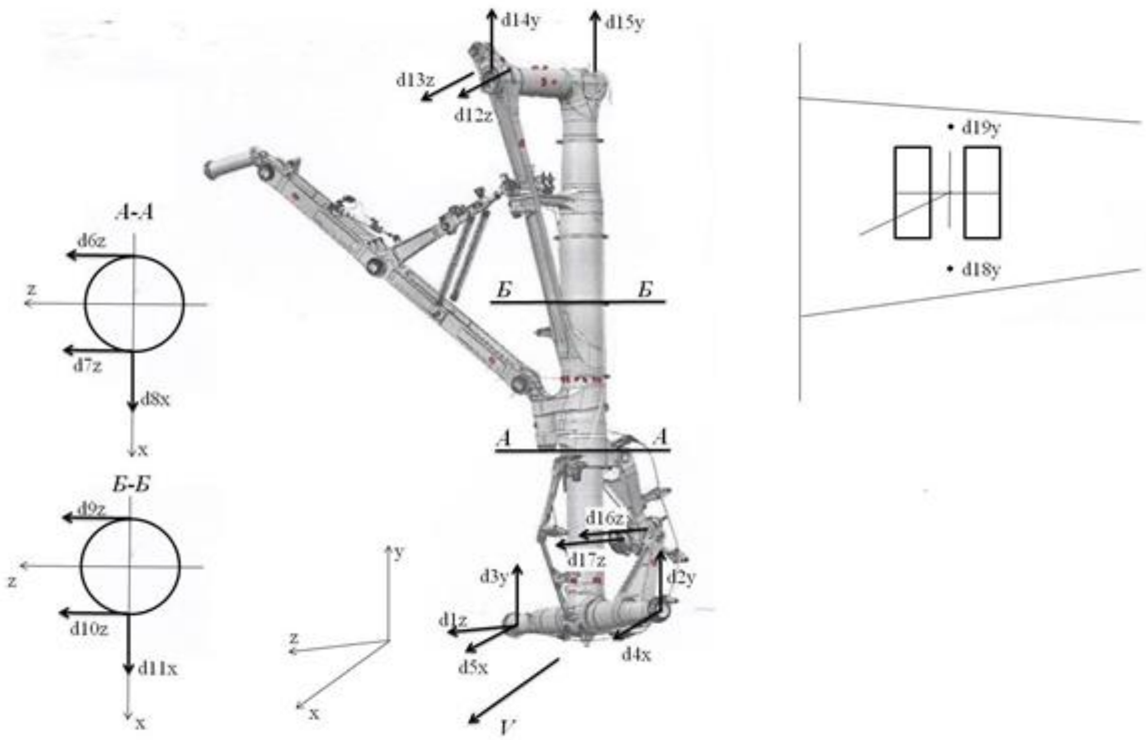

Figure 7: An example of accelerometers layout on main landing gear.

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6. Methods of processing experimental data

The primary data obtained while measuring are frequency response functions (FRF) of overloads and force sensors data readings. As accelerations are not of a particular interest and are transformed into displacements through double integration, work at the initial stage is carried out with displacements. In the process of obtaining FRF of structure using sensors located on axes of wheels, it is possible to estimate modes and amplitudes of vibrations. Also there is a possibility of increasing a force level without a damage risk of a structure or the excitation system.

It is worth noticing that excitation system of LG is an interaction of moving masses of exciters, their carriages and LG themselves. The inertia of these masses can significantly affect resulting dynamic characteristics. Sensor responses measured at GVT determine characteristics not only strut itself but of the entire system. In order to eliminate the influence of excitation system, transfer functions are applied.

Resonance characteristics of oscillations processing is carried out using functions of dynamic compliance and functions of dynamic stiffness. At the first stage, a method of processing using functions of dynamic compliance, which are the ratios of response functions of structure at characteristic points (z_i, y_i x_i) to the force acting on the structure (F_x, F_y, F_z), is used. Since in some cases 2 exciters and, respectively, 2 force sensors are used, the sum of forces for bending vibrations or the total force moment for torsional vibrations is taken as acting on the structure. To determine resonant frequencies various transfer functions are used:

$D_z = z_i / F_z$, where $F_z = F_{z1} + F_{z2}$ – for lateral bending vibrations;

$D_x = x_i / F_x$, where $F_x = F_{x1} + F_{x2}$ – for longitudinal bending vibrations;

$D_\theta = \theta / M_y$, where $M_y = F_{x1} \cdot l_1 + F_{x2} \cdot l_2$, $tg\theta = (d_4 - d_5)/ l$ – for torsional vibrations;

On the determining mode function, a frequency range close to resonance is distinguished at which the determining function is approximated by a polynomial (a frequency range is selected where the accuracy of the approximation $R^2 > 0.98$, usually 0.25-1 Hz). Using obtained approximation, the phase resonance method ($\mathrm{Re}\, D_\mathrm{i} = 0$) is used to determine the resonance frequency with a given accuracy and the damping coefficient using the following formula:

$$\nu = 2\pi \frac{\mathrm{Im}(di / F)}{f_{рез} \times k} \tag{1}$$

where the value of k is calculated as the value of derivative of a real part of the polynomial at the resonant frequency. The degree of mode purity is also calculated for sensors located on wheel axle:

$$tg\varphi = \frac{\sum \left| \mathrm{Re} d_\mathrm{i}(fr) \right|}{\sum \left| \mathrm{Im} d_\mathrm{i}(fr) \right|} \tag{2}$$

7. Representation of shapes

Along with determination of resonant frequencies modes shapes are also determined during operational processing in order to identify vibration modes of interest. The representation of mode shapes in the form of histograms (figure 8a) is used. Numerical values of imaginary parts of dynamic compliance functions normalized to the value of mode determining sensor are deposited on the plane of histogram. This way of shapes representation of structure vibrations is the most informative for LG GVT. Also, shapes can be represented as elastic lines (figure 8b) or in isometric view (figure 8c). But due to peculiarities and low self-descriptiveness of GVT these representations are rarely used when it is necessary to determine the principled behavior of complex geometric structures.

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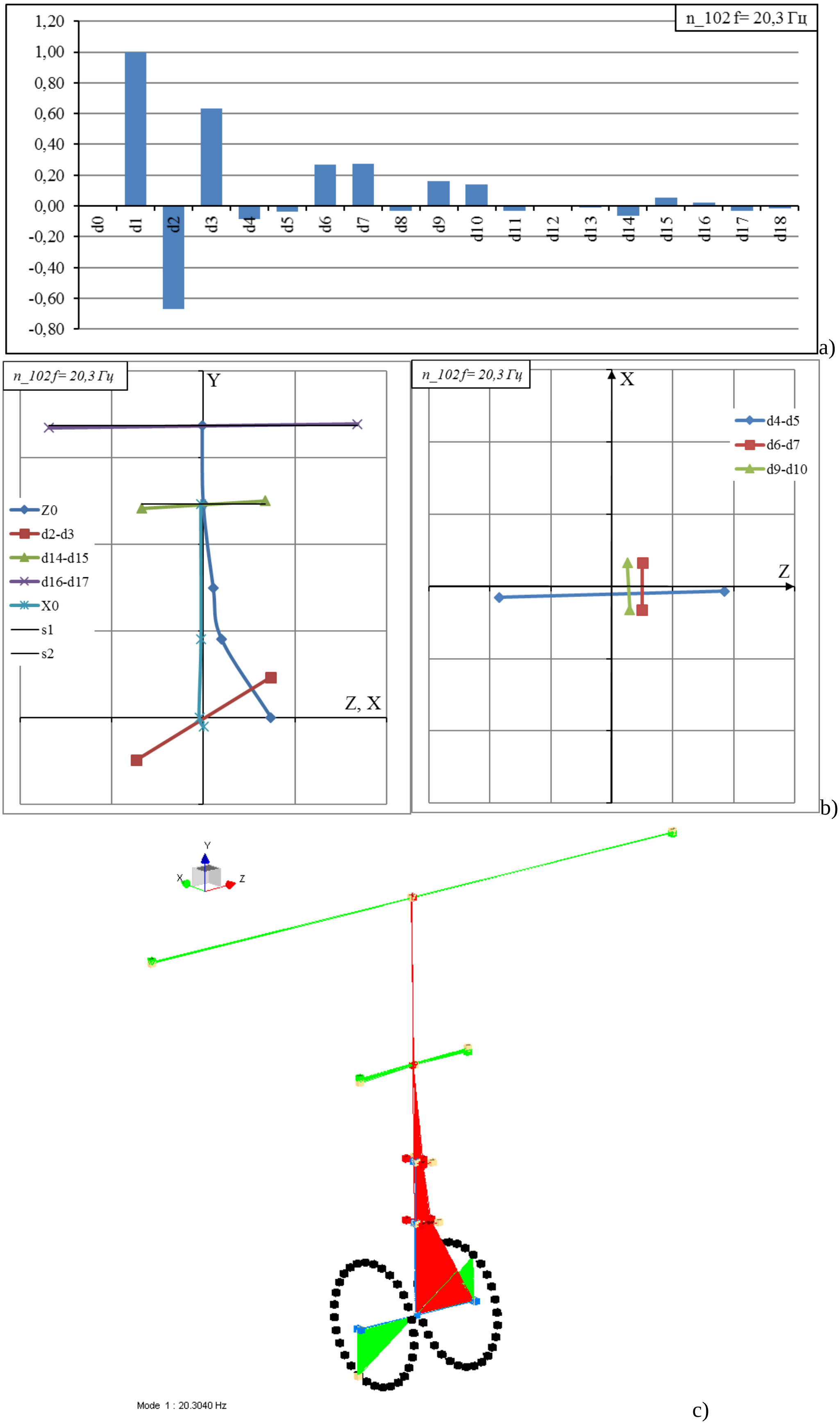

Figure 8: Representation of mode shapes.

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8. Method of processing experimental data using dynamic stiffness functions

Along with the method of processing dynamic compliance functions, for a more detailed research functions of dynamic stiffness are used:

$$D_z = \frac{F_z(j\omega)}{Z(j\omega)},\ j = \sqrt{-1} \tag{3}$$

$$D_\theta(j\omega) = \frac{M_y(j\omega)}{\theta(j\omega)} \tag{4}$$

$$D_{z\theta} = \frac{F_z(j\omega)}{\theta(j\omega)} \tag{5}$$

$$D_{\theta z} = \frac{M_y(j\omega)}{Z(j\omega)} \tag{6}$$

D_z, D_θ, $D_{z\theta}$, $D_{\theta z}$ – dynamic stiffness for bending, torsional vibrations and cross-functions. With these functions, it is possible to obtain effective stiffness and effective damping:

$$C_{ef}^{z} = \mathrm{Re}(F_z / Z) + m \cdot (2\pi f)^2 \tag{7}$$

$$C_{ef}^{\theta} = \mathrm{Re}(M_y / \theta) + I_y \cdot (2\pi f)^2 \tag{8}$$

$$C_{ef}^{z\theta} = \mathrm{Re}(F_z / \theta) + I_{xy} \cdot (2\pi f)^2 \tag{9}$$

$$C_{ef}^{\theta z} = \mathrm{Re}(M_y / Z) + I_{xy} \cdot (2\pi f)^2 \tag{10}$$

$$h^{ef} = \frac{\mathrm{Im}(D)}{\omega} \tag{11}$$

, where the moments of inertia are defined as:

$$I = -\frac{d\,\mathrm{Re}(D)/d\omega}{2\omega} \tag{12}$$

Effective stiffness, damping and moments of inertia of landing gears are parameters directly included in the shimmy equations.

9. Application of impact method

The method of impulse action on a structure is an effective and widespread method of quickly obtaining resonance frequencies and mode shapes. Commonly it is used in GVT of linear structures, but currently it is successfully applied in GVT research of nose landing gear of a transport aircraft. In order to quick obtain of preliminary characteristics that allow identify the lowest modes of vibrations and picking out frequency ranges for detailed research, resonance frequencies and vibration shapes of both free and loaded support were obtained. For this purpose, a special hammer equipped with a force sensor is used. Impulses were hit at characteristic points of structure, most suitable for excitation of particular modes of vibrations:
- Along wheels axis - to excite lateral bending mode.
- In longitudinal direction of one of tires - to excite modes of longitudinal bending vibrations and torsional vibrations.

For each of selected points 5 shots were applied, measurement results were averaged. Time processes were recorded at a sampling rate of fd = 1024 Hz, which made it possible to obtain amplitude spectra and functions of dynamic compliance in the range of 0–512 Hz with a frequency resolution of $\Delta f = 0.25$ Hz. The characteristics of vibrations under impulse excitation were obtained both for the free support S = 0, and for loaded support S = 72 mm. The results of determining resonant frequencies and damping coefficients by the impact method showed a satisfactory correspondence to resonant frequencies and damping coefficients obtained using harmonic excitation by the step sine.

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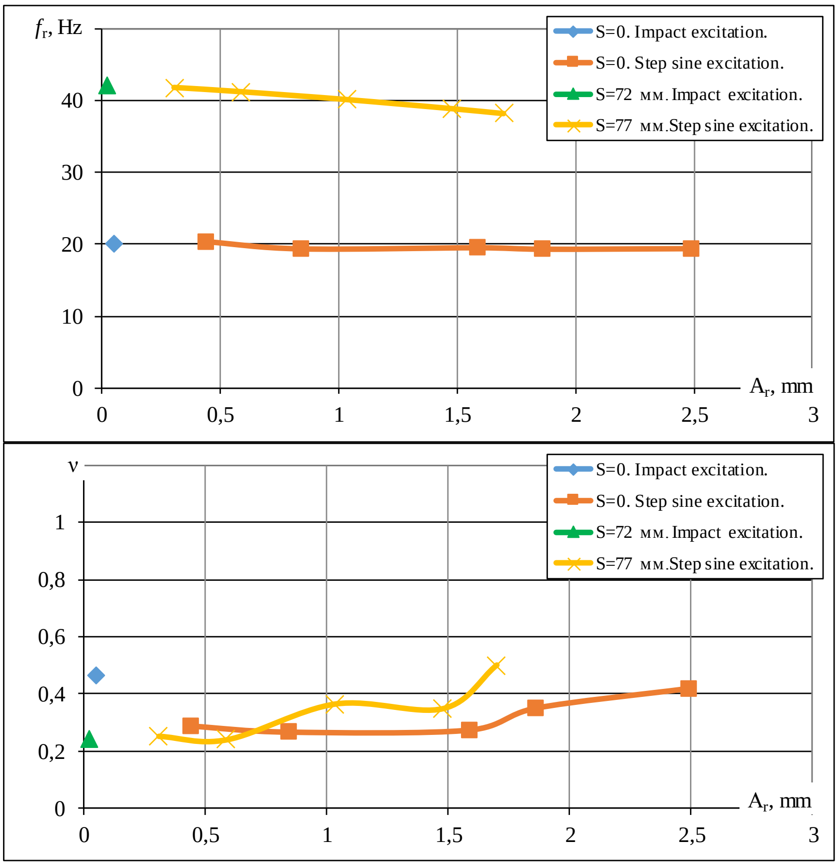

Figure 9: Comparative dependencies of resonant frequencies and damping coefficients on amplitudes at resonant frequencies with various types of excitation.

Figures 9 and 10 show the comparative dependences of the resonant frequencies f_r and damping coefficients ν on the amplitudes at resonant frequency A_r for the mode of lateral bending vibrations with various types of excitation of the structure.

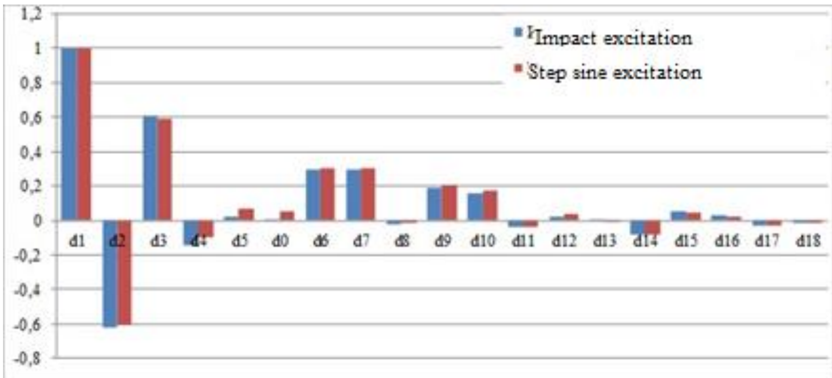

Figure 10: Shapes of lateral bending vibrations obtained with various types of excitation.

The figure 11 compares the forms of lateral bending vibrations in the form of histograms. The results show the possibility of applying the impact method for the rapid assessment of shapes, frequencies and damping factors during LG GVT.

10. Influence of hydraulic jacks on received characteristics

LG GVT are usually carried out when installing the aircraft on a regular hydraulic jacks. In order to determine the influence of the hydraulic jacks themselves on obtained characteristics, the characteristics of free landing gears of the aircraft mounted on the pneumatic supports were determined.

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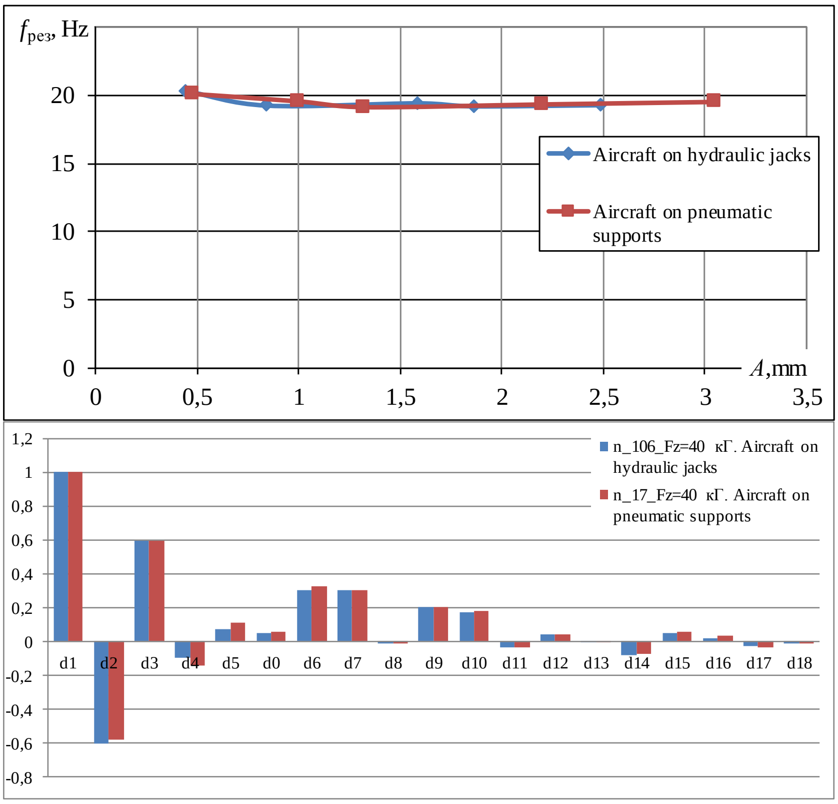

Figure 12: Dependencies of resonant frequencies and shapes when installing an airplane on hydraulic jacks and suspending on pneumatic supports.

The figure 12 shows the practical identity of the resonant frequencies and vibration shapes, which shows a slight effect of hydraulic jacks on landing gear dynamic characteristics in research lower modes of vibrations.

11. Conclusion

Experimental methods for determining dynamic characteristics of aircraft landing gear have been developed, improved and put into practice:
- Methods for determining the dynamic characteristics of landing gears, test conditions, experimental equipment, for checking initial conditions, obtaining and processing results are presented.
- Typical accelerometers arrangement schemes have been developed to determine 3 lower modes of vibration of landing gears.
- Improved phase resonance method for more accurate determination of resonant vibration frequencies and damping coefficients is shown.
- A new way for LG GVT to represent shapes is introduced into practice.
- An influence of hydraulic rams on the dynamic characteristics of landing gears is evaluated.
- The possibility of the impact method application to obtain efficient estimates of landing gear resonant characteristics and accelerate the procedure of LG GVT is considered.

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