EXPERIMENTAL METHODS OF STUDYING OF DYNAMIC CHARACTERISTICS OF AIRPLANE LANDING GEAR

A.V. Krapivko[1], V.N. Zadonskay[1], E.S. Kolyshev[1], S.E. Paryshev[1], E.A. Dubovsky[2]

[1]Central Aerohydrodynamic Institute n.a. prof. N.Ye.Zhukovsky (TsAGI),
Russia a_krapivko@tsagi.ru

[2]CJSC "SUKHOI CIVIL AIRCRAFT"
Russia E_dubovski@scac.ru

Keywords: shimmy, landing gear, dampers, resonant characteristics, ground vibration testing, development testing, ground testing.

Abstract: Some issues of forecasting airplane landing gear shimmy on the base of bench testing of a gear strut on a rotating drum, as well as airdrome tests are considered as a part of general free-of-shimmy safety considerations.

Some details of dedicated GVT techniques for landing gears and data processing algorithms to get experimental stiffness and damping of a landing gear strut used to tune mathematical models are considered.

The efficiency of the airdrome shimmy ground tests is evaluated as a means to check safety against shimmy and to assess the gear design updates. The results of evaluating the efficiency of hydraulic dampers in the torque link of a main landing gear strut are discussed, as well as fail-safe issues concerning wheels steering/control system failures.

1 INTRODUCTION

Russian domestic methodology of the research of aircraft landing gear wheels shimmy is based on the analysis and experimental methods of determining dynamic characteristics of a landing gear. Experimental techniques include: landing gears GVT, laboratory tests and ground full-scale testing of the landing gear of a prototypes aircraft (Figure 1).

Computational studies of wheels shimmy are the main method at all stages of the development of aircraft landing gear. The result of these studies is determination of important design parameters combinations that fall within the stability envelope at all the modes of wheels motion, and the comparison of this envelope with actual structural parameters values with regard to their possible in-service variation. For reliable evaluation of safety from shimmy under operating loads and ground running speeds, not only an adequate mathematical model is needed, but also the reliable methods for determining the parameters of this model. Basically, this really may be provided by mathematical models currently used in domestic practice; however the main issue is the identification of parameters of mathematical models, which in many cases are based on the use of approximate empirical formulas.

The most important characteristics necessary for generating and adjusting shimmy mathematical models are dynamic characteristics of a landing gear (resonant modes, frequencies, damping coefficients of oscillations). Computational methods for determining these characteristics due to inevitable idealization of a structure do not produce too reliable results (especially damping coefficient), so it is necessary to conduct experimental studies..

Structure to show compliance of aircraft to AR-25 requirement in terms of safety from shimmy

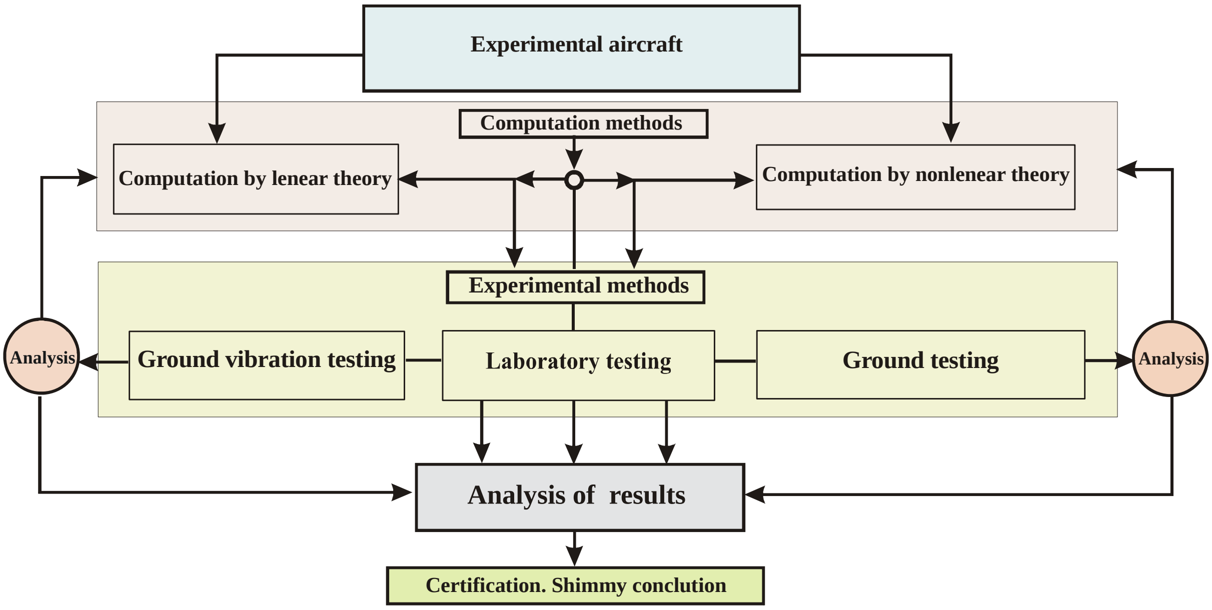

Figure 1: Structure of the research methodology shimmy of the wheels of aircraft landing gear

Below the main issues of an essential part of the methodology are reviewed: experimental methods of determination of landing gears dynamic characteristics.

2 FREQUENCY-BASED METHOD OF DETERMINING DYNAMIC CHARACTERISTICS OF A LANDING GEAR

An aircraft landing gear is a spatial, structurally variable, highly nonlinear dynamic system. The main nonlinearity in the design of the landing gear is due to the free-play in joints, dry friction in seal rings, nonlinearities in hydraulic modules of the control system and in the rubber-cord pneumatic. Nonlinearities in the main strut significantly complicate testing, processing of results and their analysis. Some nonlinear characteristics depend on the wear of structural elements of the strut in operation and make shimmy phenomenon less predictable. For example, when laboratory or ground testing are carried out to predict shimmy, their results explicitly may not indicate possible existence of dangerous oscillations. Careful analysis of shimmy characteristics is needed, which should take into account the range of nonlinear properties variation and identify the most adverse combination of design parameters and aircraft movements on the runway.

The principal method for determining dynamic characteristics of a landing gear is ground vibration testing (GVT). It is intended not only to determine dynamic (resonant) characteristics of landing gear that are necessary for correction of parameters of shimmy mathematical models. The test results make it possible to evaluate the functioning of the whole landing gear structure, including elements of the control system and the damping device, backlash size, and also, to determine properties of landing gear attachment to the fuselage, and in particular, the attachment to a movable carriage of a test bench used for shimmy drop testing on a rotating drum.

2.1 GVT Methodology

The landing gear tests are undertaken either as a full-scale aircraft testing, or as isolated tests on a test bench in lab conditions (Figure 2). In both cases this is done in two ways: a) the wheels are unloaded and do not have contact with the supporting surface, and b) the strut is loaded by airplane weight while the wheels are in contact with the supporting surface (Figure 3).

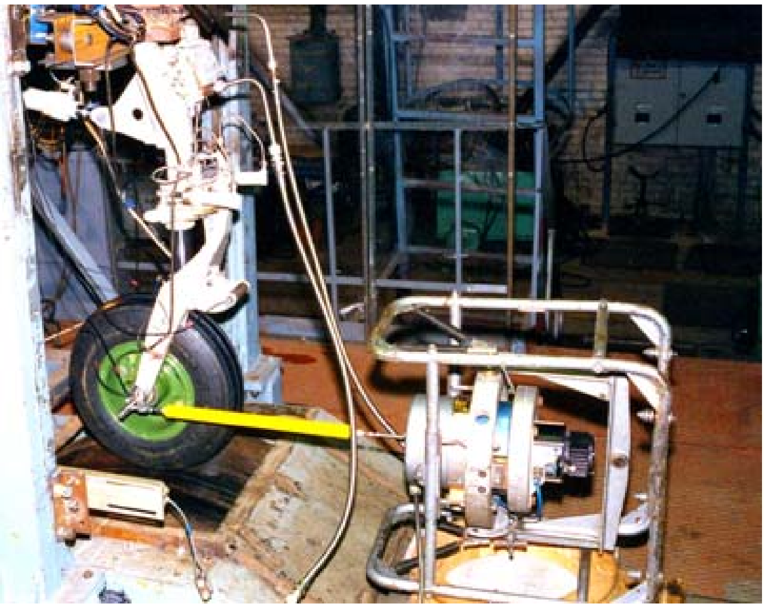

Figure 2: Ground vibration testing of NLG on a laboratory stand

Such tests, along with other ways to load the strut (for example, using air castors, Figure 4), make it possible to obtain the most reliable data on the resonant properties of the structure. When testing landing gear as a part of the aircraft, three hydraulic jacks are used. A predetermined level of compression of the strut shock-absorber rod is provided by simultaneous lowering of the plane by all three hydraulic jacks.

Figure 3: Ground vibration testing of a nose landing gear (NLG) as a part of an airplane. Measurement of tire contact spots during GVT

Figure 4: Ground vibration testing of landing gear under compression of strut with the help of air castors

The methods of testing landing gear are similar to the airframe GVT methodology, however, it has some significant differences. First, it is necessary to measure landing gear oscillations in three mutually perpendicular planes. Secondly, Frequency Response Functions (FRFs) and resonance data (resonance frequencies, mode shapes and damping coefficients) should be determined under the following conditions:

at three levels of the strut loading;
- two modes of operation of the nose wheels control system ("steering", and "free orientation")
- not less than three levels of excitation for analysis of nonlinear dependencies of landing gears.

As a result, characteristics of three lowest resonance modes for each of the above regimes should be obtained. In the process of testing it is recommended to measure geometric dimensions of the tires and tire footprints (contact spots) (Figure 3). Ground vibration testing of landing gear are conducted using electrodynamic shakers, which are mounted on special carriages with ballast weights. The shakers are equipped with individual cooling system (Figure 3). Transmission of force from shakers to the ends of the wheel axle is provided by means of special transition elements and standard rods (Figure 4). To measure the forces generated by the shakers, the standard rods must be equipped with strain gauge–based or piezoresistive force sensors.

Figure 5: Connection of the vibrator to the axis of the wheels

The electrodynamic exciters fluctuations are set:

- along the axis of rotation of the wheels and powered in opposite phase to each other to determine lateral bending vibration mode of the landing gear;
- in the direction of the longitudinal axis of the aircraft and powered in phase to determine bending vibrations mode in a vertical plane (aircraft plane of symmetry)
- in the direction of the longitudinal axis of the aircraft and powered in opposite phase to each other to determine torsional vibration mode of the landing gear about wheels vertical orientation axis.

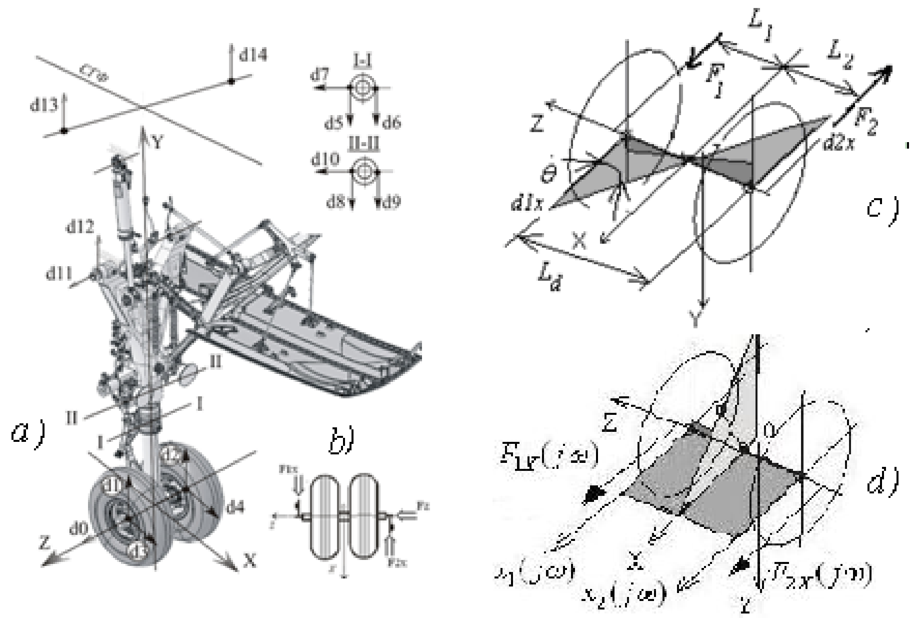

Figure 6: The scheme of arrangement of sensors and the application of force excitation

When measuring vibrations of the landing gear, it is recommended to use piezoelectric sensors (up to 20 pieces) and place them on the strut, as shown in Figure 6*a*. To estimate the effect of fuselage elasticity, at least 3 sensors should be installed to measure lateral and angular vibrations in the root attachment of the LG.

GVT of the strut is conducted under the following loading conditions:

- tires are not in contact with the supporting surface (strut not loaded);
- the travel of the shock absorber rod is ≈20% of the maximum parking compression of the rod; the tire in contact with the supporting surface;
- the travel of the shock absorber rod is equal to the parking compression of the rod;
- the travel of the shock absorber rod is ≈120% of the parking compression of the rod.

The nose landing gear test must be conducted at two modes of operation of the wheels control system: "steering" and "free orientation".

2.2 Method of determining resonant characteristics of a landing gear

The main GVT measurement results are Frequency Response Functions (FRFs) $A_i(j\omega)$ for N data acquisition channels (i=1, 2,…, N; $j=\sqrt{-1}$, ω - circular frequency of oscillation). To determine resonance characteristics (resonance frequencies, mode shapes and damping ratios), the in-phase (Re) and quadrature (Im) FRF components with respect to exciting signal are measured for accelerometers ($A_i(j\omega)$) and force sensors. As a rule, the resonant frequency is considered to be the frequency ω_r at which the in-phase component is zero ($\operatorname{Re} A_i(j\omega_r) = 0 \quad (i = 1, 2, ...)$) for a set of selected sensors (phase resonance). In practice, the resonant frequency in some cases is also determined from the conditions $max \operatorname{Im} A(j\omega)$ (amplitude resonance) or from the condition: *max ds/dω,* where *ds* is the element of the hodograph $A_i(j\omega)$ in polar coordinates (Nyquist plot). The vibration mode shapes of the landing gear are built on the basis of ratios between the quadrature components of sensor responses $A_i(j\omega)$. The in-phase component $A_i(j\omega)$ is also taken into account to characterize the pureness of each mode extraction. Generally, the pureness can be estimated through averaged phase shift φ_{av}, which is found from the relation

$$tg\varphi_{av} = \frac{\sum_{i=1}^{N} \left|\operatorname{Re} A_i(j\omega)\right|}{\sum_{i=1}^{N} \left|\operatorname{Im} A_i(j\omega)\right|} \tag{1}$$

where N – number of accelerometers.

To survey resonant mode shapes, it is convenient to represent them not only in the form of plots (Figure 7a), but for operational analysis also in the form of histogram of amplitude responses with sensors serial numbers along landing gear strut (Figure 7b).

The damping coefficient of the resonant modes of vibration of LG are presented in the form of equivalent logarithmic decrements of the linearized system and, as a rule, is determined either by the width of the resonance peak of $\operatorname{Im} A_i(j\omega)$ curve, or by the slope of $\operatorname{Re} A_i(j\omega)$ curve:

$$\nu \cong \frac{\pi \Delta\omega}{\omega_r} \quad \text{or} \quad \nu \cong \frac{2\pi \operatorname{Im} A_i(j\omega_r)}{\omega_r \, tg\varphi} \tag{2}$$

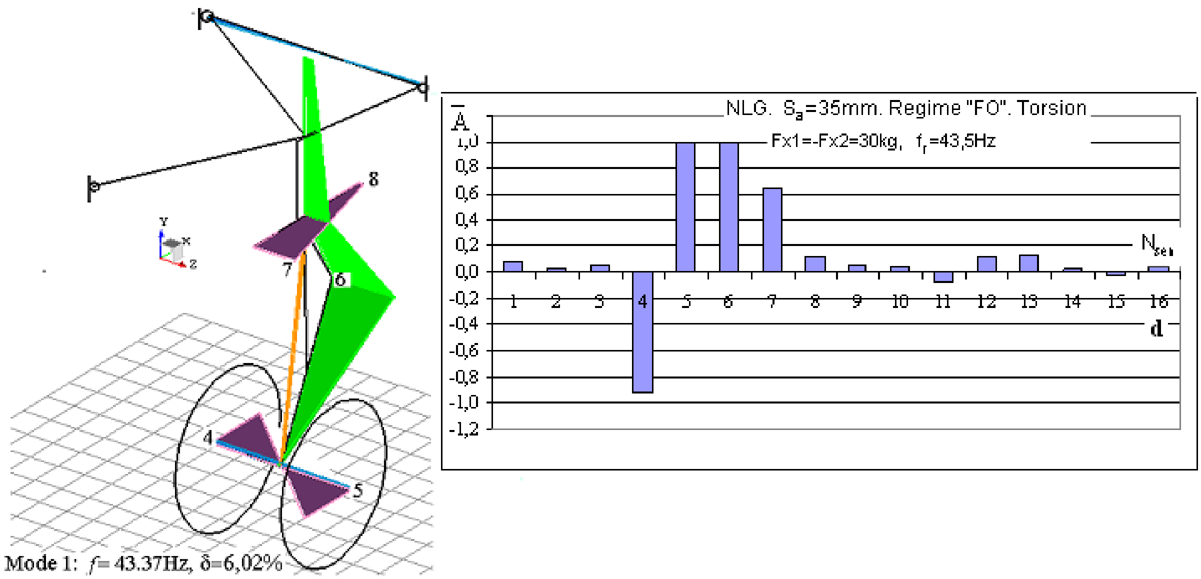

Figure 7: Plot and histogram of torsion mode of LG

where $\Delta\omega$ is the width of the resonance peak $A_i(j\omega)$ taken at the level of 0.5 from its maximum peak value; $tg\varphi$ is the angle of approximating linear function slope for $\mathrm{Re}\,A_i(j\omega)$ in the selected narrow frequency range in the vicinity of the resonant frequency ω_r.

As shown below, the use of force sensors at ground vibration testing of LG is compulsory condition for the reliable determination of resonant characteristics of a landing gear, and force signals acquisition is also necessary to determine damping and stiffness of the landing gear, which are directly included into shimmy equations.

This paper proposes a new method of processing measured FRFs to obtain resonance characteristics of landing gears. The method consists of calculating frequency-dependent dynamic stiffness (or dynamic flexibility) for the main resonance modes: torsional, lateral and longitudinal bending of the landing gear strut on the base of GVT-derived structural FRF in some representative points of the structure, particularly at the ends of the wheels axis of rotation. As an example, consider the calculation of the torsional dynamic stiffness of the strut:

$$D_\theta(j\omega) = \frac{M_y(j\omega)}{\theta(j\omega)} \tag{3}$$

Since excitation of resonance torsional oscillations of the landing gear is realized by forces F_{1x} and $-F_{2x}$ applied to the ends of wheels axis, opposite in phase to each other, in longitudinal direction (along the axis OX, figure 3. 6b,c), then FRF of the torsional moment $M_y(j\omega)$ of the strut about the vertical axis can be calculated by the formula

$$M_y(j\omega) = F_{1x}(j\omega)l_1(\omega) - F_{2x}(j\omega)l_2(\omega) \tag{4}$$

where: $F_{1x}(j\omega)$, $F_{2x}(j\omega)$ - forces FRFs; l_1 and l_2 are the distances from the points of F_{1x} and F_{2x} forces application to the equivalent centre of rotation of the wheels associated with the appropriate vibration mode shape; l_1 and l_2 are calculated as functions of ω by the formulae

$$l_1(\omega) = |d_{1x}(j\omega)| / |\theta(j\omega)|, \qquad l_2(\omega) = |d_{2x}(j\omega)| / |\theta(j\omega)| \tag{5}$$

Calculation of FRF of $\theta(j\omega)$ deflection angle of the wheels axle is made by using FRF of accelerometers located at the ends of the wheel axle at a distance l_d to measure respective amplitudes of the oscillations $d_{1x}(j\omega)$ and $d_{2x}(j\omega)$:

$$\theta(j\omega) = \frac{d_{1x}(j\omega) - d_{2x}(j\omega)}{l_d} \tag{6}$$

As an example, Figure 8 shows FRF of dynamic stiffness $D_\theta(j\omega)$, which is calculated by the formulae (3) to (6). The examination of $D_\theta(j\omega)$ shows that the resonant frequency of oscillation will be equal to the frequency of forced oscillations at which $\mathrm{Re}D_\theta(j\omega_\theta) = 0$, and for the damping coefficient (equivalent logarithmic decrement), we will have:

$$\nu_\theta \approx \frac{\pi \mathrm{Im} D_\theta(j\omega_\theta)}{J_y^0 \omega_\theta^2} \qquad (7)$$

where $J_y^{\,0}$ is the generalized moment of inertia of the landing gear for rotation, which can be taken equal to the design value.

The resonance characteristics ω_θ and ν_θ are conveniently determined by the FRF of the dynamic stiffness, the Real part of which in the vicinity of resonant frequency can be approximated by a linear function (linear trend, figure 8):

$$\mathrm{Re} D_\theta(jf) = af + b; \quad (f = \frac{\omega}{2\pi}, Hz) \qquad (8)$$

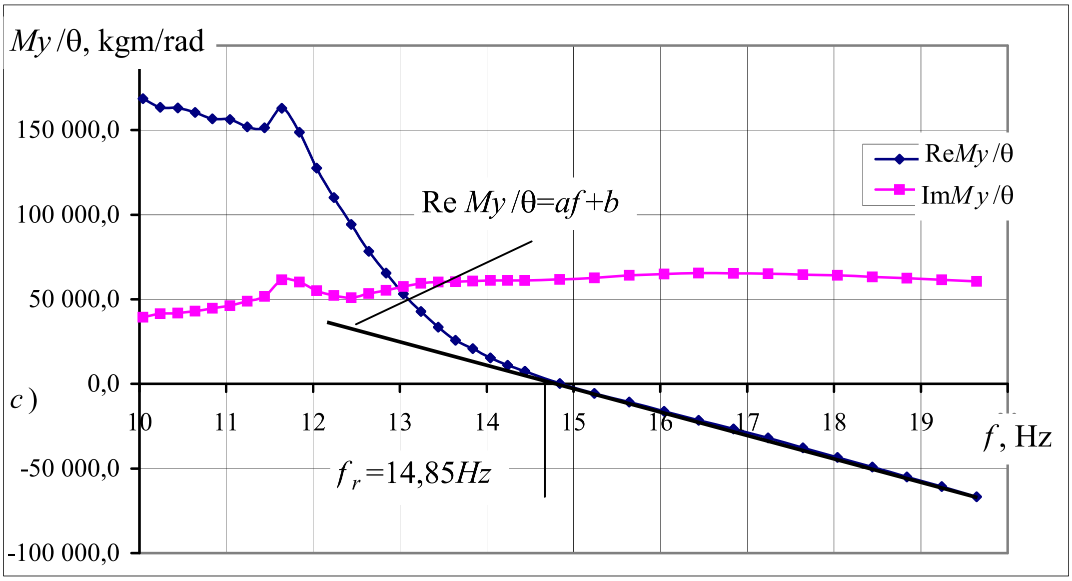

Figure 8: Determination of f_r through dynamic stiffness of LG in torsion

Then the resonant frequency and decrement of oscillations are calculated by the formulas::

$$f_\theta = -\frac{b}{a}; \qquad \nu_\theta \cong -\frac{2\pi \mathrm{Im} D_\theta(jf_{2\theta})}{b}. \qquad (9)$$

The resonant characteristics f_Z and ν_Z at the lateral oscillations of the landing gear is also proposed to be determined with the aid of FRF of landing gear dynamic stiffness (or dynamic flexibility). This characteristic is calculated on the basis of experimental FRFs of the lateral force $F_Z(j\omega)$ and of the lateral displacement $z(j\omega)$ of the wheels axle (by d_{0Z} sensor signal, Figure 6*a*). Then, obviously, the frequency $z(j\omega)$ is determined from the condition $\mathrm{Re} D_Z(j\omega_Z) = 0$, and the decrement ν_Z is determined by the formula:

$$\nu_Z \cong \frac{\pi \mathrm{Im} D_Z(j\omega_Z)}{m_z^o (2\pi\omega_Z)^2}, \qquad (10)$$

where m_z^o is the generalized mass of the landing gear that can be accepted equal to the mass of the wheels at lateral vibrations with correction for the inertial contribution of the moving parts of the strut.

Frequency f_Z, as in the previous case, is calculated from the equation of the linear approximation of the experimental dependence $\mathrm{Re}D_z(j'f) = af + b;$ in a narrow range of frequencies near the resonant frequency by the formula:

$$f_Z = -\frac{b}{a}; \qquad \nu_Z \cong -\frac{2\pi\,\mathrm{Im}D_Z(jf_Z)}{b} \tag{11}$$

The resonant characteristics f_X and ν_X of the longitudinal bending vibrations of the landing gear is also proposed to be determined according to the experimental FRF of the forces and the corresponding displacements x_1 and x_2 at the ends of the wheels axles in the longitudinal direction (Figure 6*d*). To determine f_X and ν_X, initially FRF of dynamic stiffness $D_X(jf)$ of the LG in the longitudinal direction is evaluated by the ratios

Then f_X is determined from the condition $\mathrm{Re}D_X(jf_X) = 0$, and ν_X - according to the formula::

$$\nu_X \cong \frac{\pi\,\mathrm{Im}D_X(jf_X)}{m_\delta^o(2\pi f_X)^2} \tag{13}$$

where m_x^o is the generalized mass of the LG for the longitudinal oscillations reduced to the wheels axle.

2.3 The effect of excitation system on resonance characteristics

Excitation system of LG is the interaction of moving masses of the shakers and their carriages mounted with balance weights. The inertia of these masses can have significant influence on the resonant characteristics of the tested landing gear. In this case, the structural FRFs measured during GVT will not define resonance characteristics of the landing gear, but of the “LG + excitation system". As an illustration, Figure 9 shows FRF of the displacements at selected points on the strut of landing gear, which demonstrate two phase resonances with frequencies 35,92 Hz and 39,38 Hz.

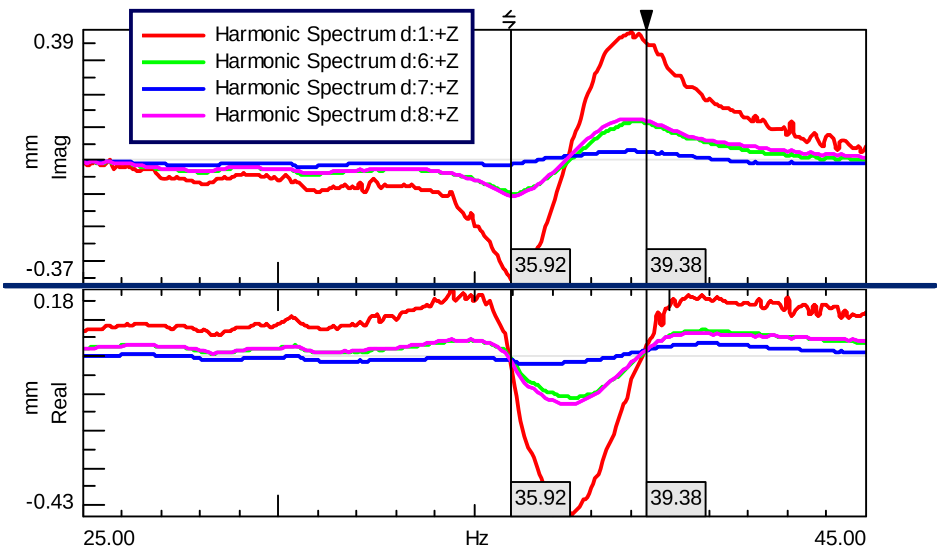

Figure 9: Amplitude-phase-frequency characteristic of lateral displacement of the axis of NLG

The corresponding resonant mode shapes of LG as shown by their examination, do not have significant differences. In order to eliminate the effect of excitation system on the resonant characteristics of LG, it is necessary to measure the FRF as a ratio of FRF of responses to FRF of the exciting force $\frac{A_i(j\omega)}{F(j\omega)}$. From Figure 10 it follows that phase resonance frequency of the lateral vibrations of LG is 37,58 Hz.

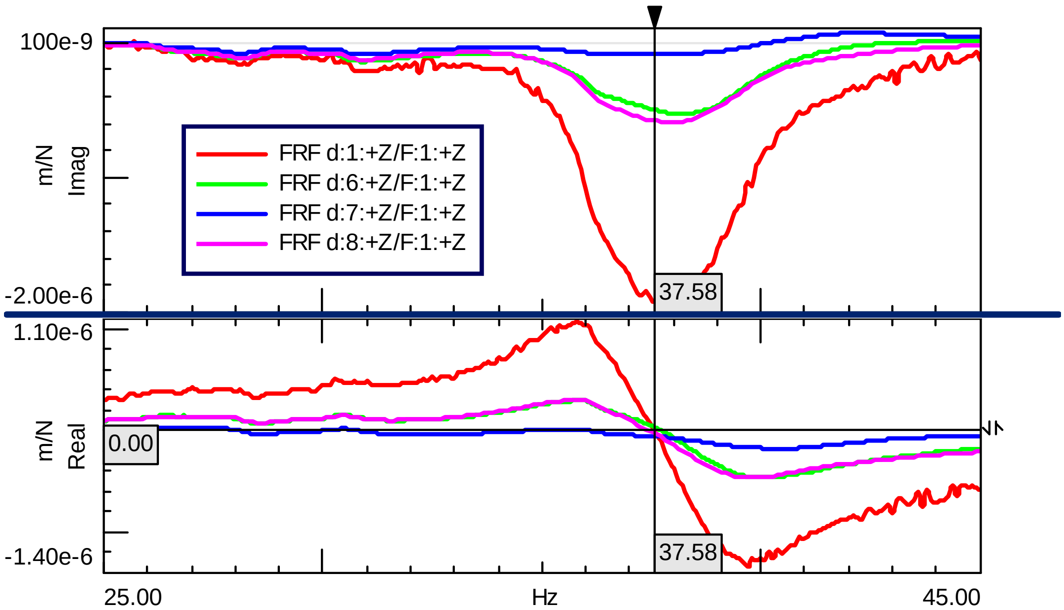

Figure 10: FRF of lateral displacement of the NLG axle

3 SHIMMY LABORATORY TESTS

Laboratory testing of landing gear wheels on shimmy are conducted in accordance with the instructions of the Russian Aviation regulations AR-25 and based on the experience of testing landing gears of domestic aircraft summarized in TsaGI's Guide for Designers. The results of laboratory tests are the constituent part of evidence-based documentation for a decision-making about the suitability of the landing gear to the operation or the need for its further development.

Laboratory testing are conducted on a dynamic testing bench with a rotating drum, which serves to simulate ground operation of an aircraft, for the purpose of:

- determination of stability safety margins at different speeds and compression of the strut shock absorber;
- determination of required parameters of shimmy dampers and other damping devices (damper orifice sizing etc.)
- evaluation of the effectiveness and reliability of wheels steering control, including the failures; improvement of the characteristics of the wheels turning valve, etc).
- determination of the optimal friction in the steering system collar;
- determination of the acceptable limits of free-play in torsion
- determination of acceptable imbalance of tires;
- development of means to increase shimmy safety margins (for example, the torsional stiffness of the strut, etc.).

Various types of LG may be subjected to the laboratory tests (Figure 11):

- with oriented wheels and with shimmy damper mounted on the strut, and without damper
- with the steering control system operating in the following modes::
    - free orientation of the wheels;
    - steering;
    - transitional
    - failure;
- not oriented wheels (main landing gear).

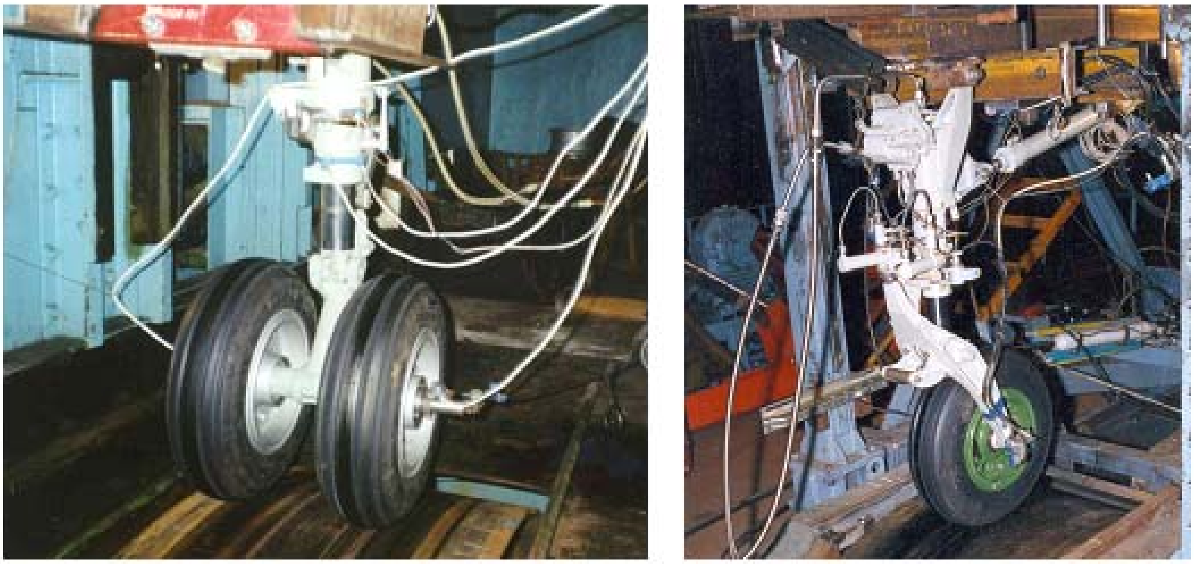

Figure 11: Laboratory tests NLG of passenger and military aircraft

The test shall be made with prototype and modified landing gears, and, by a special decision, on production gears.

3.1 Methodology of laboratory tests

The tests are carried out according to the program developed on the basis of the analysis of operating conditions of the rolling wheels and diagrams of compression of the tire and the shock absorber strut.

During the laboratory tests, shock absorbing properties of the strut and tire compression diagram are determined, geometric sizes of tires are measured and their footprints on a rotating drum are determined at a set of tire charging pressure values and values of their radial compression.

In order for the results of laboratory tests to be transferred to a full-scale airplane that make landings, takeoffs and taxiing, it is necessary to take into account the influence of the following factors:

a) conditions of landing gear attachment to the dropping carriage of the dynamic test bench and carriage dynamics;
b) curvature (radius) of the drum;
c) friction between the tires and the surface of the drum;
d) lab excitation to provoke oscillations;

The curvature of the drum affects dynamics of a rolling tire, including such factors as the cornering coefficient of the tire, the length of the relaxation area and the coefficient of tire lateral stiffness. In practice, it is considered acceptable not to take into account the curvature of the drum, if the ratio of the wheels radius to the radius of the drum does not exceed 0.3.

Before the start of laboratory testing in accordance with the test program, experimental evaluation of the conditions of landing gear root attachment on the bench is conducted either by resonance method (section 2.2) or by pulse excitation of the wheel tire with subsequent spectral analysis of the received impulse functions (Figures 12, 13). Free-plays between structure parts that fix the strut of landing gear on the bench carriage are unacceptable. The device for mounting the strut should be made taking into account the rigidity of its attachment to the aircraft. The difference in the rigidity of mount of the strut on the test bench and that on the airplane must not result in variation of wheel lateral and torsional flexibility by more than 15%. Mount of the landing gear to the carriage of the bench should also take into account the elastic vibration modes of the full-scale fuselage by means of a dummy fuselage.

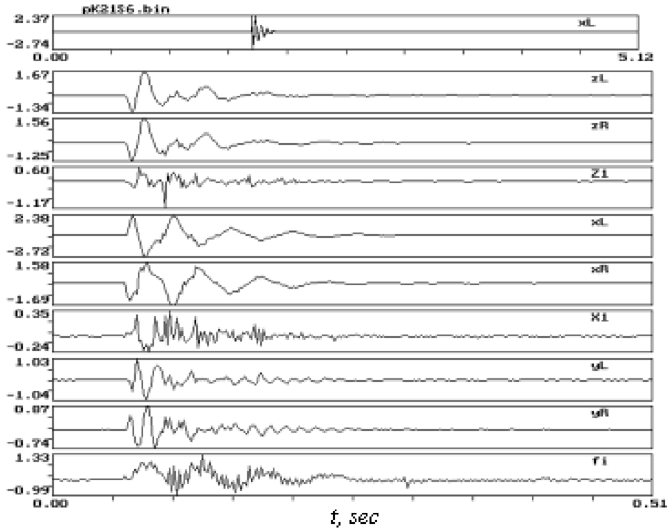

Figure 12: Pulse function of the vibrations of the wheels MLG

The accuracy of reproduction of the strut root attachment can be estimated by the ratio between the natural frequencies of bending and torsional modes of the strut with the wheel on the bench, and on the full-scale aircraft.

Test wheels on each regime is performed in the following sequence:

1. The bench drum is accelerated to a predetermined speed, the carriage of the dynamic test bench is lowered onto the abutments.
2. The mechanism of wheel deflection is activated and simultaneously sensors signals recording starts.
3. In two or three seconds after release of the wheel, the carriage with strut and the wheels is lifted over the drum.

The check whether the wheel(s) is stable from shimmy is performed at several drum rotation speed increasing by a certain increment. Minimum peripheral speed of the drum is usually taken equal to 40 km/h. Maximum speed of the wheel rolling at tests should by 20 km/h exceed maximum prescribed rolling speed in regular operation

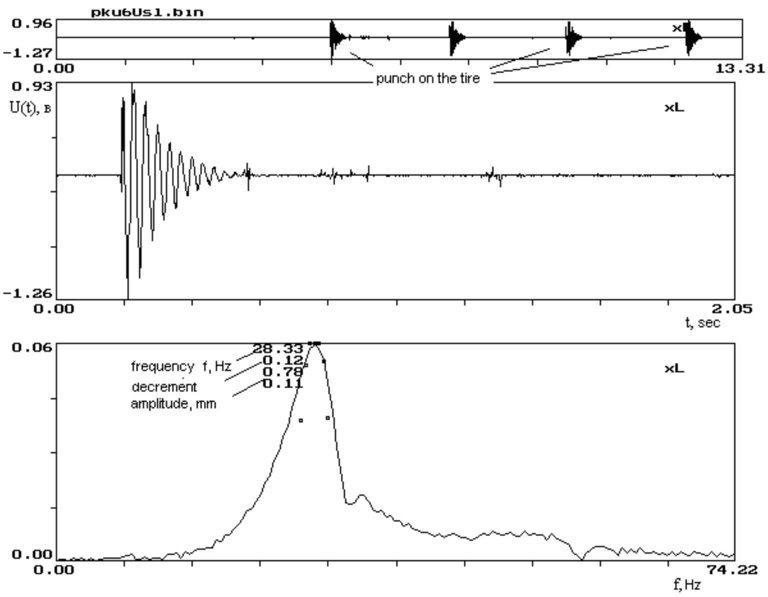

Figure 13: Spectral analysis of the impulse function

3.2 Excitation and data acquisition systems

The laboratory test bench should be equipped with the system of impulse excitation, a data acquisition system, as well as software packages for the analysis and processing of signals. To disturb the straight rolling motion, a dedicated excitation device is mounted that enables a rolling wheel on drum to be moved out from the equilibrium position, and then abruptly to be released. The initial angle of deviation of self-oriented wheels is varied during the tests from 4 to 12° to detect the conditions related to minimum damping of wheel oscillation. The initial deviation of steered and self-oriented wheels is limited by maximum permitted load on the landing gear or permitted moment that can balanced by the steering control system.

The process of perturbed motion of the wheel is being recorded by:

- one-component and 3-component piezoresistive accelerometers mounted at the ends of wheels axles and in the points manifesting the main mode shapes of the strut (Figure 11);
- strain gauges to measure strains in structural elements and angle of rotation of the sensor of the steering sleeve;
- instrumentation to measure wheels rolling speed and wheels vertical loading;
- pressure sensors in chambers of hydraulic cylinders of dampers or wheel control system.

Measurement, analysis and processing of sensor signals is performed via a PC-based data acquisition system and software modules outputting the results in spectral form (Figure 15).

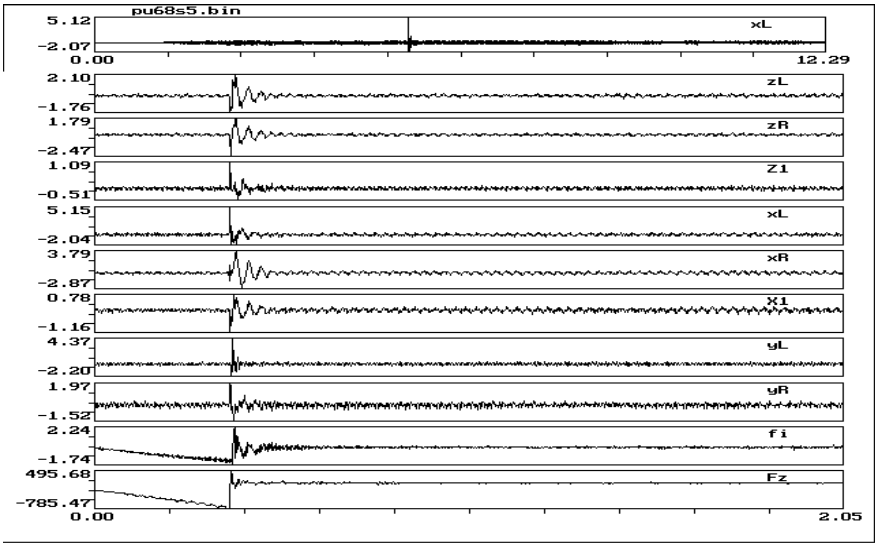

Figure 14: Example of recording data in the time implementations on the indications of 3-component accelerometers

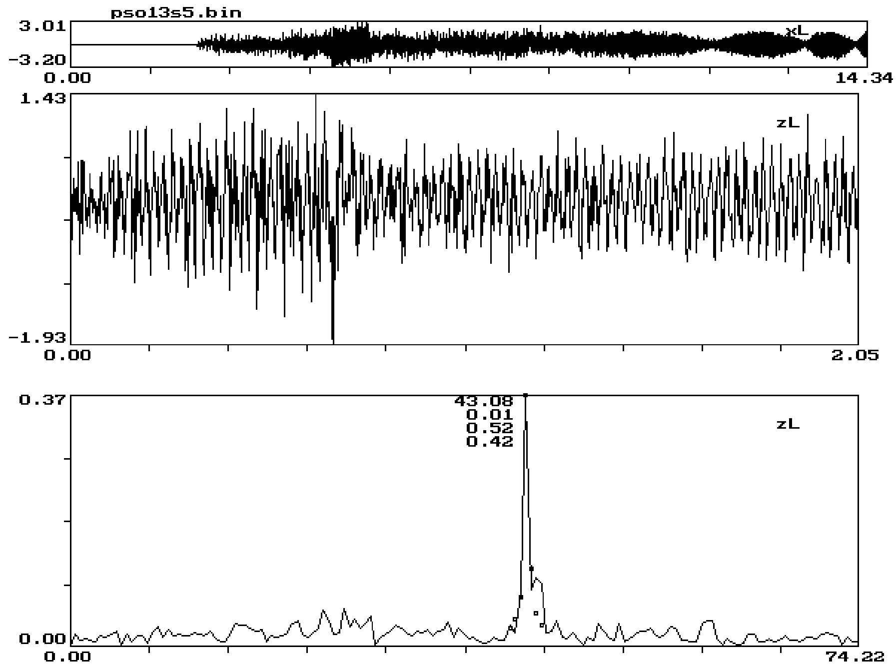

Figure 15: Amplitude Fourier spectrum by 2 seconds record of time of lateral vibrations NLG

3.3 Shimmy safety criteria

The safety from shimmy of the wheels is estimated by oscillations decay in the surveyed regimes. As an indicator of the stability, the number N of transitions of the wheel through the neutral position until the complete oscillations dying-out, or corresponding damping ratio $\delta = f(N)$ can be used (Figure 16).

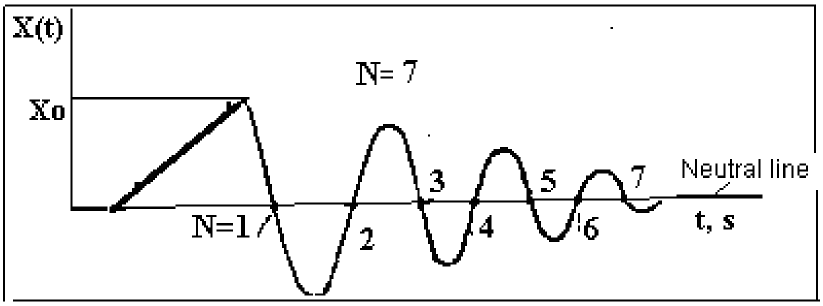

Figure 16: Estimation of stability of the wheels rolling via to the number of transitions through the

Based on the comparison of laboratory test results with those from regular operation, the following safety criteria from wheels shimmy can be recommended:

if none of the test regime demonstrate more than two passes across the neutral position (or damping ratio is not less than $\delta > 5\%$), the landing gear safe from shimmy in regular operation;

if any test show from six to eight passes through the neutral position ($2\% < \delta < 5\%$), then to ensure safety from shimmy in operation, the landing gear design has to be revised;

if the lab test results are somewhat intermediate between the two above, then to evaluate the safety of landing gear from shimmy, additional research is needed.

The above safety criteria are applicable to the results of laboratory tests in the case when only the conditions of the main strut root attachment are met properly, and no simulation of fuselage dynamics is required. In the case where even the root attachment conditions are not satisfied, the results of laboratory tests can be used to adjust a shimmy computational model.

4 AIRCRAFT GROUND TEST

From foreign and domestic experience of the ground test (GT) it follows that these tests are one of the most reliable and effective methods to check the safety of the aircraft from landing gear shimmy..

According to Aeronautical engineering review, 1941, airdrome tests were used to check the effectiveness of hydraulic dampers of shimmy on the nose landing gear of a Bell prototype aircraft. As can be seen from figure 17, a tested NLG with hydraulic dampers was mounted on a special rig towed together with the test car. It does not follow from the article that any obstacle on the ground was used for perturbation of the wheel straight rolling. Probably, the source of the disturbances were natural irregularities of the airfield.

The article by W. J. Moreland "The story of Shimmy" [1] described the AT (full-scale field tests) transport aircraft Fairchild C-119, which nose landing gear did not possessed the necessary shimmy margins at speeds over 60 knots (111 km/h). In this case the steady-state oscillations can easily be excited also at lower speeds in a collision with an obstacle of 2.5 inches (63.5 mm) height disposed at 45° to the runway. (In domestic practice such an obstacle was called the "shimmy board", Figure 18). In these tests they investigated various ways to prevent shimmy: strut bending stiffness variation due to the mount of the braces, increase of the torsional strut stiffness by replacing the torque link with the stiffer one. During GVT, the influence of the wheels steering control system, free-plays in torsion, etc. were also studied.

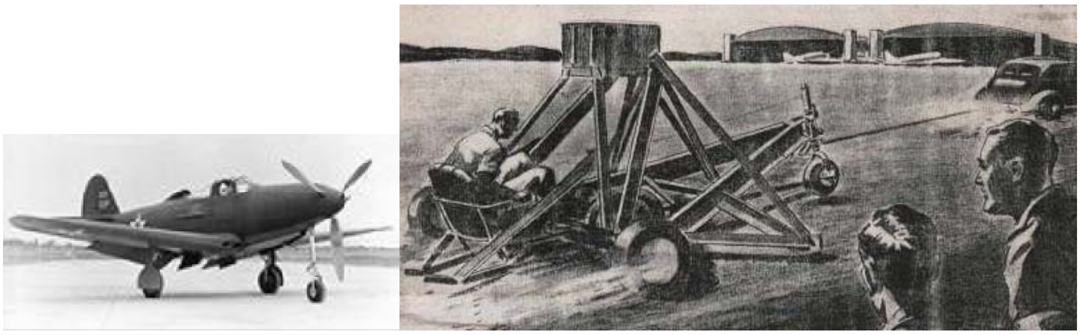

Figure 17: Tests NLG with DH of shimmy of aircraft Bell

In In Russian domestic practice the GT were first carried out in May 2008 on the RRJ-95 airplane (Figure 17), and then in 2009 and 2010 on other aircraft of the RRJ-95 series.

Figure 18: The GT of aircraft with crossing the "shimmy board"

The main purposes of the ground test of the landing gear is:

- obtaining experimental data to establish the safety from shimmy of the wheels of landing gears within the range of weights, CGs and ground speeds corresponding to the aircraft flight performance and the establishment of stability margins for damping of the wheels oscillations;
- confirmation of the results of calculations and laboratory tests;
- estimation of the effectiveness of improvements made in the construction of the strut;
- estimation of the effectiveness of shimmy dampers,
- establishment of the safety of flights of the aircraft in the event of failures in the control system of wheels, etc.

Fundamentally, the essence of the landing gear airdrome tests on the shimmy is as follows. The tests are performed on a smooth horizontal and dry runway with a special obstacle in the form of "shimmy board" made with certain size (e.g. 2 m×0.5 m and thickness of about 2.5 cm) and fixed on the runway by 45^0 to the direction of aircraft movement. The plane with the shock absorber piston of the tested landing gear compressed to a predetermined value reaches the required ground speed in a straight line and gets a lateral impulse from the collision of the wheels with the “shimmy board”. The movement of the aircraft during the main landing gear tests is shown in figure 19.

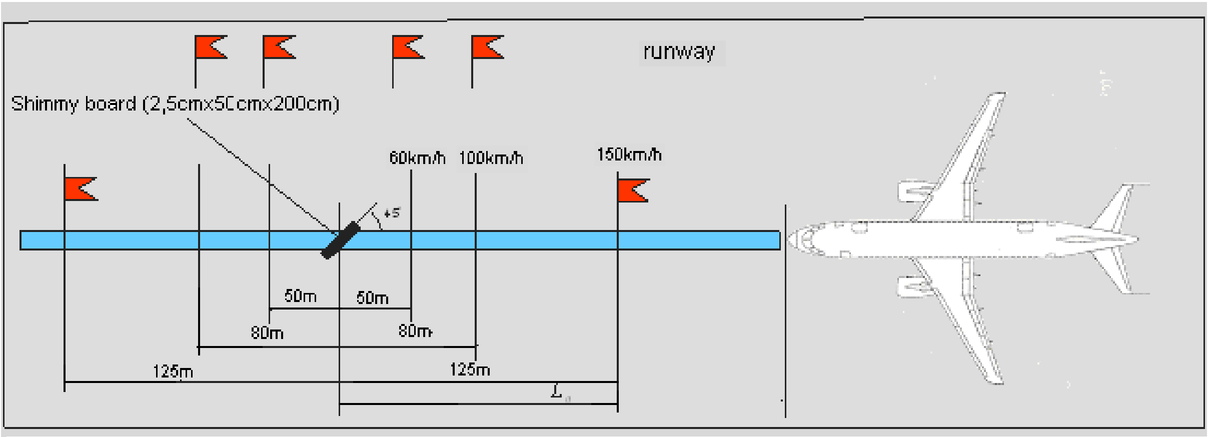

Figure 19: Aircraft movement during the main landing gear tests

In this diagram, the check marks indicate the time of inclusion (for about 3 seconds before crossing an obstacle) and the moment off of FTI-parameters of registering vibrations of the wheels (registering for about 3-5 seconds after crossing the wheels on the obstacle), corresponding to different speeds of the wheels crossing on the obstacle. Subsequent processing and analysis of obtained data recording by time gives an idea about the stability rolling of the wheels according to the set program.

4.1.The estimation of the effectiveness of hydraulic dampers in the torque link of a main landing gear

As an illustration of application of GT techniques for prediction of safety of an aircraft from shimmy, below are the results of processing FTI time recorded data related to crossing the "shimmy board" by landing gear wheels. Below, Figures 20-22 show the effectiveness of the hydraulic damper (DH) of shimmy. Processing of FTI results was performed using a spectral analysis package/

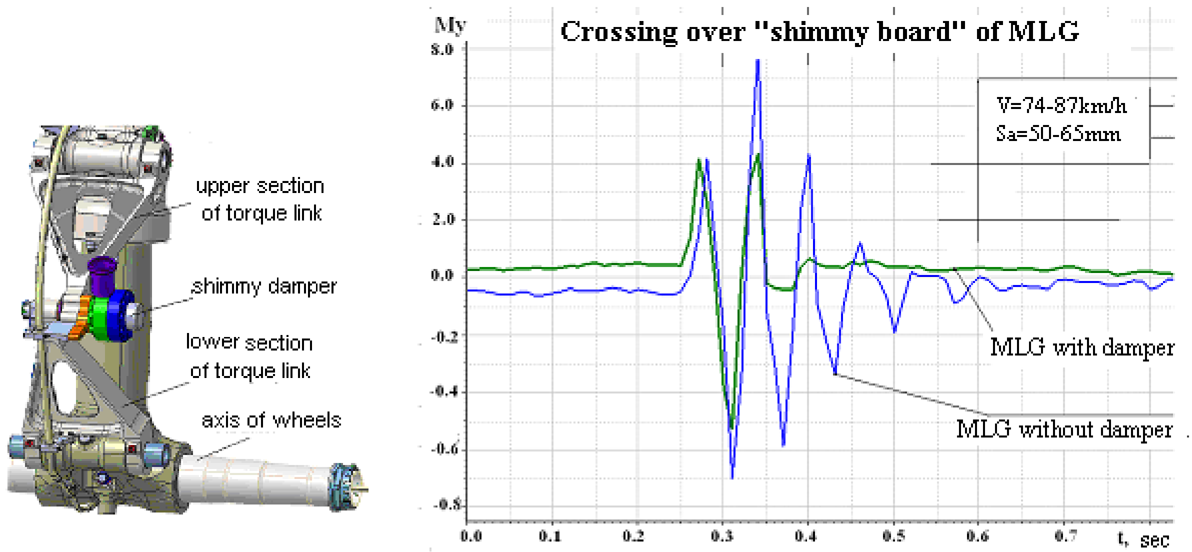

Figure 20: Comparison of bending moments in the torque link of MLG with and without a hydraulic damper at V~80km/h and the compression piston of shock absorber S_{aM}~60 mm.

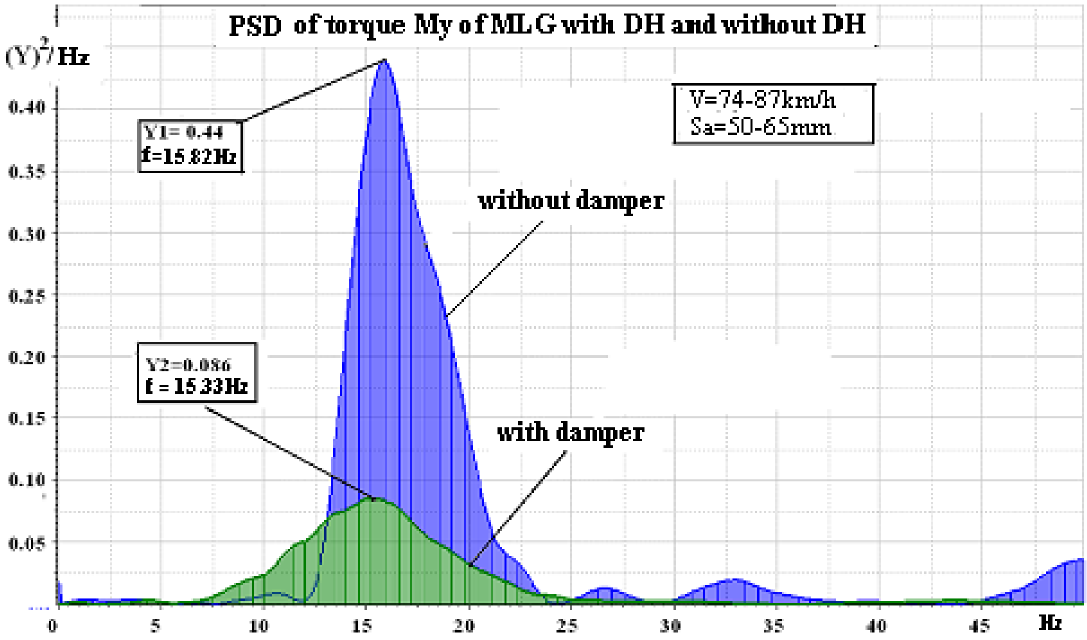

Figure 21: Comparison PSD of bending moments in the torque link of MLG with and without a hydraulic damper

The above results in Figures 20-22 indicate that at all the GT regimes investigated the aircraft is not prone to shimmy. With increasing speed of the aircraft, logarithmic decrements of oscillation increase too. From the comparison of PSD of the main landing gear with and without the hydraulic damper, it follows that MLG without the damper was exposed at resonant frequencies to higher level of vibrations

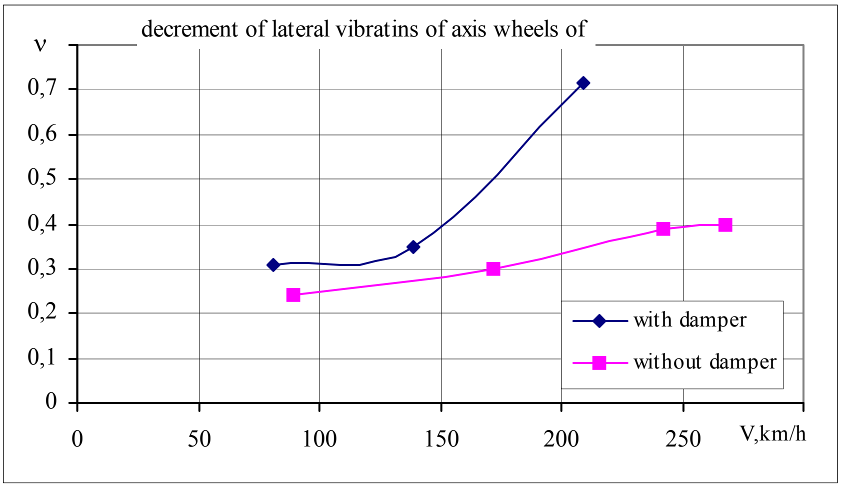

Figure 22: Comparison of decrements of MLG with DH shimmy and no damper depending on the speed crossing of the wheels on the “shimmy board”

4.2 Prediction of shimmy of the nose landing gear wheels under failed control system

Computational studies have established that at a failure mode of operation of the steering control system of the nose wheels, i.e. in the case without working fluid in the hydraulic module, there are no shimmy oscillations. It was shown that with increase of rolling speed, the damping coefficient of torsional vibrations of the LG increases for all the studied shock absorber compression values. To confirm the results of the calculations, ground test collisions with the "shimmy board" were performed at speeds of the aircraft up to 80 km/h. Absence of damping of the wheels of NLG because of the loss of fluid was simulated by creating a bypass (shunt) channels between the steering control cylinders with the electric valve, which exclude shimmy throttle from the operation (figure 23). This figure shows a fragment of the results of measurements and spectral analysis of the vibrations of NLG wheels with imitation of fluid loss in the steering control system (status "damper OFF"). These results were obtained during the ground tests in crossing the "shimmy board" at about 18 kt, 30 kt, and 43 kt (respectively: ~33 km/h, ~55 km/h, ~80 km/h).

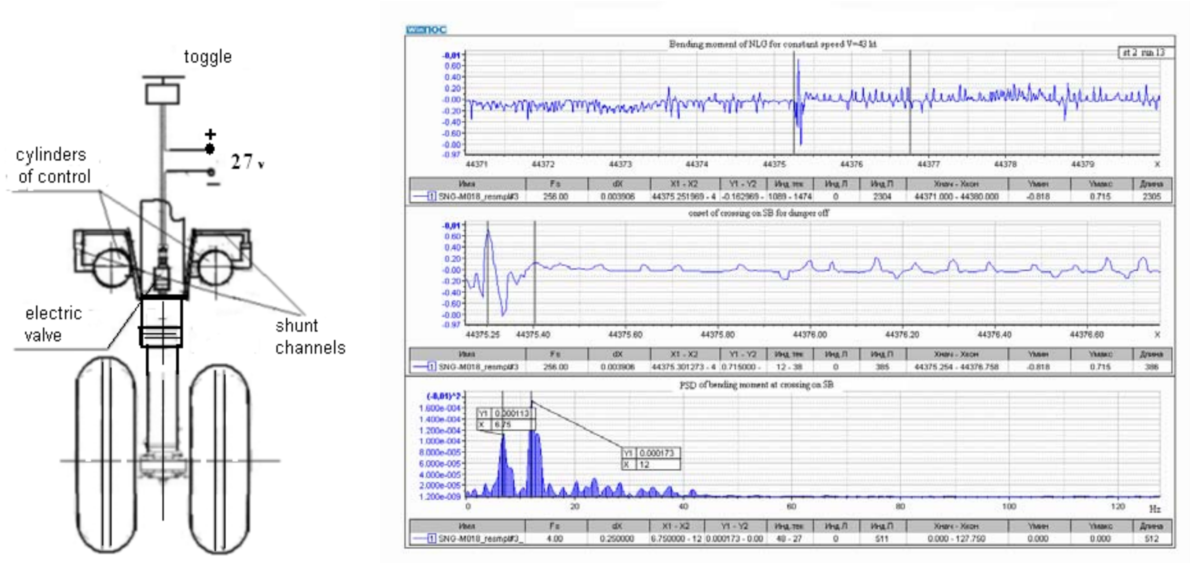

Figure 23: NLG with the shunt channels of control steering system and the results of the main landing gear wheels hitting the "shimmy board": lateral oscillations and their PSD at V=43 kt

As a result of processing of transient oscillations after hitting the obstacle, the dominant frequency f and the damping coefficient ζ were obtained (Figure 24). The comparison of obtained results with the analysis shows their satisfactory quantitative correlation. Thus, the free of shimmy conditions for nose landing gear wheels with the loss of the working fluid in the hydraulic module has been confirmed.

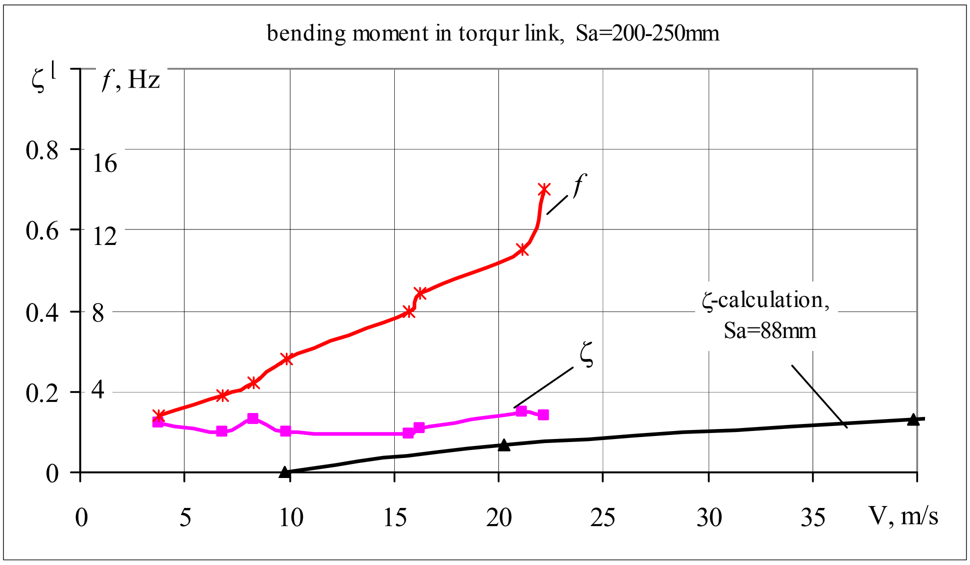

Figure 24: Dependence of damping coefficient and frequency of torsional oscillations of nose landing gear/

The ground test technique and the results of its application on a passenger aircraft for the estimation of the effectiveness of hydraulic dampers of shimmy, mounting on the main landing gears, and for estimation of the safety of the aircraft with failed steering control system with the loss of the working fluid in the hydraulic module of steering control system showed the practical value and reliability of the results and is recommended for use.

5 REFERENCES

[1] W.J. Moreland., The story of Shimmy, Journal of the Aeronautical Sciences, 1954, v.21, №12, p.793+808.