EXPERIMENTAL STUDY OF HYDRODYNAMICALLY INDUCED VIBRATIONAL PROCESSES IN VVER-440 FUEL ASSEMBLIES

Vladimir I. Solonin, D.Sc., professor, Vladimir V. Perevezentsev, Ph.D., assistant professor,
Nickolai F. Rekshnya, assistant professor, Veniamin G. Krapivtsev, Ph.D., assistant professor

Bauman Moscow State Technical University
Department of Nuclear Science and Technology
5, 2nd Baumanskaya St., 107005, Moscow, Russia
Phone: 7 (095) 263 6579; 7 (095) 263 6207; fax: 7 (095) 267 48 44;
E-mail: en7@power.bmstu.ru

One of critical issues associated with increasing safety and reliability of nuclear power reactors consists in restraining the hydrodynamic influence of the coolant flow onto enclosed structural elements and originating at that vibrational loads applied to the above structural elements. These issues are of great importance especially for fuel assemblies and fuel rods. High amplitudes of vibrations of fuel rods in the bundle that undergoes the parallel coolant flow result in considerable dynamic loads and mechanical wear of fuel rod claddings in areas, where the spacing grids are installed. Regarding the above described, one of directions to perfect the fuel assembly design deals with the problem of lowering the hydrodynamic and vibrational loads on elements of fuel assembly. In order to resolve the issue, one should need a data on hydrodynamic processes at turbulent flow of coolant in the fuel assembly and parameters of vibrations arising at that. Nowadays the most reliable data can be obtained only in experimental studies of these processes that are performed at the full-scale dummies of fuel assemblies.

In the present investigation, the hydrodynamically induced vibrations in a single fuel assembly of VVER-440 reactor were studied using a geometrically full-scale dummy installed in the closed circuit test facility.

The hydrodynamic test facility represents a closed water loop with following performances: static pressure – up to 0,5 MPa; temperature of distilled water - 10...50 °C; volume flow rate – up to 200 m^3/h. The flow velocity inside the fuel assembly at maximum flow rate has reached the value of about 6 m/s. Distilled water inside the loop is circulated by an impeller pump. The dummy fuel assembly is installed inside the vertical cylinder - “test section” of the loop. The test section is designed to provide the fastening conditions for the fuel assembly head and tail (top and bottom nozzles), which are similar to those in real reactor. In order to reduce the excitation factor from the working electric impeller pump, there are flexible sections embedded into the test facility circuit. The hydrodynamic test facility and its performances are described in details in paper [1].

Geometrically full-scale dummies of operational fuel assembly of VVER-440 reactor have been tested. The parameters of above models are as follows: outer diameter of fuel rod tubes (claddings) - 9,15 mm; supporting honeycomb grid and spacing grids have height of ~ 11 mm (11 grids); the fuel assembly case represents a hexagon tube with thickness of wall equal to 1,5 mm. The dummy fuel assembly was fastened inside the test section as illustrated in Fig. 1. The experiments covered the measurements of vibro-accelerations of three dummy fuel elements located in central zone and peripheral zones of the fuel assembly (Fig. 2), vibro-accelerations of fuel assembly case and test section of the experimental loop. The diagnosed dummy fuel elements were filled with simulators of fuel pellets. Those simulators have mass and outer geometrical dimensions same as real pellets. The rest of fuel rod tubes did not contain simulators of fuel pellets.

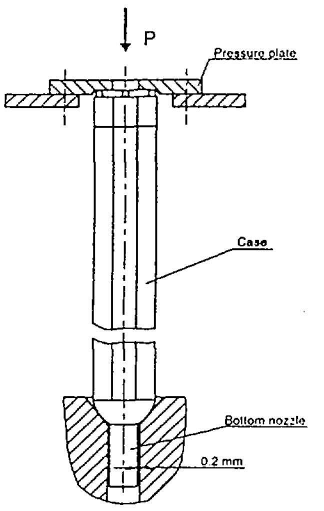

Fig. 1. Conceptual scheme of dummy assembly fastening in "test section" of hydrodynamic test facility

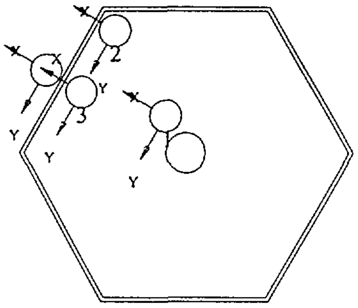

Fig. 2. Cross section of VVER-440 dummy assembly. Scheme of arrangement of vibro-accelerometers in fuel tubes and on the case

The experimental study involved usage of piezoelectric and tensoresistive accelerometers and tensoresistive pressure pulsation sensors. Two-component piezoelectric or tensoresistive accelerometers were installed inside the fuel rod tubes and fixed at the inner cladding surface by split terminals or fluorocarbon-polymer bushes. The internal volume of the fuel rod tube containing the accelerometer was filled with simulators of fuel pellets, i.e. the accelerometer was placed into the structure of column of simulators "splitting" it into two parts – bottom and top. The cable from the accelerometer was laid through the central holes of simulators of fuel pellets and led out through the removable end-plug of the fuel rod tube. Tensometric accelerometers were also attached to the outer surface of case by means of special clamps. The pressure pulsations were measured by tensoresistive sensors on the inner surface of the bottom nozzle of the fuel assembly in front of the supporting grid and on the inner surface of one of case facets. The so-called “pulse holes” by diameter of 1 mm were connected to the sensors through metal pipes by inner diameter of 4 mm and length of 50 mm. The conducted analysis has demonstrated that such connecting line does not introduce any distortions into the measured signal in the frequency range of up to 2000 Hz. The mentioned frequency range corresponds to the conditions of performed investigation.

The informational and measuring system has allowed registering and processing the signals from the primary transducers that were received at inputs of analog-digital converters. The sampling frequency was equal up to 2 kHz when using 16 channels simultaneously or up to 40 kHz when working with one channel only. The software that was used for statistical processing of experimental data allowed to obtain the time-base realizations of vibro-accelerations and pressure oscillations, estimate their root-mean-square values, conduct the spectrum analysis and determine the autocorrelation and cross-correlation functions.

The data on hydrodynamic loads applied to the bundle of fuel rods and fuel assembly case was obtained by measuring pressure oscillations in front of the supporting grid and on the inner surface of the fuel assembly case. Pressure oscillations were measured in different cross-sections along the height. Amplitude-velocity and spectral parameters of pressure pulsations were measured in the experimental runs. Fig. 3 demonstrates the distribution of root-mean-square values of pressure pulsations versus fuel rod bundle length in the dummy assembly. The levels of pressure pulsations p' in general frequency band in front of the supporting grid at maximum coolant flow velocity in the fuel rod bundle of ~ 6 m/s reached the values of ~ 4 kPa. Based on ratio $p' \sim \frac{\rho v'^2}{2}$, the latter value corresponds to the value of pulsation velocity approximately equal to 2,8 m/s.

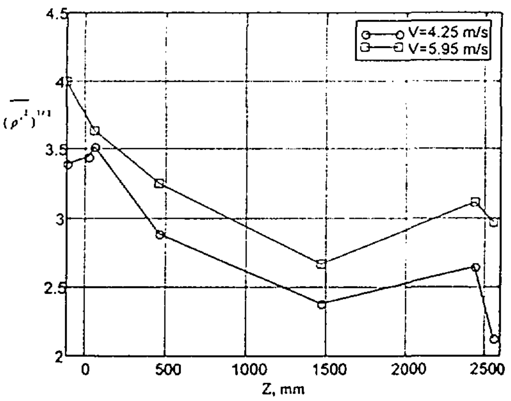

Fig. 3. Distribution of root-mean-square pressure pulsations along the fuel rod bundl

Thus the relative root-mean-square values of pressure pulsations (with respect to the dynamic head) in front of the supporting grid, i.e. beyond the bottom nozzle, were equivalent to more than 20 %. As the coolant flows inside the fuel rod bundle, the pressure pulsations are decreasing. They are lowering monotonically right up to the cross section z = 1460 mm in the area between sixth and seventh spacing grids. Then the tendency of some increase in pressure pulsations is observed, i.e. the generation of pulsation energy predominates over the dissipation processes. At the exit from the bundle, the levels of pressure pulsations diminish again. That might be associated with decrease of averaged velocity of the jet flow, which is formed behind the bundle. The regularity of dissipation of pulsation energy is defined by the internal structure of the flow that evolves behind the supporting grid and presence of spacing grids installed along the bundle height. The spacing grids appear to be the local sources of pulsation energy, and their contribution is proportional to the pressure losses in them. Taking into account that the spacing grids have relatively low hydraulic resistances, their contribution into generation of the pulsation energy is insignificant. That contribution does not define the regularity of distribution of root-mean-square pressure pulsations along the fuel rod bundle.

The spectral distribution of pressure pulsations in front of the supporting grid (Fig. 4) shows that the most part of their energy is concentrated in the low-frequency area ($f < 40$ Hz). The narrow-band resonances at the rotational frequency of the pump (25 Hz) and frequency of 13 Hz stand out against the background. The 13 Hz-peak is caused by propagation of hydrodynamic disturbances through all the loop circuit. Those disturbances are induced by the entire dummy assembly, which oscillates in the "test section" filled with water.

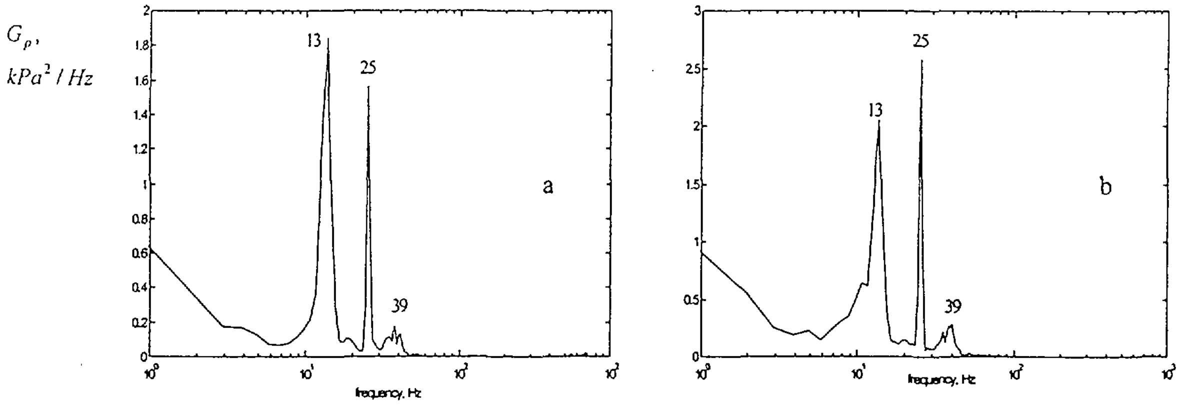

Fig. 4. Absolute spectral densities of pressure pulsations in front of the support grid of dummy fuel assembly
a – V = 4.25 m/s; b – V = 5.95 m/s

As coolant flows inside the fuel rod bundle, the above resonances in spectra of pressure pulsations persist. In comparison with pressure pulsations in front of the supporting grid, the higher frequencies start to bring in more contribution into the energy of pulsation (Fig. 5).

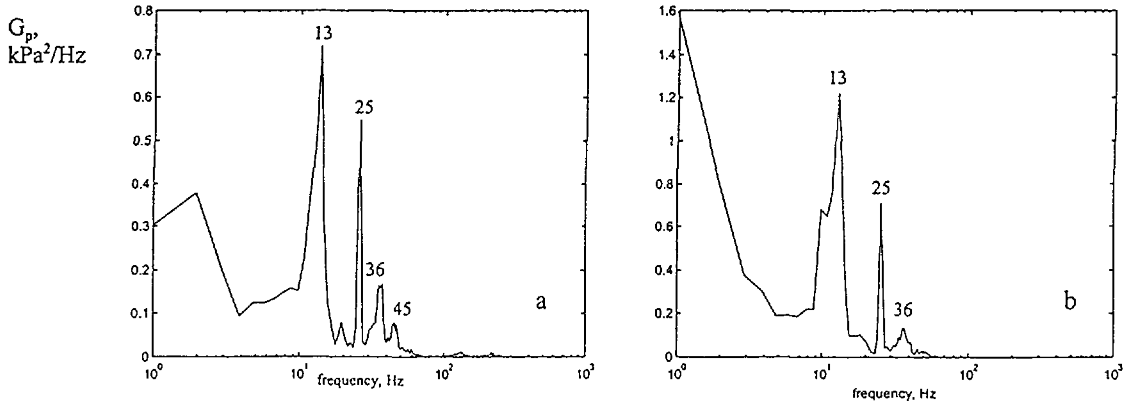

Fig. 5. Absolute spectral densities of pressure pulsations in the region of the third span of the fuel rod bundle
a – V = 4.25 m/s; b – V = 5.95 m/s

Fig. 6 illustrates the distribution of vibro-accelerations along the case of dummy assembly. The results of measurements demonstrate that the vibro-accelerations along the axis, which is perpendicular to the case facet, are essentially higher than vibro-accelerations along the axis, which is parallel to the case facet. The bending stiffness of a thin-walled hexagon tube is almost the same along any direction, since moments of inertia along x and y -axes disagree negligibly: $I_x \approx I_y$.

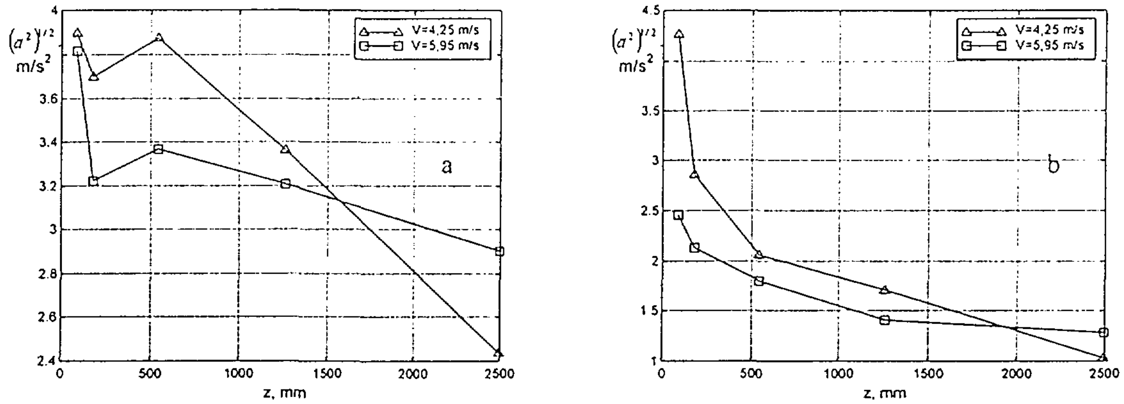

Fig. 6. Distribution of root-mean-square vibro-accelerations along the dummy fuel assembly case
a – perpendicular to the case facet (x-axis); b – in parallel to the case facet (y-axis)

Therefore, the registered differences in vibro-accelerations might be caused by shell oscillations for which the deformation of case facet along x-axis is much greater than that along y-axis. The above assumption was confirmed by measuring the vibrations of the case facets. The measuring axes of installed at the case facet vibro-accelerometer were respectively oriented towards x and y directions (Fig. 2). The accelerometer shows higher values of vibro-accelerations along x-axis, i.e. along the direction, which is perpendicular to the case facet. The observed diminution of intensity of fuel assembly case vibrations along the flow is caused by the registered dissipation of pulsation energy of the coolant and decrease in pressure pulsations. That is why the pressure pulsations define the hydrodynamic loads on the case and fuel assembly as a whole.

Vibro displacements were determined by double integrating the vibro-accelerations that were obtained in the runs of experimental study. In order to exclude the errors associated with high level of background noises of the measurement lines with vibro-accelerometers in the low-frequency area, the lower boundary of the frequency range of vibro-displacements was equivalent to 10 Hz. The data presented in Fig. 7 demonstrates the levels and behavior of vibro-displacements along the fuel assembly case. Despite of vibro-accelerations, vibro-displacements demonstrate a non-monotonic behavior versus fuel assembly length. The highest root-mean-square values of vibro-displacements are observed in the bottom part of the fuel assembly (near bottom nozzle) and near top nozzle. For example, when the flow velocity in the fuel assembly equals to 5,95 m/s, the root-mean-square values of vibro-displacements of the case along x-axis at the level of midpoint of the first span of the fuel rod bundle are equal approximately to 20 μm, and near the top nozzle they exceed the value of 17 μm. At the same time the minimum values of vibro-displacements along the same axis were registered in the area of the third span of the bundle. Those values are equal approximately to 13 μm.

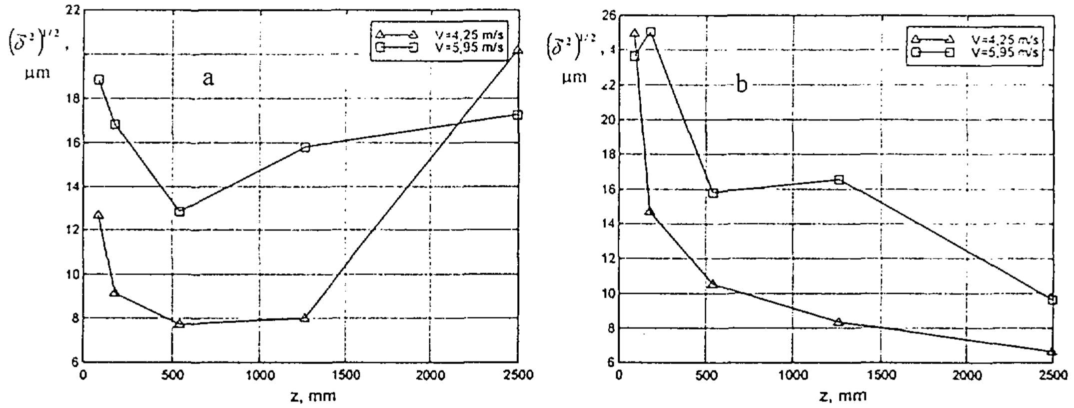

Fig. 7. Distribution of root-mean-square vibro-displacements along the dummy fuel assembly case
a – perpendicular to the case facet (x-axis); b – in parallel to the case facet (y-axis)

The spectra of vibro-displacements of the fuel assembly case testify to the fact that the essential contribution is brought in by the relatively low-frequency range (lower than 40 Hz). At the same time, the clearly outstanding against the background resonances are registered at frequencies of 11...12 Hz and 15...17 Hz. Besides, the spectral levels are getting higher at frequencies that are closer to the rotational frequency of the circulating pump (25 Hz).

Analysis of data on behavior of vibro-displacements along the fuel assembly allows making a conclusion that oscillations of supporting elements of the fuel assembly structure also appear to be a source of vibro-displacements.

The vibro-displacements of individual fuel rod tubes differ essentially. That is associated both with unequal conditions of their streamlining by the coolant flow and with influence of bending oscillations of the entire bundle resulting in different displacements of peripheral and central tubes. Fig. 8 illustrates the root-mean-square values of vibro-displacements of fuel rod tubes in different cross-sections along the bundle at flow velocity of 4,25 m/s. The maximum root-mean-square vibro-displacements, equivalent approximately to $140 \mu m$, were observed in the line of x-axis for the peripheral fuel rod in the corner in the cross-section located at the midpoint of the last span of the bundle. The minimum root-mean-square vibro-displacements ($\sim 15 \mu m$) – were observed for the fuel rod located in the first row from the central tube in the line of y-axis. For all fuel rod tubes, the highest vibro-displacements are observed for the last span of the bundle. It can be seen clearly that the vibro-displacements diminish contiguously to the spacing grids. As a rule, the smallest values of vibro-displacements in the line of both directions are observed for the fuel rod tube located in the first row (x_1 and y_1) near the central tube of the fuel assembly. The vibro-displacements in the line of x-axis, i.e. perpendicular to the case facet, exceed the respective values in the line of y-axis, i.e. in parallel to the case facet.

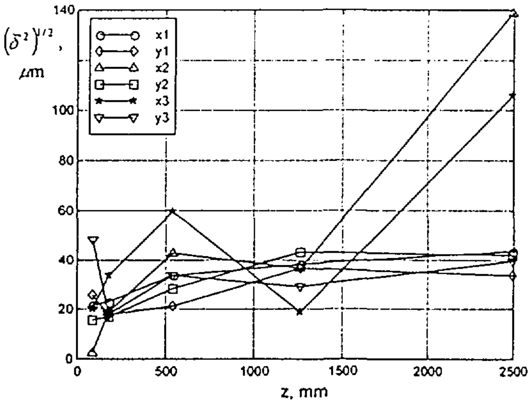

Fig. 8. Distribution of root-mean-square vibro-displacements along the fuel rod bundle of dummy assembly (coolant flow velocity V = 4.25 m/s)

Resonance at frequencies of 11 and 13...15 Hz are predominant in spectra of vibro-displacements of the fuel rod tubes. Those resonances are stipulated respectively by oscillations of the "test section" at natural frequency and bending oscillations of the fuel assembly as a whole (Fig. 9). The vibrations of the fuel rod tubes are also excited at higher frequencies (up to 40...45 Hz) but with significantly lower spectrum levels.

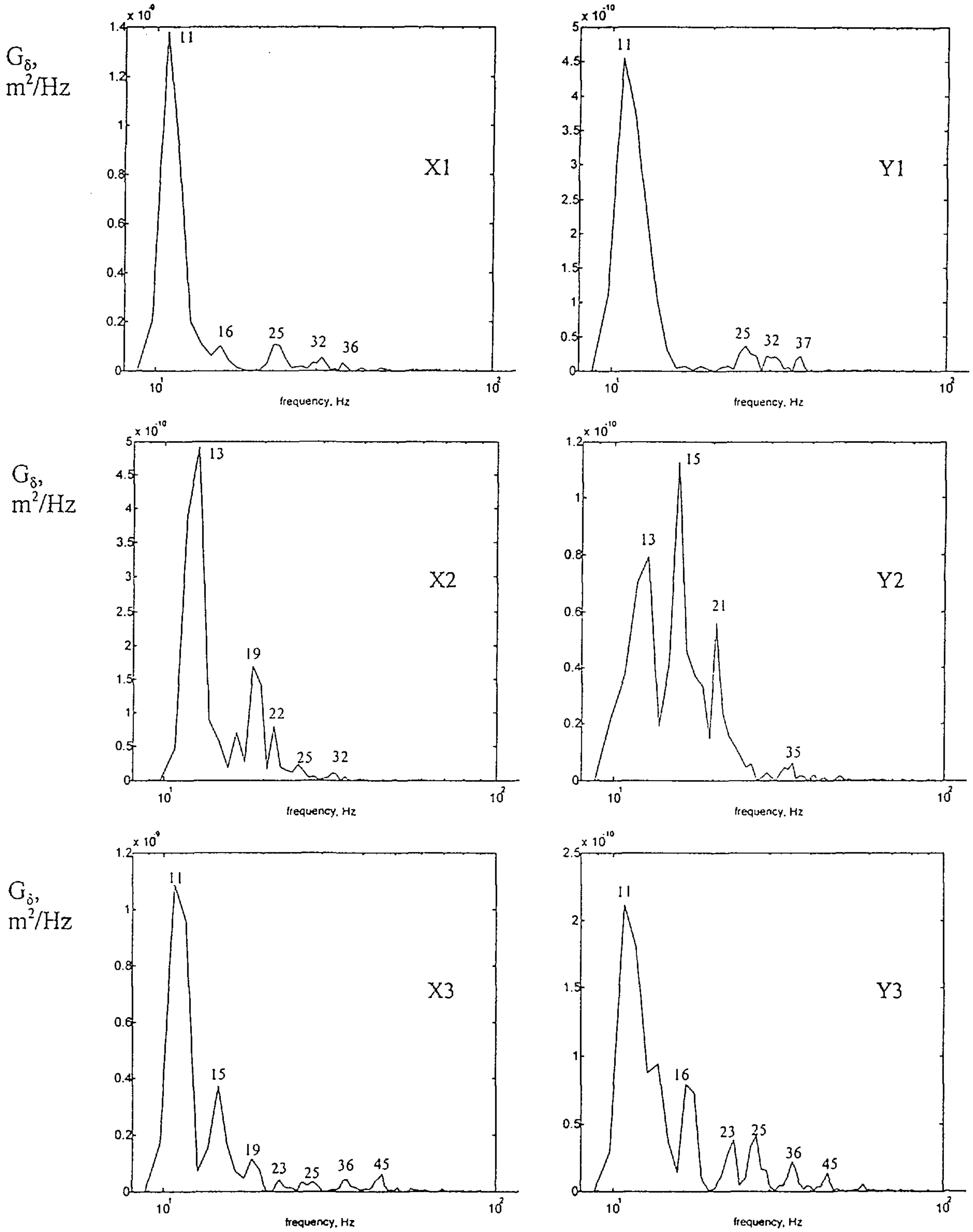

Fig. 9. Absolute spectral densities of vibro-displacements of fuel rods of dummy assembly

in the region of the third span (coolant flow velocity V = 4.25 m/s)

All the spectra contain a resonance at 25 Hz caused by the rotational frequency of the circulating impeller pump. The increase of spectrum levels at frequencies of 32...36 and 45 Hz happens due to excitation of higher-frequency (in comparison with fundamental mode) oscillations of the fuel rod bundle either together with the case or just the bundle itself. We should mention that for the free oscillations of some individual fuel rods the natural frequencies turn out to be essentially higher (~ 200 Hz), but this frequency range does not bring any significant contribution into the vibro-displacements. Therefore the induced by the coolant flow vibrations of the fuel rods can be identified as predominantly bending oscillations of the entire fuel rod bundle.

References

1. Experimental study of hydrodynamic influence of the coolant flow on the structural elements of VVER-440 fuel assemblies. /A. K. Panyushkin, G. G. Potoskaev, V. I. Solonin et al.– Hydrodynamics and Safety of Nuclear Power Plants: Thesis of industrial-branch conference "Thermal Physics-99", Obninsk, Russia, 1999. – pp. 306-308.