Statistical analysis of the vibration loading of the reactor internals and fuel assemblies of reactor units type WWER-440 from deferent projects

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Introduction

Last years the demand of monitoring systems of installations increases. It is connected not only with international reactor diagnostics requirements, according these the modern designs of WWER already content such systems, but with quite practical tasks:

- Prolongation of the designed operation term;
- Investigation of fuel failure reasons;
- Using a new type of fuel;
- Changing unit operation circumstances, for example, increasing reactor unit power.

In the report the experience of many years in vibration noise diagnostics for reactor unit type WWER is stated, gained with the help of both foreign and domestic systems produced for special noise measurements.

1. Vibration noise instrument channels

Vibration of fuel assemblies is caused by coolant flow, happens at own frequencies and also is caused by vibration of reactor pressure vessel (RPV) and internals as forced vibration. For monitoring of the RPV, internals, fuel assemblies and control assemblies vibration it is necessary vibration noise measurements channels. These channels shall be recorded both the factors that forced vibration and vibration response of monitoring equipment. As a rule the whole multitude of vibration noise measurements channels is:

- Absolute displacement transducers, mounted on the reactor cover;
- Pressure fluctuation transducers of the coolant;
- Ex-core neutron flow detectors;
- In-core neutron flow detectors – self power neutron detectors.

Vibration state (including anomalous) of loop equipment, for example, vibration state of main circulation pump is also the source of forced vibration of internals and fuel assemblies. That's why the multitude of monitoring signals includes relative displacement transducers, mounted on the main equipment of the main circulation loop. Thus the list of necessary vibration noise channels corresponds with the list of conventional vibration noise measurements channels of the vibration noise diagnostic system (VNDS).

The essential condition of successful vibration monitoring of fuel assemblies and internals is the large data-base of multi-channel records of vibration signals and/or spectral characteristics. As a result of invariability of spectral portrait of vibration we can be made the conclusion about the unimportant deterioration process in attachment point of internals, fuel assemblies and control assemblies during a long time, for example, during several operation periods (OP).

Mathematical modeling is used in case of any changes of vibration spectral image. There is a verified full-scale vibration model for WWER-440. This is a joint Russian-German soft-ware product, which describes all main spectral peculiarities of RPV and core barrel vibration at different (including out of project) fastening unit states of internals and control assemblies [1].

The begin of the vibration measurements of reactor unit and internals under operation condition for Novovoronezh NPP 3,4 and Kola NPP 1,2 can be considered 1992, when vibration monitoring systems SUS (developed by *Siemens*) at the listed blocks were applied. Systems SUS is delivered without neutron noise measurements channels, which must be developed by Russian companies. Nowadays the following ready for sale production is available:

– The equipment of internals pick up monitoring using of regular ionization chamber signals;

– The unit of separation of fluctuation component of signals self power neutron detectors and ionization chamber (the development JSC "Diaprom").

2. Vibration loading characteristics of control assemblies, internals and design peculiarities of internals of WWER-440 deferent projects

Comparison of the reactor unit vibration state of different projects WWER-440 makes sense, whether design peculiarities were taken into consideration.

In reactor project W-179 the reactor core barrel bottom is fixed relative the reactor pressure vessel bottom with the help of centering cylinder. In W-230 and W-213 reactor projects the side surface of the core barrel is centered relative the reactor vessel with the help of 8 supporting guides. In W-230 project the length of core barrel with the core barrel bottom was reduced a little as distinct from W-179 project. And at the same time the stiffness of internals mounting units, especially the core barrel bottom, were enlarged. This shall obviously increase the eigenfrequency of the core barrel vibration. In practice, however, the above listed changes of internals design don't efficiency influence the vibration state in comparison with the influence of the lower mounting units of the core barrel.

The core barrel vibration condition according the design shall be corresponded to rod vibration with two fixed ends and if the lower attachment point is runout (centering cylinder in project W-179 and supporting guides in projects W-230 and W-213) it comes to rod vibration with the loose lower end. In the last case the eigenfrequency of vibration has a lowest values, and vibration amplitude has a maximal values. It is very approximately, but it shows the important point of the problem in core barrel vibration. The decision of the vibration condition problem of internals shall include at least three levels of core barrel mounting units: the above-mentioned mounting units, flow separator as the middle mounting level, and the upper level as pipe segments.

In table 1 three not-design conditions of core barrel mounting level and according frequencies received as a result of a great number of vibration noise measurements and full-scale end-elements modeling are shown.

Some frequency intervals are given for eigenfrequencies in table 1. Nevertheless the measured eigenfrequencies of internals vibration may not be in accord with given frequency intervals. The real condition of mounting units may not be corresponded to extremal values given in table 1 (either design condition or completely runout of mounting units) but has an intermediate value. Beside the coexistence of different vibration modes of internals is possible. It is a transient vibration. At one moment one mode of core barrel vibration with two fixed ends is realized, and then another mode of core barrel vibration with the loose lower end is appears.

Essentially different from each other archive auto power spectrum density of absolute displacement transducer signals are indicated as an example on figure 1. Transducers are mounting on the reactor vessel head at Bogunice NPP, Kola NPP and Novovoronezh NPP. Nevertheless we can assert that the upper and lower diagram on figure 1 corresponds to core barrel vibration closed to design restrictions on the mounting units of internals, and the middle diagram (the first unit of NPP Kola) corresponds to core barrel vibration as vibration of rod with one fixed end.

Table 1.

Eigenfrequencies of joint vibration of the core barrel reactor pressure vessel [Hz]

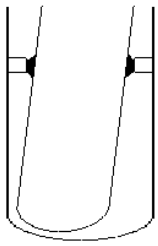
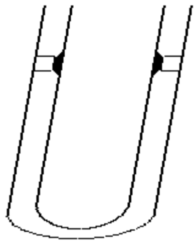
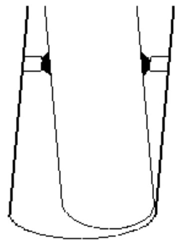
Mode of vibration	Lower mode of core barrel vibration	Co phased mode of vibration (RPV and core barrel in phase)	Antiphase mode (RPV and core barrel in antiphase)
The condition of three levels of mounting units			
The design condition of all three levels of mounting units	absent	(9 – 11)	(13 – 15)
Runout of a lower mounting units (vibration damper), and the middle (flow separator) and upper level – in the design condition	(3,8-4,0)	(6,5 – 7,5)	(7,5 – 8,5)
Runout of a lower mounting units, there is no core barrel reduction in the plane of flow separation and the upper mounting level – in the design condition	absent	(4,8 – 5,0)	(5,6 – 6,0)

Figure 1 indicates processing results of reactor units observation, and figure 2 indicates processing results during a special period of time at every reactor unit, equipped with SNDS. This diagram shows the shift of vibration state of RPV to the lower vibration types in 1999. These lower types corresponds with fuel rod vibration with one fixed end and are evidence of runout lower mounting units and about essential vibration amplitude of internals and fuel assemblies generated by coolant flow.

Another vibration loading factor of internals and fuel assemblies is pressure fluctuation of coolant. Project W-213 is most safety in this point, there the reactor bottom is made elliptic and that reduced root-mean-square value of pressure fluctuation at the input into reactor core at least twice in compare with projects W-179 and W-230 [3].

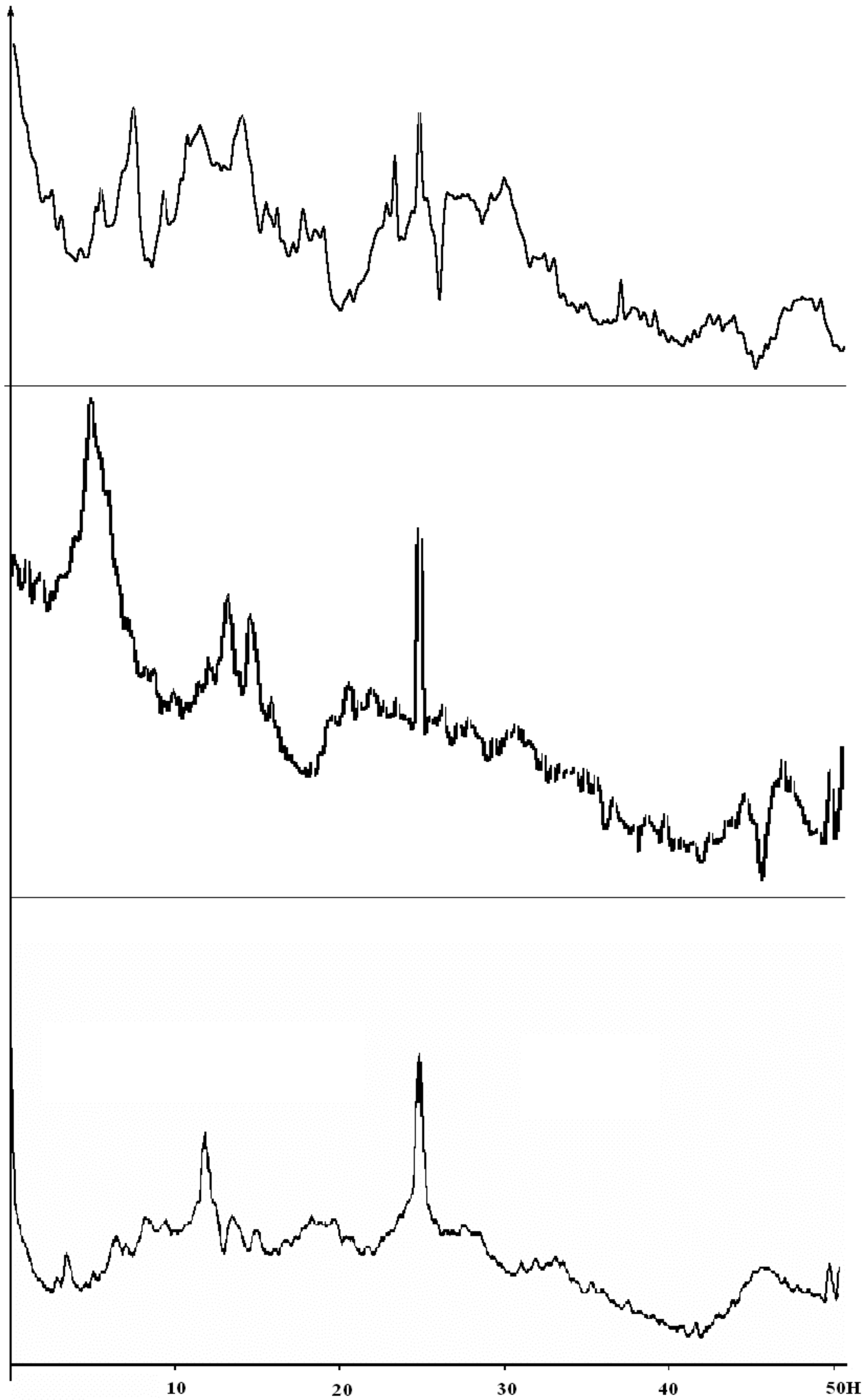


Figure 1. Auto power spectrum density of absolute displacement detector. Novovoronezh NPP 4 (upper), Kola NPP 1 (middle), Bogunice NPP 2 (lower diagram)

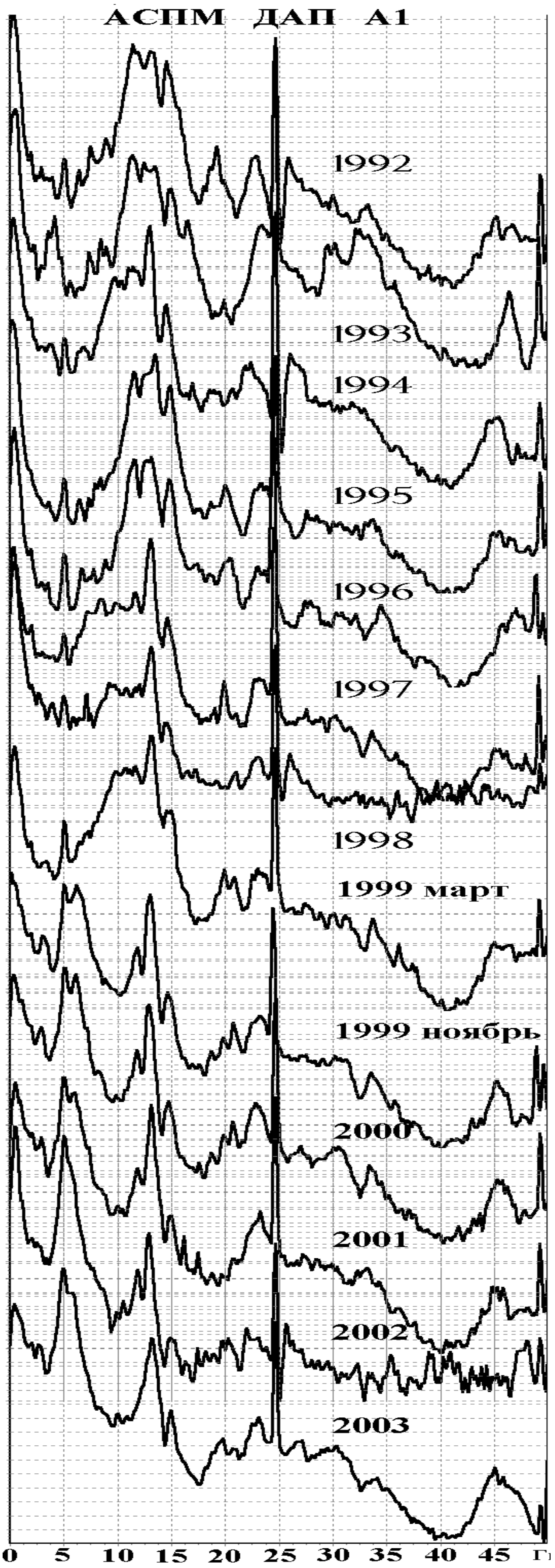


Figure 2. The change of auto power spectrum density of absolute displacement detector signal for the last 12 years of SUS monitoring the 2-th unit in NPP Kola

3. Coolant flow rate through the reactor, reactor core, fuel assemblies and control assemblies for different projects WWER-440

During WWER development [2-5] the general designer has reduces the coolant flow rate through the reactor in series (tables 2, 3).

Table 2

Design flow rate of coolant

<table>
<tr><th>Project</th><th>Flow rate project value through the reactor at the input temperature of coolant [m³/hour]</th><th>Design flow rate through fuel assemblies and control assemblies [m³/hour]</th><th>Sheet. Sources</th></tr>
<tr><td>WWER-365</td><td>49500</td><td>-</td><td>[2]</td></tr>
<tr><td>W-230</td><td>42000 – 47500</td><td rowspan="2">100 - 130</td><td>[4]</td></tr>
<tr><td>W-213</td><td>39000 - 43000</td><td>[4]</td></tr>
</table>

Table 3

Coolant flow rate, received at the stage of energetic setting into operation

<table>
<tr><th>Project</th><th>NPP unit</th><th>The measured coolant flow rate value through the reactor [m³/hour]</th><th>Flow rate through fuel assembly [m³/hour]</th><th>Flow rate through control assemblies [m³/hour]</th><th>Sheet. Sources</th></tr>
<tr><td rowspan="2">W-179</td><td>Novovoronezh NNP, 3</td><td>47000</td><td>130</td><td>108</td><td rowspan="7">[4]</td></tr>
<tr><td>Novovoronezh NNP, 4</td><td>44000</td><td>115</td><td>130</td></tr>
<tr><td rowspan="5">W-230</td><td>Kola NPP, 1</td><td>43700</td><td>118,5</td><td>130,8</td></tr>
<tr><td>Kola NPP, 2</td><td>-</td><td>-</td><td>138±10</td></tr>
<tr><td>Kozloduj NPP, 1 (before damping of some holes)</td><td>46300</td><td>-</td><td>141±10</td></tr>
<tr><td>(after damping of some holes)</td><td>46300</td><td>119,5</td><td>129,0</td></tr>
<tr><td>NPP Bogunice,1</td><td>41600</td><td>115,7</td><td>116,0</td></tr>
<tr><td rowspan="4">W-213</td><td>Loviiza NPP,1</td><td>41400</td><td>115</td><td>114</td><td rowspan="2">[2]</td></tr>
<tr><td>Loviiza NPP, 2</td><td>42300</td><td>117</td><td>116</td></tr>
<tr><td>Rovenskaja NPP, 1</td><td>40750±900</td><td>126,6±3,5</td><td>124,9±3,5</td><td rowspan="2">[4]</td></tr>
<tr><td>Rovenskaja NPP, 2</td><td>40400±800</td><td>112,6±4,0</td><td>108,9±5,0</td></tr>
</table>

The attempt to reduce the coolant flow rate through the reactor is connected with vibration incident. Vibration loading of internals, fuel assemblies and control and emergency assemblies depend directly on coolant speed, and firstly the decision on its reduction was taken in connection with the anomaly vibration of heat shield on Novovoronezh NPP, 1. The coolant speed through control and emergency assemblies was firstly reduced by General Designer after vibration incidents at Novovoronezh NPP and Nord NPP [3] as a result of it fuel assemblies and control assemblies were disconnected.

Coolant flow rate through the control assemblies can be reduced without the change of general coolant flow rate through the reactor only at the expense of coolant redistribution between fuel assemblies and control assemblies. Flow rate through the control assemblies are determined by the hydraulic resistance factor of the holes at the damper tubes. A part of theses holes were damped after above-mentioned incidents at several reactor units with WWER-440 thus the flow rate through the fuel assemblies was increased at the expense of coolant flow rate through the control assemblies.

Flow rate through fuel assemblies is determined moreover by hydraulic resistance factor of throttle washer, placed at the input of fuel assembly. At Novovoronezh NPP 4 start up a wide range of work has fulfilled in order to choose the optimal diameter of throttle washer, as a result of those the flow rate through the fuel assemblies has reduced in comparison with Novovoronezh NPP, 3.

Between the actions of vibration refusals reasons elimination of fuel assemblies at Kola NPP, 2 – reduction of general coolant flow rate through the reactor, without redistributing between fuel assemblies and control assemblies as it was the case during 30-years history of unit operation.

Let us add to this, that the average number of refusals of fuel assemblies at project W-213 of WWER-440 with minimal coolant flow rate between all WWER-440 projects is 18 times less, than on the project W-230 of WWER-440[1]. The above-mentioned incidents and actions to their elimination make a speed of coolant through the reactor, fuel assemblies and control assemblies into the most essential parameters, determining their vibration loading.

The coolant flow rate through the reactor is calculated on the basis of head characteristics of the main circulation pump (error ± 5%), measured in preliminary and main tests in hydraulic measurements cycles at the simulated reactor core, and then are made more exact during the energetic putting into operation by balancing methods (error 3%).

Typical example, illustrated the uncertain in coolant flow rate measurement, is given in the book by the authors of Main designer company personal [4]. The example of precision of coolant flow rate measurement at Paksh NPP is considered (table 4), it reaches 9 per cent.

Table 4

Coolant flow rate measurement at Paksh NPP

Measurement		Average flow rate [m^3/hour]			
		Unit 1	Unit 2	Unit 3	Unit 4
Preliminary and main tests	According head characteristics of main circulation pump	43540	42760	43400	42700
	According pressure fluctuation at the simulated reactor core	42080	40520	41400	41500
Balancing measurements at the putting into operation		40500	40780	40600	40650
Additional balancing measurements after putting into operation		39750	39450	39900	40300

Another factor of the uncertain of preliminary and main tests in internals, fuel assemblies and control assemblies is – and it means coolant speed through them – coolant quality (inclusions as: different kinds of dredges causing scurf on fuel assemblies casings, on the internals casings and so on).

We have to establish the fact, that units elements changes of different WWER-440 designs in the period of their normal operation, causing to coolant flow rate changes, and all the above mentioned factors of the uncertain of coolant indirect flow rate measements, made essential estimations of different coolant flow rate of different WWER-440 units very imprecisely. In this connection the unique method of receiving quality measuring information about channel coolant flow rate through fuel assemblies under operating circumstances is neutron noise measuring method on the fluctuation basic of pressure fluctuation transducers. Except the decision of the question about vibration loading of fuel assemblies and control assemblies, this information together with the other measuring information (test field of energy-release, measured coolant temperature) lets us to precise the real state of hot conditions in reactor core.

4. Noise measurements of coolant speed per channel

The neutron-noise method of measuring coolant speed per channel is specified in the book (1). It focuses upon calculating the coolant speed on the basis of estimation of the delay time τ0 of SPND signal with respect to the signal of another SPND of a single neutron measurement channel provided the distance between them is known. τ0 parameter is revealed repeatedly in the function of coherence of signals of 2 SPND in the shape of abscissa of local extremums: local minimums are located at the points of 1/2τ, 3/2τ, 5/2τ,..... and local maximums are located at the points of 1/τ, 2/τ, 3/τ, ... The number of possible coherence functions for 7 SPND signals of a single neutron measurement channel is 21 pcs., and the number of local extremums of a single coherence function within the operating frequency range can be up to several pieces. Therefore, there are several tens of τ0 parameter estimations for a single neutron measurement channel, which presupposes high precision of speed estimation.

JSC “Diaprom” has conducted coolant speed noise measurements on the basis of fluctuations of SPND signals:

- at all 4 units of Kola NPP since 2002 up to now;
- at Novovoronezh NPP 3 and 4 in 2004 (for the first time for Novovoronezh NPP);
- at Bogunice NPP 1 and 2 since 2000.

The highest precision of estimation of the coolant speed per channel was achieved during the experiments at Bogunice NPP. At Bogunice NPP 1 the estimation of coolant speed, as average for all measurements, amounted to 3,85 m/sec, and the random component of the estimation error amounted to ±0,035m/sec (i.e. the random component of the estimation error was lower than 1%). This means that heat-hydraulic sources of in-core neutron noise exceeded vibration sources by their power.

Heat-hydraulic sources are formed due to the fluctuations of temperature and coolant speed and are transported upwards through the channel with the coolant speed. Neutron noise vibration sources are formed due to the vibrations of reactor vessel, internals, fuel assembly and emergency and control assembly. In neutron noise spectrums they are mostly represented as high-Q peaks, whose lowest types of vibrations are within the range (2,0 – 8,0) Hz. Therefore, these 2 types of neutron noise sources are competitive.

The vibration sources at Kola NPP 1 and 2 considerably exceed all other sources of neutron noise and as a matter of fact disguise them. At first two units of Kola NPP the monitoring of vibrations of vessel, core barrel, fuel assembly and emergency and control assembly is alleviated, but it is problematic to achieve high precision of measurements of speed per channel. Thus, the estimation of speed at Kola NPP 2 amounted to 4,00±0,12 m/sec (the error was 3%) in 2002, and after the cutting of the wheels of the Main Circulation Pump in 2003 it was 3,80±0,11 m/sec.

Available measurements for multiple neutron measurements channels enable to verify the hypothesis of equality of speeds per each channel, and in the case of several measurements per OP – to verify the hypothesis of invariability of coolant speed with time. Averaging out the data of neutron measurement channels and the measurements during all OP (if both the hypotheses are verified), we obtain the only high precision estimation of speed per channel, which characterizes all neutron measurement channels and all given OP. For example, for Bogunitse NPP the average coolant speed per channel in 4 consecutive OP from 21-st till 24-th was invariable in the statical sense and was within the design limitations range.

Table 5 gives the main factors of vibration loading of fuel assembly and internals of WWER-440 type:

- average for all neutron measurement channels coolant speed per channel – the information obtained from SPND fluctuations;
- ratio of power of heat-hydraulic and vibration sources of in-core (information obtained from SPND fluctuations and Pressure Fluctuations Sensor signals);
- condition of attachment points of core barrel – the information obtained from Absolute Displacement sensors signals, Ionization chamber and SPND fluctuations.

All vibration loading factors combined in Table 5 are obtained on the basis of the same estimation parameters (realization length, spectral resolution, number of averagings-out, etc.), which minimizes the effect the method error has on the final conclusions during comparison of different WWER-440 type units.

The units of WWER-440 type are arranged in Table 5 in the order of decreasing speed per channel and the right column of Table 5 shows in a relative way the condition of 3 horizons of core barrel attachment points.

The first 4 lines of Table 5 corresponding to Kola NPP 2, Bogunice NPP 1 and 2, Novovoronezh NPP 3 have approximately the same coolant speed per channel, that is ~3,8 m/sec. This is the major risk factor from the point of view of frequency of the fuel assembly vibration failures. For example, the vibration states of internals of Kola NPP 1 and 2 are very close; moreover, the core barrel vibration amplitude of Unit 1 is bigger than that of the 2-nd one. However, the frequency of fuel assembly failures of Unit 2 exceeds considerably the indices of unit 1. Apparently, the major reason for the above difference of Units 1 and 2 of Kola NPP is the difference of coolant speed.

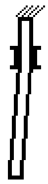
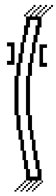
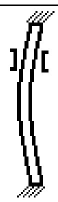
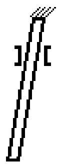
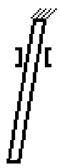
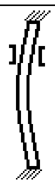
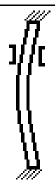
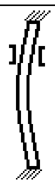
The safest units as to the vibration loading of internals and fuel assembly are Kola NPP 3 and 4. They have minimal coolant flow rate, almost design condition of core barrel attachment points and low power of vibration sources in the core due to the core barrel elliptic bottom.

It is rather difficult for WWER-440 to reveal the fuel assembly vibrations at own frequency. The main power of the fuel assembly vibrations can be observed at forced frequencies of core barrel vibrations and frequencies of acoustic standing waves. Fig. 3 gives families of auto power spectrum density signals from SPND of all neutron measurement channels of Kola NPP 1. The dominating peak is located at the frequency close to 5 Hz, which corresponds to the lowest type of core barrel vibrations. Vertical distribution of auto power spectrum density amplitudes at the given frequency bears information about the fuel assembly vibration mode, which is also a diagnostic indicator of the operating assembly vibration state. Mind, that the operating range for retrieving information about the value of coolant consumption per channel is (2,0 – 8,0) Hz. Therefore, the graphics given in fig.3 testify that in the middle of this range there is a vibration peak at the frequency of 5 Hz, which hampers the estimation of coolant speed at Kola NPP 1.

The coherence functions, given in fig.4, enable to sort 2 frequencies of the fuel assembly forced vibrations, conditioned by the vibrations of core barrel at own frequencies of 4,8 and 5,6 Hz. At these frequencies the core barrel produces near-circular but oppositely directed vibrations. Phase relationship among various SPND signals at these frequencies bear information about the averaged core barrel trajectory, which is also a diagnostic indicator of the fuel assembly condition.

Table 5

Main factors of vibration loading of internals and fuel assemblies

Unit	**Coolant channel speed [m/secк], year of noise measements**	**Proportion of warm hydraulic capacities (VH) and vibration (V) sources of in-core neutron noise**	**Attachment points conditions of core barrel**	
Kola NPP, 2	4,00±0,12 (2002), 3,80±0,11 (2003 – after wheel cut of the main circulation pump)	V>>VH		Lower bushing keys are worn out, the separator wrings on the core barrel (after preventive maintanance-2003)
Bogunice NPP, 1	3,85±0,035 (2000)	V<<VH		Lower bushing keys are in the first worn out stage
Bogunice NPP, 2	3,83±0,09(2002), 3,77±0,05(2004)	V<<VH		Lower bushing keys are in the first worn out stage
Novovoronezh NPP, 3	3,78±0,05 (2004)	V ~ VH (commensurable)		The lower centering cylinder on the core vessel floor is worn out
Kola NPP, 1	3,51±0,04 (2004)	V>VH		Lower bushing keys are worn out, the flow separator doesn't wring the core barrel properly
Novovoronezh NPP, 4	3,43±0,09 (2004)	V ~ VH (commensurable)		The lower cylinder at the core barrel floor is not essential
Kola NPP, 4	3,30±0,04 (2004)	V<<VH		close to the design
Kola NPP, 3	3,29±0,06 (2004)	V<<VH		close to the design

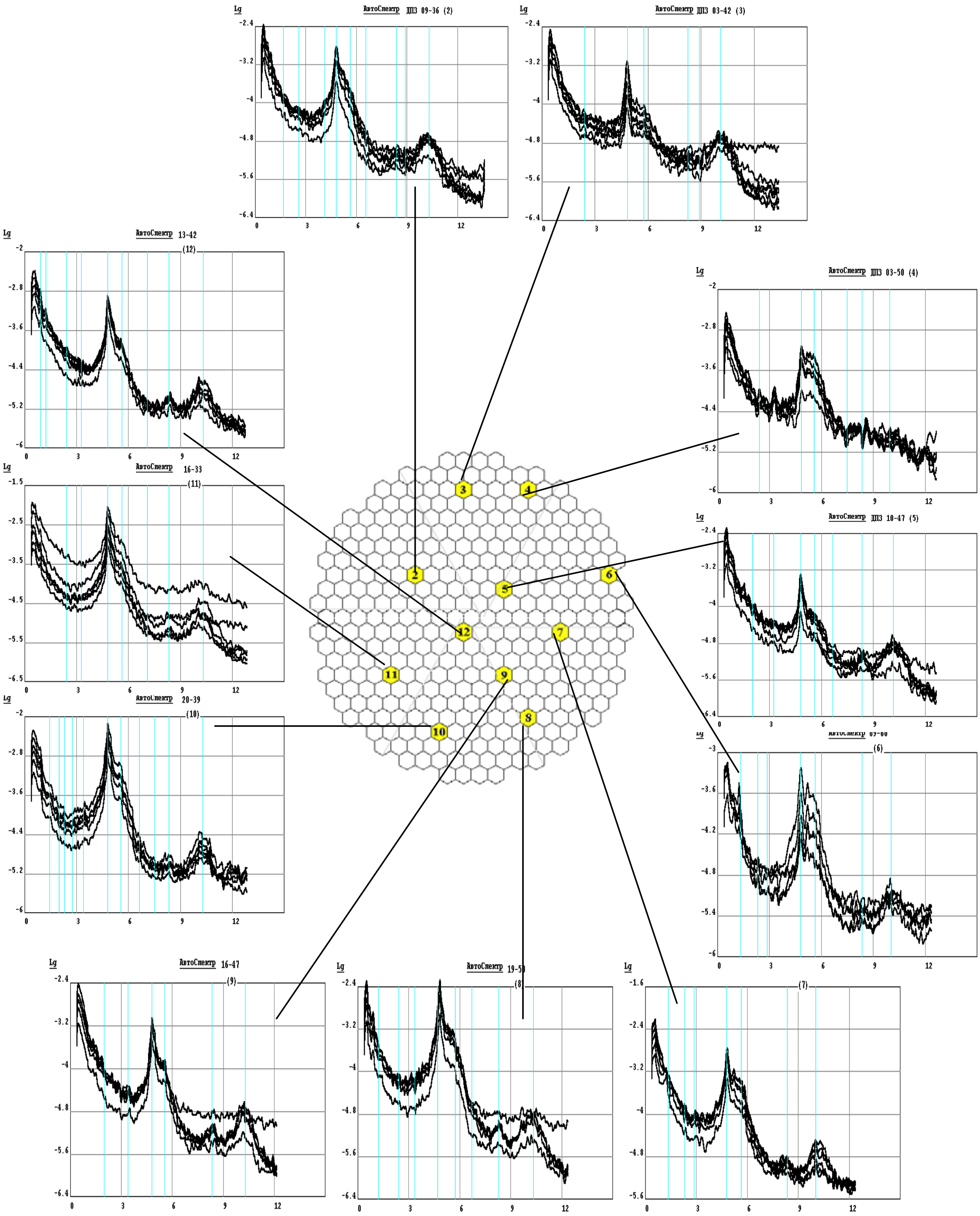


Figure 3. Auto power spectrum density group of SPND signals from 11 neutron measuring channels on Kola NPP, 1

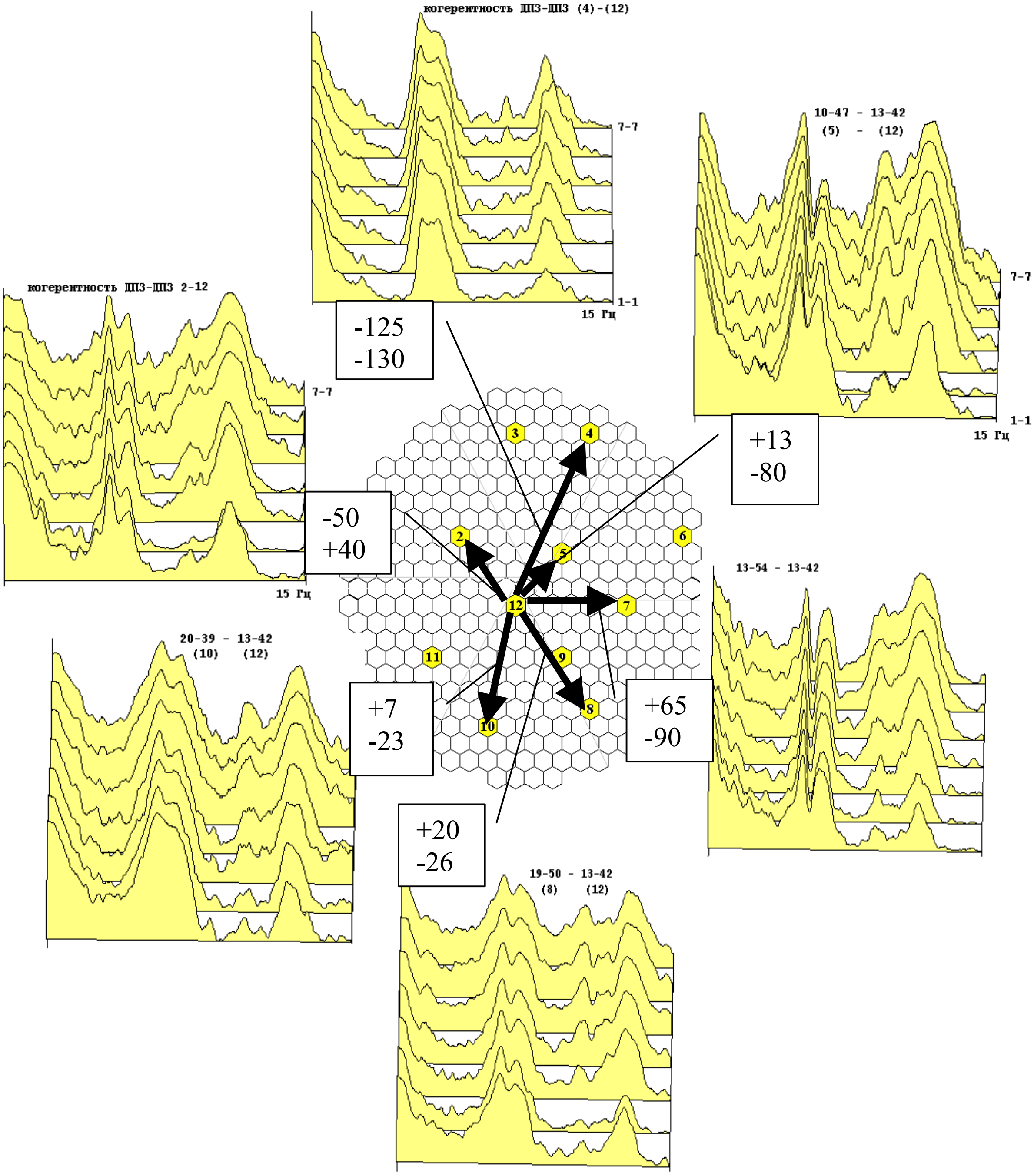


Figure 4. Coherences functions groups between two SPND of the same level. The figures are used to show the phase meaning at frequencies 4,8 Hz and 5,6 Hz. Kola NPP, 1.

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