Identification of sources of excitation of acoustic standing waves in the VVER-440 reactor unit

K N Proskuryakov¹, A I Fedorov² and M V Zaporozhets¹

¹National Research University "Moscow Power Engineering Institute"
Russia, 111250 Moscow, Krasnokazarmennaya, 14
²Novovoronezh Nuclear Power Plant, Novovoronezh, Russia

Abstract. Results of special measurements of coolant pressure oscillations in primary loops on unit No 3 of Novovoronezh NPP with VVER-440 are presented. Acoustical models and calculating algorithms for determinations of frequencies of acoustic standing waves (ASW) are designed. Models based on the Method of Electro-Acoustic Analogies gives a sensible interpretation of ASW sources. The calculated values of ASW frequencies for each acoustic element and for their compositions are presented. Identifying the sources of ASW in the first circuit held at all stages of the start-up power. Analysis of the results of comparison ASW rate with the measurement data of the main equipment vibration revealed a number of modes in which resonance of vibration with ASW occurs. Shown that developed approach can be used both in normal operation and in emergency modes for research and development of vibration - acoustic certification of reactor facilities; Improvements of process control and computer codes.

Introduction

Field experience gained from operation of nuclear power plants (NPPs) shows that the flows of working medium give rise to mechanical fluctuations and vibration of equipment and its elements. These processes are among the main factors determining the dynamic loads exerted on the equipment and the equipment service life and reliability. The most hazardous phenomena occur during interaction of equipment with a flow of fluid medium in the resonance fluctuation region of mechanical elements and flow, which gives rise to emergencies [1], [2]. For predicting the operation conditions under which resonance amplification of vibrations occurs and for determining the control measures to prevent their occurrence, it is necessary to develop vibro-acoustic certificates of the NPP reactor plant (RP). To this end, it is necessary to know the vibro-acoustic characteristics and, in particular, the natural vibration frequencies of equipment, of its elements and of their connections, as well as the natural oscillation frequencies of coolant in these systems in different modes of RP operation, when abnormalities occur, and in emergencies.

With the NPP RP’s vibro-acoustic certificate available, it becomes possible to develop methods and means to prevent the conditions causing the occurrence of resonance interaction between equipment vibrations and pulsations of coolant or working fluid in operational and emergency modes. To this end, it is necessary to ensure mismatch (discrepancy) between the peaks of spectral characteristics of signals from the sensors measuring working medium pressure pulsations and signals from the sensors measuring vibrations, displacements, and dynamic stresses.

Unsteady hydrodynamic processes in the coolant (elastic waves, turbulence, vortex generation, cavitations, etc.) and the main circulating pumps (MCPs) are the main sources exciting oscillations in
the primary coolant circuit of an NPP equipped with a water-cooled water moderated power generating reactor (commonly known in Russia and abroad as VVER). The oscillatory properties of the primary coolant circuit’s hydro mechanical system are not merely a superposition of the properties of its constituent pars (the reactor, steam generator, pressurizer (Pr.), pipelines, etc.), but acquire new systematic properties. The new qualitative effects resulting from the system properties of oscillatory processes in the reactor coolant circuit are determined by the nonlinear dependence of pressure difference across the circuit elements on the coolant mass flow rate.

Formulation of the problem
The calculated and experimental substantiation of the methods for predicting and preventing the onset of conditions under which vibro-acoustic resonances arise in the primary coolant circuits of VVER based NPPs is carried out for the following purposes:

- extending the service life, modernizing, and improving the design and engineering developments, technical diagnostic tools, and systems for controlling the technological processes at NPPs;
- reducing the probability of sudden equipment failures;
- optimizing the design and engineering solutions for ensuring seismic stability of an NPP as a whole taking into account the mutual influence of the dynamic processes that take place in NPP building structures and process systems and resonance amplification of dynamic stresses under the effect of external periodic loads.

Noise analysis in the VVER-440
Mechanical vibrations of the reactor pressure vessel (RPV) and reactor internals (RI) as well as standing pressure waves (SPW) could be detected and identified by analysis of the signals of the standard reactor instrumentation of pressurized water reactor (PWR) and VVER (Russian PWR-type reactors). The results of these measurements and identification demonstrate that noise analysis is of high usefulness for monitoring the mechanical and thermal hydraulic operating condition [3, 4].

The knowledge and monitoring of SPW can be very important for early failure detection, because even small changes in the thermal hydraulic conditions (changes of water level in pressurizer, temperature changes of cooling water, blockages, boiling etc.) will change the frequency of SPW in a forecasting way. These changes can be detected by noise analysis in a beginning stage.

Well known the effect of the forced vibrations of all primary loop components due to residual imbalances of the MCP due to the pressure fluctuations caused by it. As it showed in [1] the rotation frequency of MCP will be multiplied due to nonlinear properties of hydraulic elements of primary loops. The nonlinear hydraulic elements possess the property of transformation of the external periodic loads frequency. This means that the spectral function of the response to a harmonic impact contains new frequencies, which have not founded in the acting sources of oscillations.

The most hazardous phenomena occur during interaction of equipment with a flow of fluid medium in the resonance fluctuation region of mechanical elements and SPW, which gives rise to emergencies [1], [2]. For predicting the operation conditions under which resonance amplification of vibrations occurs and to prevent their occurrence, it is necessary to develop vibro-acoustic certificates of the NPP. To this end, it is necessary to know the vibro-acoustic characteristics and, in particular, the natural vibration frequencies of equipment, of its elements and of their connections, as well as the natural oscillation frequencies of coolant in these systems in different modes of operation, when abnormalities occur, and in emergency situations.

With the NPP RP’s vibro-acoustic certificate available, it becomes possible to develop methods and means to prevent the conditions causing the occurrence of resonance interaction between equipment vibrations and pulsations of coolant or working fluid in operational and emergency modes. To this end, it is necessary to ensure mismatch (discrepancy) between the peaks of spectral characteristics of
Signals from the sensors measuring working medium pressure pulsations and signals from the sensors measuring vibrations, displacements, and dynamic stresses.

Arising from the use of vibration significantly reduce the life of equipment, narrowing the range of acceptable modes of nuclear power, can cause serious accidents. In this connection, it is expedient development of mathematical models of acoustic vibrations of curved space and coolant pipes. Of particular importance is the use of one-dimensional models. They adequately describe the long-wavelength fluctuations of pipelines as well as acoustic oscillations of coolant, to determine the appropriate eigenfrequency and bandwidth of the acoustic circuit.

As noted in [2], important for reliable operation of equipment is the lack of coincidence between the natural frequencies of the interacting components of the system. It is important to understand that for thermal-hydraulic systems is a resonance phenomenon is observed both between the elements of equipment and external exciting force, and between equipment and working flow.

Determination of natural frequency, the rate of decay and other acoustic parameters for the working environment in the pipe, and more complex hydraulic systems, in general, is not certain.

In general, the system of equations describing the fluid dynamics of little use for the analysis of acoustic characteristics. One of the approximations used is to cast the equations of dynamics to the so-called telegraph equations.

The table 1 presents the list of the equivalent parameters [4].

**Table 1.** Equivalent parameters analogies.

| Parameter                  | Acoustic system | Unit        | Parameter                  | Electrical System | Unit        |
|----------------------------|-----------------|-------------|----------------------------|-------------------|-------------|
| pressure drop              | ΔP              | N/m²        | voltage                    | u                 | volt        |
| volume flow                | W               | m³/s        | current                    | i                 | Ampere      |
| acoustic compliance        | C               | m³ s⁻²/kg   | capacity                   | C                 | Farad       |
| acoustic weight            | m               | kg/m⁴       | inductance                 | L                 | Henry       |
| active resistance          | R               | kg/(s·m⁴)   | active resistance          | R                 | Ohm         |
| reactance                  | X               | kg/(s·m⁴)   | reactance                  | X                 | Ohm         |
| active power               | NR              | Watt        | active power               | P                 | Watt        |
| reactive power             | NX              | Watt        | reactive power             | Q                 | Var         |
| wave resistance            | Zw              | kg/(s·m⁴)   | wave resistance            | Zw                | Ohm         |
| Own circular frequency     | ω₀               | rad/s       | Own circular frequency     | ω₀               | rad/s       |
| eigenfrequency             | f₀               | Hz          | eigenfrequency             | f₀                | Hz          |
| The bandwidth              | Δf               | Hz          | The bandwidth              | Δf                | Hz          |

Like any constructive element, which has elasticity, heat transfer fluid has its own frequency, which may resonate with the sources of disturbances at the frequencies or less distinct lines in the spectrum (on site), the frequency of the working body is different frequency sources of hydrodynamic perturbations. To calculate the natural frequency of the coolant used method of electro-acoustic analogies.
Acoustic characteristics of the UNIT 3 of Novovoronezh NPP with VVER-440

Worked out methods of calculating the eigenfrequency of the coolant pressure oscillation (ECPO) in the first loop equipment is based on the using of the value hydraulic shock velocity (HSW) instead of using the value propagation of sound velocity in the working environment. Such an approach is correct also when considering the water-steam circuit, or boiling water reactors (BWR). Single-loop design of Reactor VVER-440 of Novovoronezh NPP shown in Figure 1.

**Figure 1.** Single-loop design of Reactor VVER-440 of Novovoronezh NPP.

Acoustic elements: 1 - down camera, 2 - bottom plenum, 3 - reactor core, 4 - top plenum, 5 - «a hot loop» from a reactor up to an input in hot collector steam generator (SG), 6,9 - the respiratory pipelines, 7 - volume of water in pressurizer (Pr.), 8 - volume of steam in pressurizer, 10 - a «hot loop» from valve to hot collector, 11 - hot collector of SG, 12 - tubes, 13 - cold collector SG, 14 - «a cold loop» from an output from cold collector of SG up to MCP, 15 - «cold loop» from MCP to the valve, 16 - «cold loop» from MCP to reactor pressure vessel.

Single-loop Acoustic Scheme of Reactor VVER-440 of Novovoronezh NPP shown in Figure 2.

**Figure 2.** Single-loop Acoustic Scheme of Reactor VVER-440 of Novovoronezh NPP.

Acoustic elements: 1 - down camera, 2 - bottom plenum, 3 - reactor core, 4 - top plenum, 5 - «a hot loop» from a reactor up to an input in hot collector steam generator (SG), 6,9 - the respiratory pipelines, 7 - volume of water in pressurizer (Pr.), 8 - volume of steam in pressurizer, 10 - a «hot loop» from valve to hot collector, 11 - hot collector of SG, 12 - tubes, 13 - cold collector SG, 14 - «a cold loop» from an output from cold collector of SG up to MCP, 15 - «cold loop» from MCP to the valve, 16 - «cold loop» from MCP to reactor pressure vessel. Sensor Position at Novovoronezh NPP with VVER-440 is showed in Figure 3.
Figure 3. Sensor Position at Novovoronezh NPP with VVER-440.

P – Pressure Sensor; R – Relative Displacement Sensor; A– Absolute Displacement Sensor.

Results of special measurements of coolant pressure oscillations in primary loops on unit No 3 of Novovoronezh NPP with VVER-440

Table 2 shows the measuring values of the dominant peak frequencies in the spectrum obtained by pressure pulsations sensor in nominal mode; calculated values of eigenfrequencies of coolant pressure oscillation (EFCPO) for each acoustic element and their compositions and the value of difference.

| $N_{sec}$ | $f_{calc}$ | $f_{meas}$ | $\Delta f$ | $N_{sec}$ | $f_{calc}$ | $f_{meas}$ | $\Delta f$ |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 1         | 17.5      | 17.7      | -0.2      | 1+2       | 10.9      | 11.0      | -0.1      |
| 2         | 42.8      | 42.7      | 0.1       | 1+2+3+4   | 6.1       | 6.6       | -0.5      |
| 3         | 64.9      |           |           | 10+11     | 16.3      | 16.3      | 0.0       |
| 4         | 24.5      | 24.7      | -0.2      | 13+14     | 12.2      | 12.7      | -0.5      |
| 5         | 17.3      | 17.7      | -0.4      | 11+12+13  | 8.9       | 8.8       | 0.1       |
| 6         | 6.3       | 6.6       | -0.3      | 10+11+12+13+14 | 4.5 | 4.5 | 0.0 |
| 7         | 23.9      | 23.6      | 0.3       |           |           |           |           |
| 8         | 11.5      | 11.4      | 0.1       | 7+8       | 3.8       | 3.8       | 0.0       |
| 9         | 5.9       | 6.6       | -0.7      | 6+7       | 0.8       | 0.8       | 0.0       |
| 10        | 37.0      | 36.6      | 0.4       | 9+7       | 0.8       | 0.8       | 0.0       |
| 11        | 35.7      | 35.1      | 0.6       | 6+7+8     | 0.1       | -         | -         |
| 12        | 17.4      | 17.7      | -0.3      | 9+7+8     | 0.1       | -         | -         |
| 13        | 40.9      | 41.4      | -0.5      | 16+1+2    | 4.5       | 4.5       | 0.0       |
| 14        | 20.0      | 19.5      | 0.5       | 16+1+2+3  | 4.1       | 3.8       | 0.3       |
| 15        | 54.8      |           |           | 16+1+2+3+4 | 2.8 | 3.4 | 0.6 |
| 16        | 35.0      | 35.1      | -0.1      | 16+1+2+3+4+5 | 1.9 | 2.1 | 0.2 |
| 16+1      | 6.9       | 6.6       | 0.3       |           |           |           |           |

The following abbreviations are used in Table 2:

$f_{meas}$ – dominant frequency peak in the spectrum obtained from the pressure sensor ripple, Hz;

$f_{calc}$ – calculated ECPO at the sector $N_{sec}$, Hz;

$\Delta f$ – difference between the calculation and measurement , Hz;

$N_{sec}$ – Number of acoustic circuit section.

APSD WWER-440 (unit 3 of Novovoronezh NPP) is presented in Figure 4.
Figure 4. APSD WWER-440 (unit 3 of Novovoronezh NPP) obtained by pressure pulsations sensor in nominal mode.

It should be pointed out that the natural coolant pressure pulsations caused by elastic waves do not have a strictly fixed frequency and usually manifest themselves in the definite range Hz depending on many factors (the equipment acoustic parameters, which are individual for each power unit; the temperature and pressure parameters; the level in the pressurizer - H; etc.) [5, 6].

It should be pointed also that pressurizer manifest itself as controlled Helmholtz resonator generating a number of SPW (with eigenfrequencies of steam volume, water volume and their combination with coolant volume of respiratory line) [5].

The values of the geometric characteristics of acoustic circuit sections adopted in accordance with the project of the first circuit unit 3 of Novovoronezh NPP. The propagation velocity of acoustic waves is determined in accordance with [7].

Identifying the sources of ASW in the first circuit

Table 3 shows the calculated values of ASW frequencies in Acoustic circuit section in start-up mode № 3 WWER-440 (unit 3 of Novovoronezh NPP)

| № of Acoustic circuit section | ASW frequency, Hz |
|-------------------------------|-------------------|
| 1                             | 17.5              |
| 2                             | 42.8              |
| 3                             | 64.9              |
| 4                             | 24.5              |
| 5                             | 17.3              |
| 6                             | 6.3               |
| 7                             | 25.2              |
| 8                             | 10.9              |
| 9                             | 5.9               |
| 10                            | 37.0              |
| 11                            | 35.7              |
| 12                            | 17.5              |
| 13                            | 40.9              |
| 14                            | 20                |
| 15                            | 54.8              |
| 16                            | 35.0              |

Table 4 shows the calculated values of ASW frequencies in compositions of Acoustic circuit section WWER-440 (unit 3 of Novovoronezh NPP).
Table 4. Calculated values of ASW frequencies in compositions of acoustic circuit section for start-up mode № 3.

| Number of Acoustic circuit sections included in the combinational circuits | ASW frequency, Hz start-up mode № 3 |
|---|---|
| 16+1 | 6.9 |
| 16+1+2 | 4.5 |
| 16+1+2+3 | 4.1 |
| 16+1+2+3+4 | 2.8 |
| 16+1+2+3+4+5 | 1.9 |
| 1+2 | 10.9 |
| 1+2+3 | 9.3 |
| 1+2+3+4 | 6.1 |
| 10+11 | 16.3 |
| 13+14 | 12.2 |
| 11+12+13 | 8.9 |
| 10+11+12+13+14 | 4.5 |
| 7+8 | 3.8 |
| 6+7 | 0.8 |
| 9+7 | 0.8 |
| 6+7+8 | 0.1 |
| 9+7+8 | 0.1 |

APSD VVER-440 (unit 3 of Novovoronezh NPP) of pressure pulsations sensor in the start-up mode № 3 shown in Figure 5.

Table 5 shows the measuring values of the dominant peak frequencies in APSD obtained by pressure pulsations sensor in start-up mode № 3 and calculated values of eigenfrequencies of coolant pressure oscillation (EFCPO), i.e. of ASW, for each acoustic element and their compositions and the value of difference.

Figure 5. APSD VVER-440 (unit 3 of Novovoronezh NPP) of pressure pulsations sensor in the start-up mode № 3.
Table 5. Comparing the calculation results of ASW frequency with measured data of pressure pulsations sensor in the start-up mode № 3.

| N_sector | f_{calc} | f_{meas} | ∆f  | N_sector | f_{calc} | f_{meas} | ∆f  |
|----------|----------|----------|-----|----------|----------|----------|-----|
| 1        | 17.5     | 17.7     | -0.2| 1+2      | 10.9     | 11.0     | -0.1|
| 2        | 42.8     | 42.7     | 0.1 | 1+2+3    | 9.3      | 9.5      | -0.2|
| 3        | 64.9     | -        | -   | 1+2+3+4  | 6.1      | 6.6      | -0.5|
| 4        | 24.5     | 24.7     | -0.2| 10+11    | 16.3     | 16.3     | 0.0 |
| 5        | 17.3     | 17.7     | -0.4| 13+14    | 12.2     | 12.7     | -0.5|
| 6        | 6.3      | 6.6      | -0.3| 11+12+13 | 8.9      | 8.8      | 0.1 |
| 7        | 23.9     | 23.6     | 0.3 | 10+11+12+13+14 | 4.5 | 4.5 | 0.0 |
| 8        | 11.5     | 11.4     | 0.1 | 7+8      | 3.8      | 3.8      | 0.0 |
| 9        | 5.9      | 6.6      | -0.7| 6+7      | 0.8      | 0.8      | 0.0 |
| 10       | 37.0     | 36.6     | 0.4 | 9+7      | 0.8      | 0.8      | 0.0 |
| 11       | 35.7     | 35.1     | 0.6 | 6+7+8    | 0.1      | -        | -   |
| 12       | 17.4     | 17.7     | -0.3| 9+7+8    | 0.1      | -        | -   |
| 13       | 40.9     | 41.4     | -0.5| 16+1+2   | 4.5      | 4.5      | 0.0 |
| 14       | 20.0     | 19.5     | 0.5 | 16+1+2+3 | 4.1      | 3.8      | 0.3 |
| 15       | 54.8     | -        | -   | 16+1+2+3+4 | 2.8 | 3.4 | 0.6 |
| 16       | 35.0     | 35.1     | -0.1| 16+1+2+3+4+5 | 1.9 | 2.1 | 0.2 |
| 16+1     | 6.9      | 6.6      | 0.3 |

An approximate estimate of the error in the calculation of the ASB frequencies was carried out by the method of [9].

**Resonances of the ASW with the vibrations of the equipment**

Identification of sources of DIA in the primary circuit was carried out in all 18 stages of the start-up of the power unit.

The results of calculating the frequency of the ASW for all stages are compared with the vibration measurements of the main equipment of the primary circuit given in [8]. The results of the comparison indicate that in the elements of the NPP equipment listed below, in the stages of the start-up phases studied, resonances of the ASW with the vibrations of the equipment may occur:

1.5 - 3.0 Hz - vibration frequencies of fuel assemblies with one fixed end are observed:

- in the combinational circuit (16 + 1 + 2 + 3 + 4) from the cold phase of the cold thread to the exit from the core in the temperature range 281-296 °C and pressure 12.1 - 12.3 MPa at the reactor outlet;
- in the combinational circuit (16 + 1 + 2 + 3 + 4 + 5) from the cold seam of cold thread to the hot dip galvanizing line in the range of temperature and pressure at the outlet of the reactor, respectively, 60-296 °C and 1.8 - 12.3 MPa;
- in the pressure compensator (7 + 8, where 8 - nitrogen pad) in the range of temperature and pressure, respectively, 95-232 °C and 2.9 - 7.1 MPa;
- in the combination circuit (6 + 7), including the left connecting pipe of the pressure compensation system and the water volume of the compensator itself in the range of temperature and pressure in the compensator, respectively, 74 – 197 °C and 1.8-7.0 MPa and the connecting pipeline 67-175 °C and 1.8-7.0 MPa;
- in the combination circuit (9 + 7), including the right connecting pipe of the pressure compensation system and the water volume of the compensator itself in the range of temperature and pressure in the compensator, respectively, 74 – 140 °C and 1.8 - 4.8 MPa and the connecting pipeline 67-138 °C and 1.8 - 4.8 MPa.
4.0 - 6.0 Hz - vibrations frequencies of TVS with two fixed ends are observed in:

- the left connection line of the pressure compensation system (section 6) at a temperature of 310 °C and a pressure of 12.2 MPa;
- Combination circuit (16 + 1 + 2) from the cold-gasification process of the cold line to the lower part of the core in the range of temperature and pressure at the outlet of the reactor, respectively, 60 - 296 °C and 1.8 - 8.3 MPa;
- Combination contour (16 + 1 + 2 + 3) from the cold seam of cold thread to the top of the core in the range of temperature and pressure at the outlet of the reactor, respectively, 60 - 296 °C and 1.8 - 12.3 MPa;
- Combination circuit (10 + 11 + 12 + 13 + 14) from the hot dip galvanizing line to the MCP in the range of temperature and pressure at the reactor outlet, respectively, 201 - 296 °C and 7.3 - 12.3 MPa.

8.0 - 12.0 Hz - The second mode of TVS oscillations with two fixed ends is observed in:

- the left connection line of the pressure compensation system (section 6) in the range of temperature and pressure, respectively 67 – 219 °C and 1.8 - 8.9 MPa;
- the right connecting pipe of the pressure compensation system (section 9) in the range of temperature and pressure, respectively 67 - 219 °C and 1.8 - 8.9 MPa;
- Nitrogen volume of CD (section 8) in the range of temperature and pressure, respectively, 74 – 232 °C and 1.8 - 7.1 MPa;
- steam volume of CD (section 8) at a temperature of 326 °C and pressure 12.0 MPa;
- a combination circuit (16 + 1) from the cold-gasification process of the cold line to the lower part of the reactor downcomer in the range of temperature and pressure at the reactor outlet, respectively, 60 – 201 °C and 1.8 - 7.3 MPa;
- Combination circuit (1 + 2) from the beginning of the descending section of the reactor to the lower part of the core in the range of temperature and pressure at the outlet of the reactor, respectively, 241 – 296 °C and 10.7 - 12.3 MPa;
- Combination circuit (1 + 2 + 3) from the beginning of the lower section of the reactor to the upper part of the core in the range of temperature and pressure at the reactor outlet, respectively, 136-296 °C and 4.8 - 12.3 MPa;
- Combination circuit (1 + 2 + 3 + 4) from the beginning of the descending section of the reactor to the exit from the reactor in the range of temperature and pressure at the reactor outlet, respectively, 60 – 136 °C and 1.8 - 4.8 MPa;
- Combination circuit (11 + 12 + 13) from the beginning of the cold collector to the end of the hot collector in the range of temperature and pressure at the outlet of the reactor, respectively 172 - 296 °C and 7.0 - 12.3 MPa.

6.6 Hz - the frequencies of forced oscillations of the hull caused by the ASV coincide with the frequencies of the SCCHDT in:

- the left supply pipeline (section 6) at a temperature of 302 °C and a pressure of 12.2 MPa;
- the right supply pipeline (section 9) at a temperature of 293 °C and a pressure of 12.2 MPa;
- Combination circuit (1 + 2 + 3 + 4) from the beginning of the descending section of the reactor to the exit from the reactor at the temperature and pressure at the outlet of the reactor, respectively 268 °C and 12.2 MPa.
11.5 - 13.5 Hz - the frequencies of the pendulum oscillations together with the case are observed in:

- nitrogen volume of the pressure compensator (section 8) in the range of temperature and pressure, respectively, 232-301 °C and 7.1-10.7 MPa;
- a combination circuit (1 + 2) from the beginning of the descending section of the reactor to the lower part of the core in the range of temperature and pressure at the outlet of the reactor, respectively 172 – 241 °C and 7.0 - 10.7 MPa;
- Combination circuit (1 + 2 + 3) from the beginning of the descending section of the reactor to the upper part of the core in the range of temperature and pressure at the outlet of the reactor, respectively, 60 – 136 °C and 1.8 - 4.8 MPa;
- in the combination circuit (13 + 14), which includes the cold collector PG and the fcc section from the collector to the MCP in the range of temperature and pressure at the outlet of the reactor, respectively, 241 - 296 °C and 10.7 - 12.3 MPa;
- Combination circuit (11 + 12 + 13) from the beginning of the cold collector to the end of the hot collector in the range of temperature and pressure at the outlet of the reactor, respectively, 60 – 172 °C and 1.8 - 7.0 MPa.

16.0 - 17.0 Hz - the frequencies of the vertical oscillations of the housing coincide with the frequencies of the ACB in:

- in the combination circuit (13 + 14), which includes the cold collector of the PG and the fcc section from the collector to the MCP at a temperature of 61-136 °C and a pressure of 1.77 - 4.6 MPa;
- in the combinational circuit (10 + 11), which includes the hot collector of the SG and the fcc section from the collector to the GPB at a temperature of 60-136 °C and a pressure of 1.77 - 4.8 MPa.

14.2 Hz - the oscillation frequency of the reactor shaft with two fixed ends is observed in the combination circuit, which includes the cold collector of the SG and the FCC section from the collector to the MCP at a temperature of 201-219 °C and a pressure of 7.1-8.7 MPa.

25 Hz - the reverse frequency of the pump can be observed in: space above the core at a pressure of 12.2 MPa and temperature 287-296 °C;

The area from the cold collector PG to the MCP at a pressure of 4.6 - 6.8 MPa and a temperature of 136-172 °C.

50 Hz - the doubled circulating frequency of the pump coincides with the calculated DIA frequencies in:

- the hot SG collector at a temperature of 172-200 °C and pressure 6.9 - 7.1 MPa;
- space under the active zone at a temperature of 173 °C and pressure 7.1 MPa.

The results of measurements confirm the validity of calculation by developed technique

The modes in which vibration- acoustical resonances appears in the main equipment of unit 3 of Novovoronezh NPP frequencies ASW are determined.

In assessing the residual life should take into account the duration of vibration acoustical resonances in the derivation of the reactor to nominal power level and number of starts (stops) of NPP unit for the entire period of operation of the power unit.

The developed model can be used for the following tasks:

- Development of vibro-acoustic certification of reactor facilities;
- Diagnosis, prognosis and prevention of conditions of vibration- acoustic resonances appearance;
• Improvement of process control;
• Study design and design decisions in the selection of equipment and layout of the reactor heat removal systems;
• Improvement of computer code.

Conclusions
Worked out models of sources of excitation of acoustic standing waves in the VVER units will allow giving a scientific substantiation of directions of modernization and improvement of the design development, technical diagnostics and process control systems, NPP. These new systems will be an important additional means of improving the safety, efficiency and operating life, both existing and planned NPP.
The developed methods and algorithms for the identification of the sources of the SPW in the primary circuit of NPP with VVER and PWR are designed for use in the following thematic areas of current research and design work, which should be reflected in the work of the industry:

• Justification for the integrity of the main equipment on the life of 60-80 years;
• Study the possibility of extending the operation of existing units over the design life;
• Study the possibility of prediction and prevention of vibro-acoustic resonances in the nuclear power plant equipment in maneuvering and emergency modes, as well as under the influence of shock and seismic loads.

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