Computer modeling of acoustic standing waves in the coolant of nuclear power plants

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Abstract. In nuclear power plants (NPPs), the dynamic interactions of the coolant with the structures are among the main factors determining the dynamic loads on the equipments, its service life and reliability. The most hazardous is the resonant interaction of vibrations of the equipment with acoustic standing waves (ASW) that arise in accidental conditions. It is pointed out that the study of accident conditions on a full-scale object model is not possible and, accordingly, the development of adequate computer models to simulate the conditions is of prime importance. The analysis of acoustic systems with single-phase and two-phase fluid media is based on the theory of elastic wave propagation in liquids and gases. The analysis is based on the equations of fluid state, equations of motion, continuity equation and the equation expressing the law of conservation of energy. It is shown that in view of the unity of the differential equations of acoustic and electrical systems, the study of the propagation of the volume flow rate of one-dimensional pulsating flow of a compressible single-phase or two-phase fluid in the acoustic system can be replaced by the study of the propagation of electric current in the lines of electrical circuits. The paper presents an acoustic scheme of the NPP coolant circuit formed by acoustic elements considering their inherent thermal-hydraulic and geometric parameters. It is shown that the results of calculations of the frequencies of the ASW are confirmed by the measurements carried out at the NPP.

1. Introduction
The operational experience of nuclear power plants (NPP) shows that the fluid flow causes vibrations of equipment and their elements. These processes are among the main factors determining the dynamic loads on the equipments, their service life and reliability. The most hazardous case occurs due to resonant interaction of vibrations of equipment with acoustic standing waves (ASW) arising in the coolant [1].

One of the most important mechanical systems that determine the reliability and safety of nuclear reactors are fuel assemblies (FA). To improve the economic performance of the nuclear fuel cycle and achieve the required level of safety, it is necessary to increase the service life and reliability of fuel assemblies and fuel rods (FR). The solution of these problems is largely related to the vibration processes in the structural elements upon the impact of the coolant flow.

To predict the reliability of existing FA and substantiate the reliability of new FA designs, research have been carried out on vibration and hydrodynamic processes, including test loops, computational modeling and vibration control during commissioning tests and in operating reactors. The FA under operating conditions, is a hydro elastic oscillatory system consisting of two interacting
subsystems – mechanical and hydrodynamic. Currently, the mechanical subsystem is the most studied part and for which there already exists a sufficiently reliable computational analysis. The hydrodynamic subsystem, due to the complexity of the description of the processes of formation of random hydrodynamic loads on streamlined surfaces, and due to the influence of thermal-hydraulic and acoustic characteristics of the flow on the occurrence of self-excited oscillations, has been studied to a large extent, insufficiently.

It is very important to be able to predict adequately FA reliability, since its experimental study in an operating reactor is impossible, and it is also not possible to reproduce the interrelations of thermal-hydraulic, neutron-physical and vibroacoustic processes that determine the complicated dynamic loads.

The principles of mathematical modeling of mechanical systems are known, which allows to analyze both the oscillations of FA (usually, low-frequency) and the oscillations of individual fuel rods. As it is known, the main sources of excitation of oscillations, are non-stationary hydrodynamic processes in the coolant (acoustic waves, turbulence, vortex formation, cavitation, etc.) and the imbalance of rotating mechanisms, primarily circulation pumps (mechanical forces). In this case, the vibrational characteristics of the acoustic system of the coolant are not reduced to the sum of the properties of its individual elements, since the interaction of vibrational processes in these elements gives the system new properties that are not present in individual elements.

2. The method of electro-acoustic analogies
In modern acoustics, methods of solving problems that are borrowed from electrical engineering are widely used. This became possible due to the fact that in many fields of physics, including acoustics and in electrical engineering, many problems are described by the same differential equations. The rapid development of electrical and radio engineering has led to a more complete study of similar problems in electrical systems.

Combination of individual acoustic elements can lead to formation of complex devices, which are similar in their action to various electrical (or mechanical) systems. If the geometrical dimensions of these devices are small compared to the length of acoustic waves, then such devices could be considered systems with concentrated rather than distributed parameters. The analysis of acoustic systems with single-phase fluid media is based on the theory of elastic wave propagation in liquids and gases [2, 3]. The analysis is based on the equations of fluid state, equations of motion, continuity equation and the equation expressing the law of conservation of energy.

An important stage in the development of methods for analyzing acoustic systems of coolant in nuclear power plants was the justification of the validity of electroacoustic analogies for one-dimensional pulsating flow of a two-phase medium, both with single valued and multi-valued hydrodynamic characteristics [4]. Taking into account the assumption that the sound pressure $\Delta p$ at all points along the channel length is only a function of time, the equations of continuity and conservation of momentum of a one-dimensional pulsating flow of a two-phase medium are obtained in the form of a system of linear differential equations

\[
\begin{align*}
\frac{\partial \omega}{\partial x} + \frac{1}{a} \frac{\partial p}{\partial t} + G_a \Delta p &= 0 \\
\frac{\partial \Delta p}{\partial x} + m \frac{\partial \omega}{\partial t} + R_a W &= 0
\end{align*}
\]

Here $\Delta p$ is the pressure change, which occurs during the passage of a sound wave in a fluid, in steam or in a mixture environment (sound pressure). The sound wave when propagating in a fluid, forms compression and rarefaction, which create pressure changes in relation to the average static pressure $p$.

$W$ is volumetric flow rate of the coolant in the pipe; $L$ is the length of the pipe; $S$ is the cross section of the pipe; $C_a = \frac{L S}{k p}$ is the acoustic compliance of the medium; $a$ is the speed of sound; $k$ is the adiabatic factor; $R_a$ is the active acoustical resistance of fluid flow; $G_a = \frac{1}{k} \frac{W - L}{p}$ is the wave...
conductivity of the medium; \( m = \frac{\rho_{lv}L}{s} \) is the acoustic mass; \( \rho_{lv} \) is the density of the two-phase (liquid and vapor) medium.

These equations are known in the literature under the name of Telegraph equations [5]. The solution of the system of linear differential equations (1) gives functional dependences of sound pressure and volume flow of the compressed medium in the pipeline with distributed constant acoustic compliance of the medium, acoustic mass, wave conductivity of the medium, and active resistance of the medium flow on variables \( x \) (distance along the pipeline axis) and \( t \) (time).

The solution of system of linear differential equations (2) gives functional dependences of electric current \( i \) propagation along the cable and voltage \( u \) with distributed constant capacitance \( C \), inductance \( L \), conductivity \( G \) and ohmic resistance \( R \)

\[
\begin{align*}
\frac{\partial i}{\partial x} + C \frac{\partial u}{\partial t} + Gu &= 0 \\
\frac{\partial u}{\partial x} + L \frac{\partial i}{\partial t} + Ri &= 0 \quad (2)
\end{align*}
\]

Due to the unity of the differential equations of acoustic (1) and electric (2) systems, the study of the propagation of the volume flow of a compressible single-phase or two-phase fluid in the acoustic system can be replaced by the study of the propagation of an electric current along the cable [4].

From the joint consideration of systems (1) and (2), a number of analogies between acoustic and electrical quantities follow. These analogies are shown in table 1.

| Table1. Analogies between acoustic and electrical parameters. |
|-------------------------------------------------------------|
| Acoustic system | Electrical system | \( \Delta p \) | \( Pa \) | \( \rho_{lv} \) | \( kg/m^3 \) | \( V \) | \( u \) | \( m^3/s \) | \( i \) | \( A \) | \( C \) | \( F \) | \( L \) | \( H \) | \( R \) | \( \Omega \) |
| Sound pressure | Parameter symbol | measurement unit | Parameter symbol | measurement unit |
| Volume flow rate | \( W \) | \( m^3/s \) | Current | \( i \) | \( A \) |
| Acoustic compliance | \( C_a \) | \( m^4/s^2/kg \) | Capacitance | \( C \) | \( F \) |
| Acoustic mass | \( m \) | \( kg/m^4 \) | Inductance | \( L \) | \( H \) |
| Active acoustical resistance | \( R_a \) | \( kg/m^5/s \) | Active resistance | \( R \) | \( \Omega \) |

The acoustic systems are introduced in the form of a set of electrical circuits and the resulting electrical circuit (equivalent) is analyzed by methods developed in electrical engineering. As shown in [6], in the system of electroacoustical analogy, a longitudinal element of a pipe is equivalent to a passive quadric pole made in the form of a power transmission line segment. Thus, the self frequency of liquid pressure fluctuations in the pipe is determined by the formula

\[
f_0 = \frac{1}{2\pi\sqrt{m_c}} \sqrt{\frac{1}{m_c e}} \quad (3)
\]

For any segment \( i \) satisfying the conditions in [4, 6]
where \( a_i \), m/s – the speed of sound in the liquid in the pipe; \( \rho_i \), m/s – the density of the liquid; \( L_i, S_i \) – the length, and the cross-sectional area of the \( i \)-th section, respectively.

For \( n \) segments connected in series:

\[
C_a = \sum_{i=1}^{n} C_{ai} \quad m = \sum_{i=1}^{n} m_i \quad f_0 = \frac{1}{2\pi \sqrt{m \cdot C_a}}
\]

The problem of developing acoustic models of coolant motion in the main NPP equipments, its individual components and in a set of structural elements was first solved in [4]. Developed methods of modeling and calculation of acoustic waves in the coolant of nuclear power plants allowed to their author K. N. Proskuryakov create an acoustic model of a nuclear reactor and organize its testing and verification at a nuclear power plant with a light water reactor.

The radiation of elastic waves by the coolant flow was investigated in paper [7]. A method of acoustic measurements, has been developed to identify hazardous modes associated with the processes of spontaneous vortex formation and self excited swirling of the streams of coolant. The experimental method is based on the measurement of the amplitude-frequency characteristics of sound vibrations in a swirling jet. In contrast to traditional methods of non-destructive testing of thermal-hydraulic parameters, such as ultrasonic, radiation, and magnetic, a new method of acoustic resonances is used in this research work. This method allows to register the radiation of elastic waves by fluid caused by local dynamic reformation of its structure and to predict the appearance of dangerous periodic fluctuations, the frequencies of which are close to the natural frequencies of the NPP components.

It was found that in the resonant flow mode, the flow decomposes into separate spiral vortices, the rotational frequency of which coincides with the natural frequency of bending vibrations of the end surface of the vortex chamber.

Some special series of experiments have shown that in the critical transition region corresponding to the frequency range of acoustic oscillations generated during the formation of a system of stable coherent spiral-vortex structures, the sound pressure recorded by the amplitude-frequency characteristics, increases by 2 to 3 orders of magnitude. Therefore, when the vortex frequencies approach to the natural frequencies of the hydro-mechanical system, the probability of detecting a dangerous resonance mode increases due to a sharp increase in the amplitude of the signal. The research results are aimed at the development of theoretical foundations and instrument complex to provide the technology of vortex diagnostics of the coolant flow states of nuclear power plants.

3. Development of methods for predicting and preventing acoustic oscillations of the coolant, that lead to amplification of fuel rod and fuel assembly vibrations

As a result of the conducted research studies, some methods and algorithms of calculations have been already developed to predict and to prevent the conditions for the increase of vibrations of fuel rods and fuel assemblies due to acoustic vibrations of the coolant. The dependence of the bandwidth on the operation mode of the reactor plant is investigated. For this purpose, an acoustic model of the coolant in the core is used, in which the presence of the gas phase formed during radiolysis, is taken into account.
The algorithms for calculation of the quality factor for the coolant oscillating circuit and the bandwidth are given in paper [8], that makes it possible to specify the location of the fuel assemblies with an increased level of vibration in the investigated mode of operation of VVER-1000 core. It should be emphasized that the appearance of acoustic vibration frequencies and vibrations in the bandwidth is possible only at a certain value of the average temperature of the coolant in the fuel assembly.

The developed methods and algorithms can be used for quantitative estimates of the natural frequency of coolant pressure fluctuations, quality factor and bandwidth of the acoustic elements of the primary circuit and their connections, for existing and for projected power plants such as VVER, VVER-SCP (reactor cooled by water in super critical pressure) [8]. It is shown that in order to prevent resonance of coolant and fuel assembly vibrations, it is necessary and sufficient to bring the natural frequency of fuel assembly oscillations outside the coolant bandwidth.

3.1. Prediction of operating conditions that lead to vibro-acoustic resonances of the coolant with vibrations of FA and fuel rod

The data related to parameters of hydrodynamic loads, vibro dynamic behavior and stress-strain state of the reactor internals (RI) of VVER-1000 equipments in stationary and transient conditions are provided in paper [9]. These data were obtained during the implementation of a set of laboratory, test loop and in-core studies of the RI and FA of VVER-1000 (including physical models of various scales, as well as the full scale assembly and in-core components). The factors determining the hydrodynamic loads and vibro dynamic behavior of the RI and FA of VVER-1000, were identified as a result of many years of experimental and computational work. The studies have confirmed that the main factors determining the parameters of hydrodynamic loads and vibro-dynamic behavior of the equipments are the thermal-hydraulic characteristics of the primary circuit, the combination of operating main circulation pumps, as well as those factors not considered at design stage.

It is noted in [10], that the problem of vibrations at the NPP arose due to the fact that at the design stage of the first reactors, the dynamic impact of the coolant flow on mechanical vibrations of structural elements had been underestimated. However, ensuring the vibration strength of the equipments and pipelines of the reactor plant continues to be an actual problem. There are several reasons that make it difficult to solve this problem, the main of which, is the impossibility of forecasting of exciting vibration impacts with acceptable accuracy at the design stage, as well as due to following reasons: the lack of reliable data on the characteristics of the cyclic strength of structural materials for the hypercycle zone of the fatigue curve, high sensitivity of vibrations to small changes in design, external influences, the variety of structural forms of equipment elements, the reasons behind vibration excitations and their mechanisms.

The formation of acoustic field of the reactor plant, is mainly caused by self-oscillations of the coolant flow that are generated in the acoustic elements of the primary circuit. The methods for the determination of ASW, are provided in [11].

The acoustic elements of the primary circuit of VVER 440 NPP [12] are shown in the figure 1. The results of the calculation of the frequencies of ASW in the first circuit of a VVER – 440 NPP, are given in table 2 [12].

The software package of the vibration control system of the main equipment named SUS, is currently implemented and used in Novovoronezh NPP successfully; it consists of a program for automatic process of spectra and a program for automatic selection of peaks in the vibration spectra [13].

The results of the calculation of the frequency of ASW for all stages are compared with the measured data of vibration of the main equipment of the primary circuit that are provided in [14]. The results of the comparison indicate that in the studied stages of start-up modes, resonances of the ASW with vibrations of the equipments can occur in the following elements of NPP equipments:
1 – downcomer region of the reactor; 2 – lower grid; 3 – reactor core; 4 – upper grid; 5 – section of the main circulation circuit (MCC) from the reactor to the main gate valve (MGV); 6 – surge line from the hot leg to the pressurizer (P); 7 – pressurizer (water side); 8 – pressurizer (steam side); 9 – surge line from the pressurizer to the hot leg; 10 – section of the hot leg of MCC from the MGV to the hot collector; 11 – hot steam generator (SG) collector; 12 – heat exchange surface of the SG; 13 – cold SG collector; 14 – section from cold SG collector to main circulation pump (MCP); 15 – cold leg section of MCC from MCP to MGV; 16 – cold leg section of MCC from MGV to the entrance of downcomer region of the reactor

**Figure 1.** Acoustic scheme of VVER-440 NPP.

**Table 2.** The results of the calculations of ASW frequencies in sections of acoustic scheme of first circuit.

| Parameters of mode 1 | Section No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|----------------------|-------------|---|---|---|---|---|---|---|---|
| Frequency, Hz        | 9.3         | 44.1| 71.7| 28.6| 20.4| 7.1| 23.7| 11.5|
| Section No.          | 10          | 11 | 12 | 13 | 14 | 15 | 16 |   |
| Frequency, Hz        | 6.7         | 43.6| 42.5| 19.3| 42.6| 20.7| 56.9| 36.3|

| Parameters of mode 2 | Section No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|----------------------|-------------|---|---|---|---|---|---|---|---|
| Frequency, Hz        | 17.7        | 43.1| 69.2| 27.6| 19.5| 6.8| 29.5| 9.9 |
| Section No.          | 9           | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| Frequency, Hz        | 6.4         | 41.8| 40.6| 18.5| 41.3| 20.1| 55.3| 35.3|

\[ T = 256 \, ^\circ C, \ P = 12.7 \, \text{kg/cm}^2, \ H=4.34 \, \text{m} \]

\[ T = 268 \, ^\circ C, \ P = 125 \, \text{kg/cm}^2, \ H=3.37 \, \text{m} \]
1.5 - 3.0 Hz – frequency of vibrations of FA with one fixed end are observed:
  • in combination circuit consisted of several numbers of sections, (16+1+2+3+4), from cold leg of MGV to core exit in the range of temperature values, at the reactor outlet, of 281 - 296 °C and pressure values of 12.1 - 12.3 MPa;
  • in combination circuit consisted of several numbers of sections, (16+1+2+3+4+5), from cold leg to hot leg of MGV in the range of temperature and pressure values, at the reactor outlet, of 60 - 296 °C and 1.8 - 12.3 MPa, respectively.
4.0 - 6.0 Hz – frequency of vibrations of FA with two fixed ends are observed:
  • in the combinational circuit consisted of several numbers of sections, (16+1+2), from MGV cold leg to the bottom of the core in the range of temperature and pressure values, at the reactor outlet, of 60 - 296 °C and 1.8 - 12.3 MPa, respectively;
  • in the combination circuit consisted of several numbers of sections, (1+2+3+4), from the beginning of the downcomer region of the reactor to the reactor outlet in the range of temperature and pressure values, at the reactor outlet, of 60 °C - 136 °C and 1.8 - 4.8 MPa, respectively;
8.0 - 12.0 Hz – 2nd mode oscillations of FA with two fixed ends are observed:
  • in the combination circuit consisted of several numbers of sections, (1+2+3), from the beginning of the downcomer region of the reactor to the top of the core in the range of temperature and pressure values, at the reactor outlet, of 136 - 296 °C and 4.8 - 12.3 MPa, respectively;
  • in the combination circuit consisted of several numbers of sections, (1+2+3+4), from the beginning of the downcomer region of the reactor to the exit from the reactor in the range of temperature and pressure values, at the reactor outlet, of 60 °C - 136 °C and 1.8 - 4.8 MPa, respectively.

4. Prediction of vibroacoustic resonances in the reactor cores of VVER NPP in case of loss of coolant accidents
To calculate the self-frequency of coolant pressure oscillations in the steam-generating channel, the following relation is obtained in [4]

\[ f = \frac{a_t}{2\pi} \sqrt{\frac{\rho_{tv}}{\rho_t}} (L_t \cdot L_{tv})^{-0.5}, \quad (7) \]

where \( \rho_{tv} \) is the density of the coolant in two-phase region; \( \rho_t \) is the density of the coolant in single-phase region; \( L_t \) is the length of section in single-phase coolant; \( L_{tv} \) is the length of section in two-phase coolant; \( a_t \) is the speed of sound in two-phase medium; \( f \) is self frequency of coolant pressure oscillations.

In paper [15] it is shown that the calculated values of the frequencies of the ASW obtained by using the relation (7), that was developed for analysis of acoustic systems with two-phase fluid medium [4], coincide with the results of measurements of the pressure fluctuations of the coolant in the reactor core. The experimental evidence that was given in [15], and the justification of the use of the method of electroacoustic analogies for the calculation of the frequencies of ASW in boiling reactors, that was developed in [4], are now of particular importance for improving the competitiveness and safety of nuclear power plants. Prediction and control of frequencies of ASW at different stages of accidental conditions in boiling condition of core coolant, will optimize the emergency cooling system of the reactor and manage severe accidents and reduce capital costs for the construction of NPPs. The
developed methods and algorithms of calculations are applied in [8] to quantify the range of change of self frequency of coolant pressure oscillations in VVER-1700 (reactor with fast-resonance neutron spectrum) and VVER-1200.

In paper [9] it is shown that the interdisciplinary approach is necessary for the solution of actual current problems as for calculation of the ASW frequencies of the coolant in a reactor core in different conditions of maneuverable, transitional and accidental modes.

One of the ways to suppress the self-oscillations of the coolant is the use of dampers, which are devices that filter the acoustic vibrations of the working fluid and dissipate their energy. The Helmholtz resonator is one of the most effective dampers. When designing a Helmholtz resonator, it is important to take into account the effect of the vortex flow in its path. For this purpose, it is advisable to use the techniques of finite element modeling, with which the calculated justification of the damper scheme and the optimal values of its acoustic characteristics are determined. This method is used by Areva company [16], which in 2013 developed a complex program for the comprehensive study and analysis of the vibro-stressed state of NPP equipments, its internals and pipelines. The program includes measurements of the vibro-stressed state of equipments and pipelines, and determination of the safety margin for material strength in the stationary state and transient conditions.

In this program, it is noted that in assessing and predicting the service life, it is necessary to take into account the hydrodynamic and acoustic parameters of the coolant flow, as well as the current state of the equipment contacts with the RI and with the construction structures. The disadvantage of this approach is the dependence of the results on the current state, which makes it difficult to predict the service life, and the complexity and high cost of evaluation calculations.

In contrast to this approach, in paper [17] it is proposed an alternative option to ensure carrying ability of the nuclear installation equipment design, which provides for preventing the occurrence of conditions which lead to the maximum possible dynamic loads caused by vibration-acoustical resonance.

As the most effective means of preventing vibration-acoustical resonance, it is proposed to use an acoustic filter of the Helmholtz resonator type. This installation will provide suppression of acoustic fluctuations of the coolant coinciding with natural frequencies of fluctuations of fuel assemblies and fuel rods, and the excited fluctuations of pressure caused by the main circulation pump rotation or external and seismic impacts.

5. Conclusions
It is proved that the pressure fluctuations of a one-dimensional pulsating flow of a compressible single-phase or two-phase fluid used as a coolant of a nuclear reactor can be replaced, through investigation, by the similar voltage fluctuations in electric circuit lines.

The developed mathematical models are versatile, quite simple and, as evidenced by the results of measurements at NPPs, are effective for determining the acoustic properties of complex systems with an accuracy sufficient to solve a number of important practical problems.

Developed methods of modeling and calculation of acoustic waves in the coolant, allowed to their author K. N. Proskuryakov to create an acoustic model of a nuclear reactor and organize its testing and verification at a nuclear power plant with a light water reactor.

The obtained results can be used to predict the occurrence of vibration-acoustical resonances in NPP equipments under operating and accidental conditions, as well as under seismic and shock impacts.

References
[1] Proskuryakov K N 2005 Vibroacoustic certification of nuclear power plants-an urgent problem of nuclear power plants Thermal engineering (Moscow, Russia) 12 pp 30-34
[2] Charny I A, 1951 Unsteady Movement of a Real Fluid in Pipes (Moscow: State publication of Technical – Theory Literature)
[3] Lependin L F 1978 Acoustics The Manual for Higher Educational Institutions (Moscow: High School Publishing House) p 448
[4] Proskuryakov K N 1984 *Thermal-hydraulic Excitation of Vibrations of the Coolant in Reactor Internals of the Nuclear Power Plants* (Moscow: MPEI) p 67

[5] Atabekov G I 1970 *Theoretical Foundations of Electrical Engineering Part 1* (Moscow: Energia)

[6] Olson G 1947 *Dynamic Analogies* (Moscow: State publishing house of foreign literature)

[7] Pozdeeva I G and Mitrofanova O V 2018 Diagnostics of the vortex structure of coolant flows based on the method of acoustic resonances *Thermophysics and Aeromechanics* (Russia, Obninsk) p 182

[8] Proskuryakov KN and Novikov K S 2010 Determination of the region of vibro-acoustic resonances of the coolant and fuel assemblies in future high-power reactor *Journal of Atomic Energy* (Russia, Moscow) 3 pp 151 – 155

[9] Dragunov Y G, Dranchenko B N, Abramov V V and Khai redt inov V U 2007 *Proc. of Con. On Safety Assurance of VVER NPP* (Podolsk, Russia) Vibro dynamic research in support of design decisions for VVER, Materials of the conference "Safety provision in VVER NPPs" JSC EDB "GIDROPRESS", section No. 2

[10] Shary N V 2008 Calculation methods of substantiation of the strength and dynamics of reactor plant structures for VVER NPP author’s abstract of thesis submitted for scientific degree of Ph. D (Podolsk, Russia)

[11] Proskuryakov K N 1999 *The Use of Vibro Acoustic Noise for the Diagnosis of Technological Processes in Nuclear Power Plants* (Moscow: MPEI publication) p 68

[12] Proskuryakov K N, Fedorov A I, Zaporozhets M V and Volkov G Y 2016 Study of acoustic standing waves in the primary circuit of NPP VVER-440 NPP in the start-up modes *Global Nuclear Safety* (Russia, Volgodonsk) 2 (19) pp 59 – 69

[13] Slepov M T 1999 Development of methods and interpretation of data with regard to the noise diagnostics of the reactor units of Novovoronezh NPP,author’s abstract of thesis submitted for scientific degree of Ph. D (Obninsk, Russia)

[14] Arkadov G V, Pavelko V I and Usanov A I 2004 *Vibration Diagnostics of VVER* (Moscow: Energoatomizdat) p 344

[15] Fomichev M S 1989 *Experimental Hydrodynamics of Nuclear Power Units* (Moscow: Energoatomizdat) p 247

[16] ANP-10306NP 2013 Comprehensive vibration assessment program for internal parts of U.S. EPR reactor, Technical report

[17] Proskuryakov K N and Zaporozhets M V 2016 Study of acoustic vibrations in reactors and prospects of their use for the justification of residual life *Vestnik MEI* 5 pp 19-24