Verification of digital models of coolant self-oscillation of NPP with VVER

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Abstract. The results of verification of VVER-440 digital acoustic model are presented. The vibration control system of the main equipment, named SÜS, which is used in normal operation of nuclear power plants (NPP), is used to measure coolant pressure pulsations and mechanical vibrations. The method of calculation of acoustic standing waves (ASW) generated in the equipment is developed; the calculated values of ASW frequencies are in agreement with the results of measurements of signals from pressure pulsation sensors. It is proved that in the nominal and start-up modes, as a result of transformation of stochastic random pulsations caused by turbulence and vortex formation into ordered oscillations, acoustic waves appear. It is shown that the frequencies of acoustic waves depend on the operating conditions and can coincide with the vibration frequencies of the equipment. It is proved that the acoustic properties of a nuclear reactor, regardless of the number of coolant circulation loops, are similar to the properties of a group of simultaneously used Helmholtz resonators. The use of the acoustic model of the reactor allows optimizing design and engineering solutions by creating equipment capable of minimizing unwanted cyclic loads. This capability is the most important to ensure long-term operation in manoeuvrable modes of small modular reactors.

1. Introduction
Increasing the efficiency of operation and service life of the main equipment, as well as the operation of power plants in manoeuvring modes are among the priority requirements for the new generation of nuclear power plants (NPPs). One of the urgent and science-intensive tasks is to improve the programs of neutron-physical and thermal physical calculation of full-scale reactor cores of water-cooled power reactors (VVER). The neutron-physical calculation programs of BIPR-8 [1] and MOBY-DICK [2] that are widely used are given as an example of including feedbacks in their full-scale reactor core calculations of VVER. However, these and other modern approaches do not take into account the coolant density and temperature feedbacks that are caused by: the operation of pumps, acoustic standing waves (AWS) and thermal-hydraulic instability, that lead to periodic changes in the slowing down and absorbing properties of the coolant. It is known that the vibration amplitudes increase sharply at the two-phase state of the coolant and at the occurrence of vibration - acoustic resonances (VAR). In paper [3] it is shown that the conditions for occurrence of VAR are determined by a set of design characteristics and operating conditions of a specific NPP. Due to the need to take into account feedbacks in the software packages of neutron-physical, thermal-physical and acoustic calculations, the problem of verification of the digital acoustic model of the reactor is relevant.
2. Justification of the validity of the use of electro-acoustic analogies for the study of pulsating of single-phase and two-phase coolant flows

The analysis of acoustic systems with single-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. Methods of electroacoustic analogies have been developed and successfully applied [4, 5, and 6]. An important stage in the development of methods for analysing coolant acoustic systems in NPPs 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 [7]. The primary circuit of the VVER is a branched hydraulic system of pipelines containing elements with complex geometry. There are a number of elements in the connection in which there may be fluctuations in the coolant flow caused by the formation of vortices, and acoustic waves that, along with other cyclic loads, lead to vibrations of the equipment and reduce its service life [8, 9]. Like any structural element with mass and elasticity, the coolant in the primary circuit has self-frequencies that can resonate with sources of hydrodynamic disturbances at the same frequency or appear as less pronounced lines in the spectrum if the resonant frequency of the coolant differs from the frequencies of sources of hydrodynamic disturbances. Thus, the reduction of pressure pulsations and coolant velocity is one of the necessary criteria for pre-venting or reducing vibrations. In figure 1, the simplified electrical equivalent system of acoustic elements of the primary circuit of NPP [7]. The number of excited waves in this model corresponds to the number of acoustic inhomogeneities in the circuit. Determination of self-frequencies of the coolant pressure oscillations (SFCPO) using Thomson formula [1] is based on the method of electro-acoustic analogies [6, 7]. The acoustic mass of pipelines connected to the reactor and the acoustic compliance of the reactor volume, make it possible to determine the SFCPO generated by this acoustic system according to the Thomson formula (1):

\[
f_{so} = \frac{1}{2\pi \sqrt{m_s C_R}}
\]

where \( f_{so} \) – calculated frequencies of self-oscillations of system, Hz; \( m_s \) – the summation of acoustic mass of the system that consists of six parallel pipelines connected to the reactor that have equal acoustic masses, and its calculation is done by formulas (2) and (3); \( C_R \) – acoustic compliance of the reactor volume. In accordance with the acoustic model of a reactor plant consisting of a reactor and attached pipelines, self-oscillation frequencies are calculated for several variants, which take into account different number of acoustic inhomogeneities in the pipelines. The number of such inhomogeneities depends on the layout of the pipeline route.

\[
\frac{1}{m_s} = 6 \left( \frac{1}{m_{com}} + \frac{1}{m_{com}} \right)
\]

(2)

\[
C_R = \frac{V_R}{\rho_m \times a_m^2}
\]

(3)

where \( a_m \) is the average speed of sound, calculated by the formula (4) [11], and taking into account the deformation of the pipes and the compressibility of water,

\[
a_m = \frac{1}{\sqrt{\rho_m \times \left( \frac{D_m}{E_m \times \delta} + \frac{1}{E_l} \right)}}
\]
or \[ a_m = \sqrt{\frac{1}{\rho_m \left( \frac{D_R}{E_m \times \delta} + \frac{1}{\rho_m \times c_m^2} \right)}} \]  

where \( D_R \) – the diameter of the reactor; \( V_R \) – reactor volume; \( \rho_m \) – the value of reactor volume average of water density; \( C_m \) – the value of reactor volume average of speed of sound in water; \( \delta \) – thickness of the wall of the reactor; \( E_l \) – modulus of elasticity of the liquid; \( m_{comc} \) and \( m_{comh} \) – acoustic masses of the system formed by the cold (inlet) and hot (output) portions of the loops, respectively; \( C_R \) – acoustic compliance of the reactor coolant at reactor volume average pressure and temperature.

3. Verification of acoustic model of the reactor VVER -440

The acoustic scheme of primary circuit of NPP with VVER – 440, unit 3 Novovoronezh NPP is shown in figure 1.

The vibration control system of the main equipment SÜS developed by Siemens company has successfully implemented in Novovoronezh NPP. Due to the fact that Siemens supplies SÜS to NPPs with different types of reactors (BWR, PWR), in each case a strictly individual set of converters is used. The SÜS system that is used in normal operation of NPP, provides vibration diagnostics of the main equipment and pipelines of NPP (reactor internals and FA, MCC, SG) for the purpose of early detection of abnormal vibration conditions of this equipment caused by changes in the fixing.
conditions of the stiffness characteristics of supports or increasing hydrodynamic loads from the coolant of the circuit of VVER-440 NPP. According to the instructions, the operation of the system during transients, as well as during start up and shut downs, is not allowed. Primary transducers in the SUS system are: absolute displacements sensors (ADS), relative displacements sensors (RDS), pressure pulsation sensors (PPS). The system SUS is an informational type (as a result of its function, there is no operational switching). The system is designed for periodic measurements. The principle of operation of the system is that at the beginning of each fuel cycle, the vibrational condition of the equipment is monitored, as a result of which the operator receives the spectra of mechanical vibrations of the components of the circuit - such spectra are considered basic. During the operation of the power plant with a frequency of at least 2 times per fuel cycle, the measurements are made, and based on their comparison with the basic values; it is decided about the failure possibility of any elements of the controlled equipment. Two programs are implemented and used in the form of a software package: a program for automatic rejection of spectra, and a program for automatic selection of peaks in vibration spectra [12]. The table shows the results of calculating the ASW frequencies that occur in the VVER-440 reactor model in the nominal mode. The method of calculating ASW frequencies developed at the “NRU” MPEI” is currently the only one that is scientifically justified and verified. Figures 2 and 3 show the results of measuring and calculating the ASW frequencies in nominal mode and mode with zero power of the VVER-440 reactor for three models of acoustic mass corresponding to five variants (with different amounts of acoustic elements taken into account in the design model).

Table. Results of Calculation of ASW Frequencies (Hz) in Sections of the Acoustic Scheme of the Primary Circuit.

| Section       | Pipe Lengths | Variant 1 | Variant 2 | Variant 3 | Variant 4 | Variant 5 |
|---------------|--------------|-----------|-----------|-----------|-----------|-----------|
| Reactor +6in+6out | 19.51        | 10.38     | 9.58      | 7.66      | 23.11     |
| Reactor+6in    | 13.90        | 8.25      | 8.25      | 6.56      | 13.90     |
| Reactor+6out   | 14.17        | 6.30      | 5.25      | 3.93      | 19.54     |

In [13] it is shown that the spectral characteristics of the ADS, Ionization chamber (IC), PPS signals are dominated by peaks near the frequencies of three, five and six Hz. They are also present in the mutual characteristics of all kinds of pairs of signals ADS, IC, PCS, which indicates the vibrational nature of their origin, as they are observed in the signals of ADS, and as a significant power of these oscillations capable of exciting both the reactor vessel (ADS signals) and the core barrel (IC signals) together with PPS signals. The auto-spectral power density (ASPD) of the PPS signals for the nominal mode is shown in figure 2. The ASPD of PPS of different loops practically coincides with each other [12]. In the figure, the peaks with frequencies obtained as a result of the calculation based on the developed technique, are highlighted with lines. Figure 3 shows the agreement of the calculation results of the ASW frequencies generated in the equipment of the 1st circuit at zero reactor power with the ASPDs of the signals from the PPS signals, which is satisfactory for practical application.

As a result of the wide program verification of the acoustic model for several start up modes, there has also obtained good agreement of the calculation results of the ASW frequencies that generated in the equipment of the 1st circuit in the start-up modes with ASPDs of the signals from the pressure pulsation sensors that is satisfactory for practical application. Figure 3 shows ASPD of VVER-440 obtained at zero reactor power. Figure 3 shows good agreement between the results of the calculation of the frequencies of the ASW generated in the equipment of the 1st circuit at zero power of the reactor, with ASPDs of signals from pressure pulsation sensors of the SUS system that are satisfactory
for practical applications. In the figure, the peaks with frequencies obtained as a result of the calculation based on the developed technique, are highlighted with lines. Figure 2 shows the agreement of the calculation results of the ASW frequencies generated in the equipment of the 1st circuit in the nominal mode with the ASPDs of the signals from the pressure pulsation sensors of the SÜS system, which is satisfactory for practical application. As a result of the program verification of the acoustic model, there has also obtained good agreement of the calculation results of the ASW frequencies that generated in the equipment of the 1st circuit in the start-up modes with ASPDs of the signals from the pressure pulsation sensors that is satisfactory for practical application. Figure 3 shows ASPD of VVER-440 obtained at zero reactors power. Figure 3 shows good agreement between the results of the calculation of the frequencies of the ASW generated in the equipment of the 1st circuit at zero power of the reactor, with ASPDs of signals from pressure pulsation sensors of the SÜS system that are satisfactory for practical applications.

![Figure 2. ASPD of VVER-440 in Nominal Mode](image-url)
It is known that a nuclear reactor is a non-equilibrium open acoustic system with negative dissipation in its main elements, thanks to which chaotic pressure pulsations in the coolant caused by turbulence and vortices are converted into self-oscillations in the form of acoustic waves. However, most of the dominant peaks in the ASPD indicating the presence of ASV have not yet been identified [13, 14].

The SÜS systems installed on four Russian units with VVER-440 (units 1 and 2 of the Kola NPP, units 3 and 4 of the Novovoronezh NPP) show very close spectral portraits of vibrations of the reactor vessel. The results of calculating the ACV frequencies according to the developed method are compared with the data of vibration measurements of the main circuit equipment and pressure pulsations for VVER-440, which are given in the reference [13].

The results of the comparison are as follows:

- 5.7-6.8 Hz – “First loop ASW”;  
- 6.2 Hz – bending vibrations of the fuel bundle;  
- 5.3-7.3 Hz – joint oscillations of the pressure vessel and the barrel along a circular path (in the opposite direction);  
- 8.0-8.37 Hz – “Reactor First ASW” (with antinode on the vertical axis of the reactor);  
- 8.2 Hz – bending vibrations of the fuel bundle;  
- 10-12 Hz – pendulum oscillations of the reactor vessel;  
- 11.0-11.5 Hz – multiplet (circular oscillations of the reactor vessel and reactor internals);  
- 11.9 Hz – rotational oscillations of the fuel bundle;  
- 13.5-14.0 Hz – pendulum oscillations of the reactor vessel;  
- 18.75-19.12 Hz – vertical oscillations of the reactor vessel;  
- 20.1 Hz – the self-frequency of the fuel bundle, bending oscillations;  
- 2.4 Hz – the self-frequency of the fuel bundle, bending oscillations;
- 23.13-23.37 Hz – vertical oscillations of the reactor vessel;
- 24.63-24.75 Hz – rotation frequency of MCP;
- 24.8 Hz – the self-frequency of fuel bundle + clad, bending oscillations.

Most of the noticeable peaks are caused by coolant pressure fluctuations in the individual elements of the acoustic circuit and in the combinations of the acoustic elements that have been considered in calculations. The overlapping of the calculated ASW frequency with the measurement results of the vibration frequency of the FA [13], leads to the conclusion that the main cause of the vibrations of the fuel assembly (FA) is self-excited ASW (“reactor First ASW”). “Reactor First ASW” covers the reactor core and reaches a maximum near the vertical axis of the reactor. It is practically not observed in coolant loops where the ASW dominates at a frequency of about 6.0 Hz. But it is in the loops that the pressure pulsations are monitored. The results of the frequency calculation of the ASW in the primary circuit of the VVER-440 are characteristic of its individual acoustic field, which could not be reproduced in the laboratory conditions. The reasons behind this fact are that each modification of the reactor has its own individual acoustic field, in which the FA vibrations fulfill the requirement not to exceed the permissible level. To ensure that this requirement is fulfilled in a different acoustic field, a corresponding change in the design of the FA is necessary. In this study, the acoustic model of a nuclear reactor developed at “NRU “MPEI” was applied and verified on the case of NPP with VVER-440. The value of the obtained results lies in the possibility of predicting dynamic loads in the small and medium sized power reactors designed for long-term operation in maneuverable conditions. This model can be adapted to VVER reactors regardless of their geometric dimensions, single-phase or two-phase state coolant circulation types (forced or natural). This model can be adapted to VVER reactors regardless of their geometric dimensions, single-phase or two-phase coolant state and coolant circulation types (forced or natural). However, verification of the model developed for the specific NPP can be carried out only on itself. It should be emphasized that the digital acoustic model of a VVER-type reactor created at “NRU “MPEI” has no analogues, and the developed and verified methods for calculating the ASW frequencies generated in the primary circuit of a NPP remain the only ones suitable for practical use to date.

4. Conclusions
* It is proved that the self-organization of chaotic turbulent pulsations and vortices that occur in a nuclear reactor is transformed into ordered oscillations.
* The developed method and algorithm for calculating the ASW frequencies are confirmed by measurement data at Novovoronezh NPP, unit 3 have clear physical meaning, mechanical interpretation.
* Verification of the acoustic model of the VVER-440 reactor was carried out under the conditions of interaction of neutron-physical and thermo hydraulic processes that lead to an uneven distribution of the coolant temperature in the reactor volume.
* It is proved that the acoustic properties of a nuclear reactor, regardless of the number of coolant circulation circuits connected to it, are similar to the properties of a group of simultaneously functioning Helmholtz resonators.
* The use of an acoustic model of the reactor allows optimizing design and technological solutions by designing equipment that can suppress unwanted cyclic loads.
* The digital acoustic model of a VVER-type reactor created at NRU MPEI has no analogues.
* The developed and tested methods for calculating the ASW frequencies generated in the primary circuit of a nuclear power plant are currently the only ones suitable for practical use.

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