Development and verification of methods for predicting the frequency of self-oscillations in swirling coolant flows of nuclear power plants

KN Proskuryakov¹, AV Anikeev¹

¹National Research University "MPEI", Russia, 111250 Moscow, Krasnokazarmennaya str., 14
proskuriakovkn@mpei.ru

Abstract. Methods and algorithms for calculating the frequency of self-oscillations in swirling coolant flows of nuclear power plants with VVER reactors have been developed. The frequency of self-oscillations occurring in the acoustic sections of the primary circuit and their connections in the starting modes of the power unit and when operating at the rated power level is predicted. It is established that the self-oscillation frequencies can fall into the frequency bandwidth of mechanical vibrations and vibrations of the reactor plant's internal devices. It is shown that in order to prevent the resonance of self-oscillations of the coolant with the vibration frequencies of internal devices, it is necessary and sufficient to take the frequency of self-oscillations outside the bandwidth of the vibration frequency of structures. The results of verification of the results of forecasting the frequency of self-oscillations in swirling coolant flows at a nuclear power plant unit with VVER are presented. The application of the developed technique shows that the pendulum oscillations of the VVER - 1200 body are caused by an increase in the parameters of the coolant and the geometric dimensions of the VVER - 1200 reactor compared to VVER-1000.

1. Introduction
The Currently, problems related to the study of the conditions for the occurrence and stability of large-scale vortex structures in the elements of nuclear power plants (NPS) are of great interest in theoretical and applied thermophysics. In some cases, the generation of a twist of the coolant flow in the elements of the nuclear power plant can be created in a turbulent flow mode with a sharp change in the size of the passage section of the channels and the direction of the flow velocities. The analysis of experimental data carried out in [1] shows that the relatively low mixing intensity of turbulent loop coolant flows due to the presence of stable local eddy formations in them is common for the lowering sections of VVER and BN type reactors. The formation of vortices that prevent mixing of the coolant at the entrance to the core can lead to reactivity accidents (due to the effects of cooling the coolant or reducing the concentration of the boron absorber). One of the actual problems of the hydrodynamics of nuclear power plants with hull-type reactors is the physical explanation and mathematical modeling of the flow swirling conditions in the reactor downhill sections and in reactor internals (RI).
In vortex chambers, examples of which are the downfall sections of VVER reactors or fast reactors with liquid metal coolants, as a result of the formation of vortices due to their rotation, an ordered structure of clusters, which are dipoles, is created in the form of layers, with a positive charge being created along the flow axis, and a negative charge at the periphery. The scheme of coolant circulation in the reactor VVER is shown in Figure1.
Figure 1. The scheme of coolant circulation in the reactor.
1 – cold thread pipeline; 2 – the lowering section of the reactor in which the coolant flows down; 3 – support cup; 4 – space under the reactor core; 5 – holes of the elliptical bottom; 6 – space above the reactor core; 7 – fuel assemblies.

In Figure 2, it is shown that in addition to the appearance of a torus vortex caused by a sharp turn of the flow when the coolant exits the lowering section, one or more central vortices with a vertical axis can occur, leading to a decrease in flow due to a decrease in pressure in the central, most energetically stressed channels of the core.

Figure 2. The occurrence of central vortices at the exit of the coolant from the lowering section.

Negative resistances occur when a sudden expansion of the coolant flow coming through the cold thread pipelines from the main circulation pumps (MCP) to the downfall section of the reactor. The flow diagram of the coolant in a VVER-type reactor plant (RP) is shown in Figure 1. The flow expansion scheme at the entrance to the downfall section is shown in Figure 2. The scheme of formation of vortices at sudden expansion and at sudden narrowing of the flow is presented in Figure 3. The flow around the roughness protrusions is accompanied by the intensive formation and separation of vortices, which then move to the core area of the flow. In the case of a sudden expansion of the flow, local pressure losses can be determined by the formula of J. Borda, obtained theoretically [2]:

$$h_l = \frac{(V_a - V_b)^2}{2g} \tag{1}$$

$V_a$ – average flow rate in the narrow part of the pipe, m/s; $V_b$ – average flow rate in the wide part of the pipe, m/s.

Figure 2. The formation of vortices at sudden expansion and at sudden narrowing of the flow.

It follows from formula (1) that the local head loss in the case of a sudden expansion of the flow is equal to the velocity head of the lost velocity. This statement has gone down in history under the name "Bord's theorem". The creation of a digital acoustic tunnel of a nuclear reactor (NRDAM) at the "NRU" MPEI became possible due to the combination of three fundamental scientific results: the Thomson-Kelvin formula for the discharge of a capacitor [3]; the discovery of the properties of an acoustic resonator formulated by Helmholtz [4]; proof of the validity of the applicability of the method of electroacoustic analogies for the study of pulsating flows of single-phase and two-phase media in the presence of negative friction [5]. To study the process of establishing vibrations in an acoustic channel with negative friction under the influence of external disturbances, the equation is obtained in [5, 6]. The electrical analogue of which is the Van der Pol equation]. Van der Pol also proposed an approximate
analytical method for solving a nonlinear differential equation of an auto generator with transformer feedback. According to the analysis given in the monograph [7], the acoustic analogue of the transformer is a nozzle. In [6], the results were obtained on the basis of the assumption of the existence of acoustic mutual induction, due to which a vortex electric field arises in water. The validity of this hypothesis, applied in [5], is confirmed by modern high-tech research [8]. In vortex chambers, examples of which are the descent sections of VVER reactors or fast reactors with liquid metal coolants, as a result of the formation of vortices due to their rotation, an ordered structure of clusters is created, which are dipoles, in the form of layers, with a positive charge being created along the flow axis, and a negative charge at the periphery. In [8 ], the influence of acoustic waves in the range of 1 Hz ≤ ω ≤ 880 kHz with an intensity of 15 – 80 dB on the structural properties of water was studied by the method of light scattering of laser radiation with λ = 0.65 microns. It was found that the effect of infrasound waves on the water structure occurred at separate frequencies (5 Hz and 10 Hz) and consisted in the destruction of clusters with sizes r < 1.6 microns. The discreteness of the impact of infrasound waves is associated with the resonant mechanism of interaction of the wave with clusters of certain masses and sizes. In the sound and ultrasonic ranges, the interaction of acoustic waves with clusters was non-resonant and led to a decrease in the concentration of medium and small clusters (r < 0.9 microns) and the formation of ultra-large clusters (r > 3 microns).

2. Justification of the legality of using electroacoustic analogies for the study of coolant pulsations

The method of calculating the frequency of acoustic vibrations in the heat carrier of the VVER hot loop is based on the fact that the heat carrier, like any structural element with mass and elasticity, has its own oscillation frequencies that can resonate with sources of hydrodynamic disturbances and vibrations. An important stage in the development of methods for analyzing acoustic coolant systems at nuclear power plants was the substantiation of electroacoustic analogies for a one-dimensional pulsating flow of a two-phase medium, both with unambiguous and multi-valued hydrodynamic characteristics [5, 6]. The primary VVER circuit is a number of elements in which fluctuations in the coolant flow caused by the formation of vortices and acoustic waves can occur, which, along with other cyclic loads, lead to vibrations of the equipment and shorten its service life. The determination of the ASW frequencies is based on the application of the method of electroacoustic analogies [6, 7] and is carried out according to the Thomson formula (2):

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

(2)

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 (3) and (4) \( C_R \) – 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. It should be noted that in the “NRU “MPEI” the simpler Proskuryakov formula is usually used to calculate the frequency of self-oscillations of the NPP coolant instead of the Thomson-Kelvin formula (2):

\[
f = \frac{a}{2 \pi l},
\]

where \( a \) -is the speed of sound, \( l \) -is the length of the acoustic section.

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

(3)
\[ C_R = \frac{V_R}{\rho_m \times a_m^2} \]  

(4)

where; \( m_{\text{com}} \) and \( m_{\text{com}} \) are acoustic masses of the system formed by the cold (inlet) and hot (output) portions of the loops, respectively; \( a_m \) is the speed of sound (taking into account the deformation of the pipes).

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

Acoustic scheme of primary circuit of NPP with VVER-440, Novovoronezh NPP is showed in the Figure 4. The main sensors in the SÜS system are: absolute displacement sensors (ADS), relative displacement sensors (RDS), pressure pulsation sensors (PPS). 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 the oscillation spectra [9]. The method of calculating the ASW frequency developed at the “NRU “MPEI” is currently the only scientifically justified and proven one. Figure 5 shows the results of measuring and calculating the ASW frequencies in the nominal mode of the VVER-440 reactor. The results of the inspection became a significant addition to the scientific foundations justifying the possibility of extending the service life of power unit No. 4 with the VVER-440 reactor of the Novovoronezh NPP [10, 11]. Figure 5 shows the correspondence of the results of calculating the ASW frequencies generated in the equipment of the 1st circuit in the nominal mode to the ASPDS signals from the pressure pulsation sensors of the SÜS system, which is satisfactory for practical application.

Figure 4. Acoustic scheme of primary circuit of NPP with VVER – 440, Novovoronezh NPP.

The scheme in Figure 4 consist of: 1 – the lowering section - 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 section ); 8 – pressurizer (steam section ); 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.
4. Studies of acoustic standing waves at various stages of VVER-1200 start-up

The article [13] presents the results of the ASW study at various stages of the VVER-1200 launch. Based on the measured PPS signals in the temperature range of 116 – 286 °C, the almost linear dependence of the ASW frequency on the temperature of the primary circuit coolant was confirmed. The use of this half-century-old approach, devoid of physical interpretation, does not allow the authors to identify the source of self-oscillations that cause "pendulum oscillations" of the VVER-1200 body with a span of up to 5 microns, which were not previously observed on the VVER-1000. The application of the technique developed in [7,14] shows that the pendulum oscillations of the VVER-1200 body are caused by an increase in the parameters of the coolant and the geometric dimensions of the VVER-1200 reactor compared to VVER-1000 and are in the range of 4.5 – 6.5 Hz. This feature of the VVER-1200 was revealed at the stage of practical use of acoustic models verified at the Novovoronezh NPP [10]. Despite the lack of data explaining the reason for the fluctuations of the VVER-1200 reactor vessel, Joint-Stock Company "Scientific And Technical Center "Diaprom" decided to use vibration accelerometers placed on the primary circuit to describe the properties of the ASW, and exclude PPS from the supply for VVER-1200. Forecast of vibrations [14] of the VVER-1200 hull showed that this problem deserves more attention precisely in nominal and maneuverable modes, in which information from PPS is especially important for identifying the causes of vibrations. The presence of PPS is also necessary for monitoring the reactor installation acoustic field in the event of accidents with loss of coolant and under the influence of seismic and shock loads. In this regard, the unconvincing motivation for the decision to exclude PPS, in our opinion, is unacceptable. Identification of the sources of self-oscillations of the coolant for almost all types of VVER and PWR reactors provides the ability to control their frequency using an automated control system. If it is necessary to prevent vibration- acoustic resonance (VAR) in operational and emergency modes, as well as in the event of a threat of seismic and shock impacts, the possibility of shifting the ASW frequencies beyond the bandwidth, vibration frequencies of equipment responsible for the safety of nuclear power plants, allows you to maintain the operability of this equipment. It is obvious that any emergencies and accidents are possible when developing a new NPP generation, and the accumulation of information from PPS in these conditions is extremely important, since a significant part of them cannot be reproduced on experimental stands. The presence of PPS is also necessary for monitoring of the reactor installation acoustic field in the event of accidents with loss of coolant and under the influence of seismic and shock loads.

5. Conclusion

- To study the process of establishing vibrations in an acoustic channel with negative friction, under the influence of external disturbances, is obtained the equation, electrical analogue of which is Van der Pol equation.
As a result of self-organization, chaotic turbulent pulsations and vortices in nuclear power plants with VVER are transformed into ordered oscillations.

The developed method and algorithm for calculating acoustic standing waves has a clear physical meaning and mechanical interpretation.

The results of theoretical analysis and calculation of acoustic standing waves generated in digital acoustic models are confirmed by measurement data at NPP with VVER.

The acoustic field of reactor, regardless of the number of coolant loops connected to it, is similar to the properties of a group of simultaneously functioning Helmholtz resonators.

Digital acoustic models make it possible to optimize design and technological solutions by minimizing cyclic loads in operational and emergency modes and during seismic impacts.

6. References

[1] P L Kirillov 2003 The experience of operating reactors indicates the need for new thermohydraulic research Nuclear Engineering abroad. 9 3 – 9

[2] R R Chugaev 1982 Hydraulic: textbook. (Moscow: Energy) 672

[3] M Lotssi 1970 The History of Physics (Nauka: Moscow)

[4] H Helmholtz 1860 Theorie der Luftschiwingungen in Rohren mit offenen Enden J. Reine Angew. Math. 57(1) 1–57

[5] Proskuryakov K. N. 1984 Thermohydraulic excitation of coolant vibrations in Internal Devices of Nuclear Power Installations (Moscow: MPEI)

[6] Proskuryakov K N 2015 Nuclear power plants. (Ed. house of MPEI) p. 446

[7] Olson G 1947 Dynamical analogy. (Moscow: State publishing house of foreign literature)

[8] V F Kovalenko and VV Glazkova 2013 Biomedical engineering and Electronics 1 (3) 2-14

[9] T Slepov 1999 Development of Methods and Data Interpretation in Relation to the Systems of Noise Diagnostics of the Reactor Facilities of the Novovoronezh NPP, Candidate’s Dissertation in Engineering, ths. Obninsk

[10] A I Fedorov et al. Performing vibroacoustic certification of power plant to justify the possibility of extending their operational life Gazette of Voronezh State Technical University. 5 85-91

[11] Pavarov V. P. Some aspects of re-extending the life of the reactor plant with VVER-440 on the example of power unit No. 4 of the Novovoronezh NPP

[12] Pavorov V P, Fedorov A I, Vitkovsky S L 2019 News of higher educational institutions. Nuclear power engineering. 2. 91-104

[13] Bhattachary A, Yu S D, Kawall G 2012 Numerical simulation of turbulent flow through a 37-element CANDU fuel bundle Ann. Nucl. Energy 40 87–105

[14] Pavelko V I, Slepov M T, Khayretdinov V U 2016 The experience of conducting complex measurements using heterogeneous systems at various stages of the start-up of the VVER-1200 power unit Nuclear power engineering 4 44-52

[15] Proskuryakov K N, Belova S K, Anikeev A V, Afshar E 2019 Development of Methods for Calculating the Frequency of Acoustic Standing Waves Generated by WWER Reactors Global nuclear security 3 (32) 80-88