Scientific basis for modelling and calculation of acoustic vibrations in the nuclear power plant coolant

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Abstract. Created new scientific direction: "Diagnosis, prognosis and prevention of vibration - acoustic resonances in the nuclear power plant (NPP) equipment. The possibility of using methods for calculating and analyzing electric oscillation systems in the study of the properties of acoustic systems with a two-phase medium is proved, based on the similarity of the differential equations describing the state of these systems. Is shown that the developed methods can be used to predict and prevent the occurrence of vibration - acoustic resonances in the NPP equipment. Is shown that the volume of pressurizer at NPPs with VVER and PWR as well as boiling water reactor that exploded at Japan's NPP Fukushima Daiichi is a Helmholtz resonator, which contain water and steam volumes and able many times increases the impact on them of outside periodic oscillations. Paper presents most important results published long before the severe accidents at NPPs Three Mile Island (TMI), Chernobyl and Fukushima Daiichi that could be used for the prediction of a severe accident scenario, identification of measuring data and process control in order to minimize the damage. Worked out results also could be useful in another industrial technologies based on applications of single and two-phase flows.

1. 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 vibration-acoustic certificates of the NPP reactor plant (RP). To this end, it is necessary to know the vibration-acoustic characteristics and, in particular, 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 vibration-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 WWER). The oscillatory properties of the primary coolant circuit’s hydro mechanical system are not merely a superposition of the properties of its constituent parts (the reactor, steam generator, pressurizer, pipelines, etc.), but acquire new systematic properties. The new qualitative effects [2] resulting from the system properties of oscillatory processes in the reactor coolant circuit are determined by the nonlinear dependence of pressure drop on the coolant mass flow rate in the circuit elements.

2. Formulation of the problem
The calculated and experimental substantiation of the methods for predicting and preventing the onset of conditions under which vibration-acoustic resonances arise in the primary coolant circuits of WWER 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.

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 WWER. The results of these measurements and identification demonstrate that noise analysis is of high usefulness for monitoring the mechanical and thermohydraulic operating condition [3].

In [4], proved the possibility of a thermal-hydraulic instability (self-oscillation) in a single steam generating channel and their effect on the reduction of the critical heat flux by increasing the length of the evaporation area. Article translated into English and published in the United States, its content is reflected in [5], in which systematized publication, selected to be the new knowledge to the study of boiling crises and critical heat fluxes.

The article [4] proved the physical nature of occurrence of self-oscillations of the flow rate in a single steam generating channel, the frequency of which is the natural frequency of the fluid contained in it. It is shown that a strong decrease of the critical heat flux occurs at high steam content and due to increased evaporation portion length.

It is this effect, as specified in [6], has led to the destruction of the reactor at the Chernobyl NPP. "The continuing decline of water flow through the technologic channels (TC) reactor under the power growth conditions had led to an intensive steam generation, and then the crisis of heat transfer, heating fuel, its destruction, the rapid boiling of coolant, which were particles of the destroyed fuel, a sharp increase in pressure in the TC, their destruction, and heat explosion that destroyed the reactor and the part of building structures and led to the release of fission products into the environment.”

3. Method of electro-acoustic analogies
In general, the system of equations describing the fluid dynamics of little use for the analysis of acoustic characteristics. One of the approximations used [7] is to cast the equations of dynamics to the so-called telegraph equations. The table presents the list of the equivalent parameters.
Table. Equivalent parameters analogies

| Parameter            | Acoustic System | Unit       | Parameter            | Electrical System | Unit       |
|----------------------|-----------------|------------|----------------------|-------------------|------------|
| pressure drop        | ∆P              | N/m²       | voltage              | u                 | volt       |
| volume flow          | W               | m³/s       | current              | i                 | Amper      |
| acoustic compliance  | C               | m³·s²/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      | Zω              | kg/(s·m⁴)  | wave resistance      | Zω                | Ohm        |
| Own circular frequency| ω₀             | rad/s      | Own circular frequency| ω₀              | rad/s      |
| eigenfrequency       | f₀              | Hz         | eigenfrequency       | f₀                | Hz         |
| The bandwidth        | ∆f              | Hz         | The bandwidth        | ∆f               | 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.

The mass of the acoustic environment in a cell density ρ of channel length l and cross section S is given by:

\[ m = \frac{\rho l}{S} \]  

(1)

Acoustic compliance C of environment in the channel with volume V is:

\[ C = \frac{V}{nP} \]  

(2)

where n - the polytrophic index, P - the pressure in the channel.

It is known that the cumulative rate of propagation of vibrations in the environment is:

\[ a = \sqrt{\frac{nP}{\rho}} \]  

(3)

Using (3) we get:

\[ C = \frac{V}{\rho a^2} \]  

(4)

Own circular frequency of the medium in the channel:

\[ \omega_0 = \frac{1}{\sqrt{Cm}} \]  

(5)

The natural frequency of the medium:
\[ f_0 = \frac{\omega_0}{2\pi} \]  

The wave resistance is calculated as:

\[ Z_w = \sqrt{\frac{m}{C}} \]  

(7)

The Q-factor - numerical characteristic of the resonance properties of the oscillating system, indicating how many times the amplitude of the steady-state forced vibrations at resonance exceeds the amplitude of forced vibrations far from resonance, that is in such low frequencies, where the amplitude of forced vibrations can be considered independent of frequency Q-factor of an element or circuit, which determines the rate of decay of perturbations, given by:

\[ Q = \frac{\sqrt{m/C}}{R} = \frac{Z_w}{R} \]  

(8)

Quality factor and bandwidth are related by the following expression:

\[ Q = \frac{f_0}{\Delta f} \]  

(9)

Active power oscillation with the current flow \( W \) is defined as:

\[ N_R = W^2 R \]  

(10)

Reactive power fluctuations with the current flow \( W \) is defined as:

\[ N_X = W^2 X \]  

(11)

As for the electrical circuits and circuits for electro-hydraulic circuit, the following rules. When the elements are connected in series the total acoustic mass and compliance are:

\[ m_z = \sum_i m_i \]
\[ C_z = \sum_i C_i \]  

(12)

In the parallel connection of elements:

\[ \frac{1}{m_z} = \sum_i \frac{1}{m_i} \]
\[ \frac{1}{C_z} = \sum_i \frac{1}{C_i} \]  

(13)

Logarithmic decrement of oscillations (\( \delta \)) determined from the relation:

\[ \delta = \frac{\pi}{Q} \]  

(14)

4. **Electro acoustic analogy for the two-phase medium pulsating flow**

The possibility of using methods for calculating and analyzing electric oscillation systems in the study of the properties of acoustic systems with a two-phase medium is proved in [7], based on the similarity of the differential equations describing the state of these systems. Justification of the legality of electro
acoustic analogy for the one-dimensional two-phase medium pulsating flow, both with single-valued and multi-valued hydrodynamic characteristics was an important stage in the development of methods for NPP coolant acoustic systems analysis. In light of the assumption that the acoustic pressure $\Delta p$ at all points along the channel length is only a function of time, the continuity equation and conservation of momentum and the one-dimensional two-phase medium pulsating flow obtained in the form of a system of linear differential equations:

$$\begin{align*}
\frac{\partial w}{\partial x} + C \frac{\partial p}{\partial t} + G \Delta p &= 0 \\
\frac{\partial p}{\partial x} + m \frac{\partial w}{\partial t} + R W &= 0
\end{align*}$$

(15)

Where $\Delta p$ - sound pressure (pressure additionally occurs when the acoustic wave passes in the fluid in steam or steam medium). Spreading in the fluid acoustic wave forms some compressions and depressions that create extra pressure change relative to the average static pressure $P$. $W$ – volumetric flow rate of the coolant in the tube; $a$ - sound velocity of two-phase medium; $L$ – length of the tube; $S$ – cross section tube; $C = \frac{L S}{\mu a^2}$ - acoustic compliance of the medium; $R$ – acoustic active resistance; $G = \frac{W L}{n \rho}$ – is the wave conductivity of the medium; $m = \frac{\rho L}{S}$ – the acoustic mass; two-phase medium density $\rho$, the polytrophic index – $n$.

Solving systems of linear differential equations gives the functional dependence of the sound pressure and the volumetric flow rate of a compressible medium in the pipeline with the distributed constant acoustic compliance of the medium, the medium wave-conducting, the medium flow active resistance of the variables $x$ (the distance along the pipe axis) and $t$ (time).

To calculate the eigen frequency of the coolant pressure oscillations (EFCPO), i.e. frequencies of ASW, in the steam generating channel in [7] obtained the following relationship:

$$f = \frac{a}{2\pi} \sqrt{\frac{\rho_t \rho_p}{\rho_w}} \left(\frac{L_{sw} \cdot L_{tp}}{L_w \cdot L_{tp}}\right)^{0.5}$$

(16)

where $\rho_p$ – the density of the coolant in the two-phase region, $\rho_w$ – the coolant density in the single-phase region, $L_{sw}$ – the length of single-phase heat transfer; $L_{tp}$ – the length of two-phase heat transfer; $a$ – the speed of sound; $f$ - EFCPO.

The method based on electro acoustic analogy simple enough and effective in determining the acoustic properties of complex systems with several degrees of freedom, give results with accuracy sufficient to solve practical problems [8] determining the ASW frequency, the acoustic quality factor of coolant circuits, bandwidth, wave resistance and so forth. The methods can be used to predict and prevent the occurrence of vibration-acoustic resonances in the NPP equipment in the operating and emergency conditions, as well as seismic and impact [9].

In [10] it is shown that the calculated values ASW frequency obtained when using the method electro - acoustic analogies developed for analysis of acoustic systems with two-phase fluid correspond to the results of measurements of coolant pressure oscillations in steam generating channels of the nuclear reactor core. Experimental proof in [10], the legality of the method of electro-acoustic analogies to calculate the ASW frequencies in boiling water reactors, is currently of particular importance for improving competitiveness and safety of Russian NPPs.

Forecasting of frequency ASW for managing the various stages of emergency operation with boiling coolant in the reactor core, will optimize the Emergency Core Cooling System and reduce capital costs for the construction of NPP.

The developed methods and algorithms for calculating the ASW have a clear physical meaning, enable the identification of sources of generation of ASW on the results of measurements of equipment vibration and coolant pressure pulsations at the NPP in operation and emergency conditions.
In [11] it was shown for the first time that if an increase in the velocity of a two-phase flow reduces the friction force, this leads to self-oscillations of the pressure oscillations. Such conditions occur at a mass flow rate of the steam generating channel in the range corresponding to the falling part of the hydrodynamic characteristics. This phenomenon must be considered as the main factor causing the multiple increases of dynamic loads on equipment during the flow of the maximum design basis accident (MDA) at nuclear power plants with VVER reactors.

5. Severe accidents at NPPs TMI, Chernobyl and Fukushima Daiichi

It should be noted that the increased vibration and impact of channel walls and fuel assemblies were observed during operation Chernobyl nuclear reactors. Personnel Chernobyl was detected noise from the collision of metal elements of the core in a number of operational modes.

Due to the necessity of diagnosing the conditions of occurrence of such collisions and prevention based on the results obtained in [4, 7, 11], at the initiative of Chernobyl NPP in 1985, economic agreements was signed between MPEI and VNIIAES called "Research of coolant flow impact on the vibration-acoustic characteristics of fuel assemblies for the development of diagnostics methods of non-destructive inspection of the main and auxiliary equipment of NPPs with RBMK". Supervisors of this work from the NPP Department was Dr. K.N. Proskuryakov, and from the Department of automated thermal process control systems - ATPCS Dr. V.S. Mukhin. Work to measure the vibration-acoustic characteristics of the fuel assemblies of the Chernobyl plant was planned for May 1986. The work started with the Chernobyl NPP were the basis that the author of article was involved in May 1986 as an expert in the work of the Government Commission to investigate the causes of the Chernobyl accident. The expert report submitted by him were identified possible causes of the accident: Invalid growth vapor content in fuel channels had led to the development of self-oscillations of the coolant, heat exchange crisis [4] and, very likely, the emergence of vibration-acoustic resonance with the vibrations of the fuel assembly. In conclusion, it was stated also unacceptable backlog from the technologies of Hungary and East Germany in the field of technical diagnostics of nuclear facilities. As an immediate action was proposed to form a technical diagnostic service on all NPPs, and in MPEI set up: a) a new specialization "Technical NPP diagnostics" for the training, and b) material conditions for speeding up research in the field of equipment and process plant noise diagnostics.

This expert opinion was sent by Chairman of the USSR Council of Ministers to the first persons of ministries and agencies working on nuclear topics to answer the posed questions. Of particular importance was the answer the Minister of Medium Machine Building of the USSR E.P. Slavskiy. In his response, it was said that the accident scenario, which assumes the expert is quite probable that we should implement proposals formulated by him in the near future and, particularly, provide financial and material support to MPEI for training and speeding researches in the area of noise diagnostics equipment and NPP technology processes.

In pursuance of the instruction of the Council of Ministers of the USSR, PP-8768 from 18.05.86, the first persons of ministries and departments working on nuclear issues considered expert conclusions of the author of this article.

The Gosatomnadzor of the USSR, taking into account consultations with specialists from the National Research Center «Kurchatov Institute» and the Scientific Research Institute of Power Engineering (NIKIEI) were reported to the Council of Ministers:

"1) Proposition of K. Proskuryakov to the Interdepartmental Technical Council for the NPP to clarify the existing concept of the Design Basis Accident (DBA) is correct. The initial event and the way of development of the accident, supposed by the author, are potentially possible and should be analyzed by the Scientific Supervisor, the Chief Designer and the General Designer of the NPP.

2) The author of the proposals rightly points out the need to accelerate the introduction of a system of monitoring and operating diagnostics of the equipment being used, using, in particular, the monitoring of the condition of the coolant."
3) It is necessary to accelerate the work on the implementation of proposals to the Ministry of Energy to equip NPPs with vibroacoustic diagnostics.

4) Gosatomnadzor supports the recommendations of K. Proskuryakov to Ministry of Higher Education of the USSR on the need to create a specialization "Diagnosis of the technical condition of NPPs and maintenance of reliability and safety systems."

Unfortunately, the restructuring taking place in the country prevented the implementation of these recommendations.

In [11] for the first time is shown that if the increase in the two-phase flow velocity decreases the friction force, it leads to self-excited oscillations of pressure. Such conditions occur in the steam generating channel mass flow rates in the range corresponding to the falling portion of the hydrodynamic characteristics. This phenomenon must be considered as the main factor causing the multiple increases of dynamic loads on equipment during the flow of the DBA at NPP with VVER and PWR reactors. In more recent publications noted the impact of this effect on the vibrations of pipelines [12] and steam generators reliability [13, 14]. In [15], first proven that the eigen frequency of coolant pressure pulsations in emergency mode at the boiling stock in the reactor core is several times lower than the frequency corresponding to the normal operation mode. This change in pressure pulsation spectrum is diagnostic warning: of boiling in the core of VVER and PWR reactors.

The accident at TMI occurred after the appearance of this information. If the staff of NPP TMI timely recognized the start of boiling in the reactor core, it could to prevent one of the most severe NPP accidents. In the same paper offered the acoustic model of the pressurizer, is used in NPP with VVER reactors (and their foreign counterparts - PWR). This model is used to calculate the frequency of the acoustic standing waves generated by the pressurizer [16-18]. In [4,11,15] is shown that the most important results in NRU "MPEI" have been published much earlier than abroad and could be used to prevent the development of catastrophic accidents at the Chernobyl NPP and NPPs, "Three Mile Island-2". It is shown that the volume of a pressurizer at a NPP with VVER represents itself as the Helmholtz resonator, which contains of water and steam volumes, as well as reactor of exploded at Japan's NPP Fukushima Daiichi 1, capable of multiplying the effect of external periodic oscillations.

Basic research conducted in MPEI show that hidden patterns and dynamic processes present at NPP equipment which occur in forms of oscillation, parametric resonance, resonant interactions coolant vibrations with the vibrations of the equipment. In many cases, due the existence of these physical phenomena and processes occur sudden equipment failures and accidents.

The analysis shows that ahead of its time current needs of the nuclear energy research, conducted in MPEI, currently have relevance. Note that recommendations for early detection of boiling coolant in the VVER and PWR type reactors zone were published before the accident on "Three Mile Island-2" NPP (USA) [15].

6. Possibility of exceeding the design level of equipment vibrations under external periodic loads caused by an earthquake

At present, after the events occurred at the Fukushima Daiichi NPP, stress tests for external impacts exceeding the design level are to be mandatorily carried at all Russian NPPs. In view of this requirement, calculated analyses for external impacts exceeding the design level must be carried out for the NPP reactor plant equipment and pipelines apart from calculations for the design level of impacts.

In carrying out calculations for estimating the intensity of vibrations in equipment and acoustic pulsations in the coolant, the external impact during an earthquake is specified in the form of response spectra graphs of a no conservative system with one degree of freedom as a function of natural frequency of vibration and decrement of energy dissipation [19]. In so doing, the response spectra for displacements, velocities, and accelerations of the system with one degree of freedom are used. Acceleration spectra are used in most frequent cases. In so doing, the response spectra for
displacements, velocities, and accelerations of the system with one degree of freedom are used. Acceleration spectra are used in most frequent cases.

It is well known that the experimental methods of investigations carried out under laboratory conditions and under the conditions of real NPPs do not always fully simulate the specific features pertinent to interaction of an NPP with seismic loads, due to which the predicted results may differ essentially from the real ones.

Lack of the results from experimental investigations on a full-scale facility is one of the main factors behind such inconsistency. Such investigations would make it possible to substantiate the seismic stability of NPPs taking into account their specific features, the main of them being the neutron physical and thermal hydraulic processes under the conditions when they are superposed with external dynamic forces simultaneously acting on all building and process systems.

Long-term experience gained in Russia with combined calculated and experimental substantiation of NPP seismic stability [19] is of much importance for ensuring seismic stability of nuclear power facilities. The conceptual and procedural levels include the relevant IAEA standards.

One specific feature of the Russian system of regulatory documents [8] is that they put forward the mandatory requirement of studying the dynamic characteristics of systems and components important to safety using the dynamic test method under the real conditions of their fastening and associated pipe work at the NPPs.

Natural frequency oscillation can be determined by calculation methods, but it requires the most accurate simulation of the equipment, including a consideration of all possible factors affecting the natural frequencies such as breakout conditions, the availability of connected equipment, records and elastic ties etc.

For «rough» (preliminary) dynamic strength evaluation is acceptable settlement definition of natural frequencies, but to get the real forces and stresses arising in the pieces of equipment against external mechanical impacts, we must know the real resonant frequency equipment, adequately define who can only experimental way.

Decrement, in contrast to the natural frequencies can be determined only by experiment, due to the rather complex nature of damping in the physical sense, which is not amenable to rigorous mathematical analysis. Surveys have shown at numerous nuclear power plants that are very common cases where the value decrements are much lower than the standard required in the RF values (2%). Thus, the use of 5% decrement values may lead to an underestimation of seismic impact values in the resonance region in two or more times (Figure).

An example of a floor response spectrum, which determines the load on the equipment in earthquake conditions presented in Figure. 6.

![Figure](image)

**Figure.** An example of the spectrum of responses to the seismic action for the various decrements
An analysis of many spectral responses for various NPPs has shown that the frequencies of dynamic loads from seismic effects are lower than the natural frequencies of equipment vibration and the acoustic frequencies of the coolant. In [9] another spectrum of the response is shown, in which, as a result of the earthquake, a significant increase in dynamic loads is predicted as a result of the coincidence of their frequencies with the frequencies of vibration of the main equipment and the frequencies of acoustic standing waves in the first circuit of the NPP.

7. Conclusion

The possibility of using methods for calculating and analyzing electric oscillation systems in the study of the properties of acoustic systems with a two-phase medium is proved.

The most important results for modelling and calculation of acoustic vibrations in the NPP coolant have been published much earlier than abroad and could be used to prevent the development of catastrophic accidents at the Chernobyl NPP and NPPs, "Three Mile Island-2".

The volume of a pressurizer at a NPP with VVER and PWR represents itself as the Helmholtz resonator, as well as reactor of exploded at Japan's NPP Fukushima Daiichi 1, capable of multiplying the effect of external periodic oscillations.

Scientific basis for modeling and calculation of acoustic vibrations can be used to predict and prevent the occurrence of vibration -acoustic resonances in the NPP equipment and also in industrial technologies based on applications of single and two-phase flows.

Developed methods can be used to predict and prevent the occurrence of vibration-acoustic resonances in the NPP equipment in the operating and emergency conditions, and also due to seismic impact.

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