Scientific bases of creation and practical application of digital acoustic model of NPP with VVER

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Abstract. Created acoustic model of nuclear reactor is presented as self-oscillating system belonging to special class of nonlinear dissipative systems capable of generating undamped oscillations with parameters that don’t depend on the initial conditions and are determined only by the properties of the system itself. In open systems, such as coolant circuit, the energy increases over time due to negative friction (negative dissipation). It is known that self-organization, in which a wave order arises spontaneously from turbulent disorder, is possible due to the exchange of energy and mass with the environment, when dissipative losses are compensated from the outside. The creation of this model combined three fundamental scientific results: the Thomson-Kelvin formula for discharge of capacitor in 1853; the properties of acoustic resonator, formulated by Helmholtz in 1869; proof by the author in 1984 of validity of the use of the method of electroacoustic analogies for study of pulsating flows of single-phase and two-phase medium in the presence of negative friction. The acoustic model of nuclear reactor has no analogues in acoustics and is designed to predict, diagnose and prevent the occurrence of unwanted self-oscillations of coolant and resonances with fluctuations of nuclear fuel and equipment in operational and emergency modes.

1. Introduction
Increasing the efficiency of operation and service life of the main equipment, as well as the operation of power plants in maneuverable modes are among the priority requirements for the new generation of nuclear power plants (NPP). Requirements of long-term operation in maneuverable modes can be provided by minimization of dynamic loadings on reactor installations. Under these conditions, the problems of preventing hydrodynamic instability, abnormal increase of the vibration level of equipment and the occurrence of the most dangerous growth of dynamic loads in the resonant interaction of structural vibrations with coolant acoustic oscillations became of prime importance. These factors also determine the very possibility of implementation of small power plant projects designed for operation in maneuverable modes. One of the urgent and science-intensive tasks is to improve the programs of neutron-physical and thermal physical calculations of full-scale reactor cores of water-cooled power reactors (VVER). The neutron-physical calculation program of MOBY-DICK [1] that is widely used could be given as an example of including feedbacks in its full-scale reactor core calculations of VVER. However, these and other modern approaches do not take into account density and temperature feedbacks of the coolant that are caused by the operation of pumps, acoustic standing waves (ASW) and thermal-hydraulic instability, that all are causing 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 vibro-acoustic resonances (VAR). Due to the need to take into account feedbacks in the programs of neutron-physical, thermal and acoustic calculations, the problem of acoustic model development of the reactor is relevant. Information about the development of acoustic model (which has no analogues) of a nuclear reactor, appeared after the accident at Fukushima -1. The development of this model was made possible through the use of three fundamental scientific results (obtained during a period of more than 100 years). The first result is the Thomson-Kelvin formula [2], proposed in 1853, for calculating the eigen frequency of discharge of a capacitor, the second result [3] is the idea of an acoustic resonator, formulated by Helmholtz in 1869 and the third result is the proof made in 1984 by showing the validity of the use of electroacoustic analogies for the study of pulsating single-phase and two-phase flow with negative dissipation [4].

2. Modeling of self-oscillating systems

The foundations of the notion of self-oscillatory systems as a special class of nonlinear dissipative systems capable of generating undamped oscillations with parameters independent of the initial conditions and determined only by the properties of the system itself were formulated by academician A. A. Andronov [5] in the first third of the 20th century. Since then, self-oscillating systems and models have been widely used in many branches of science and technology. The most detailed theory of self-oscillations was formulated in Radio-physics, in which self-oscillating systems are one of the central objects of research. In the process of development of Radio physics, auto-generators based on different types of active elements, providing interaction between oscillatory generator systems with an energy source, were created and introduced into radio engineering practice, and stimulated the development of the theory of nonlinear oscillations. Van der Pol oscillator [6] was one of the first mathematical models of a self-oscillating system with one degree of freedom. Van der Pol also proposed an approximate analytical method for solving the nonlinear differential equation of auto-generator motion, which gives an adequate description of the dynamics of high-quality factor and weakly nonlinear self-oscillatory systems.

2.1. Generalized scheme of electronic generator, van der pol equation

The scheme of the electronic generator of self-oscillations is shown in figure 1. The oscillatory system here is the RLC circuit. The voltage from the circuit is supplied to the input of the active element: amplifier. We assume that the nonlinear characteristic of the amplifier is known, i.e. the dependence of the output current of the amplifier i on the input voltage u, can be approximated by a cubic polynomial:

\[ i(u) = g_0 u - g_2 u^3 + \ldots \]  \hspace{1cm} (1)

Figure1. Electronic generator of self-oscillations.

The \( g_n \) coefficients are considered positive. The amplifier output is loaded onto the inductor \( LI \), which is inductively coupled to the loop coil \( L \). Thus, the feedback is provided. The mechanism of excitation of self-oscillations in the generator can be qualitatively described as follows. Even when there is no voltage at the amplifier output, the voltage in the circuit experiences random fluctuations. They are strengthened by the amplifier and re-enter the circuit through the feedback circuit (M is the
transformation coefficient between the coils $L$ and $L_1$). In this case, a component of the self-frequency of a high-quality circuit will be derived from the noise spectrum of fluctuations. If the energy entering the circuit exceeds the energy loss, the amplitude of oscillations increases. This requires that the gain is large enough. However, since the dependence of $i(u)$ (1) is nonlinear, with increasing $u$ the gain decreases, which leads to the establishment of stationary self-oscillations with a constant amplitude, which is mechanism of nonlinear instability limitation. Thus, nonlinearity in self-oscillating systems plays a fundamental role, regulating energy flow from the source. In a linear system (for example, an oscillator with negative friction), the amplitude of the oscillations would increase to infinity.

At $RC > M g_0$, this is the normal equation of a linear oscillator with damping and the equilibrium state is stable, and, by following condition (2), it turns into the equation of an oscillator with negative friction.

$$M g_0 < RC$$

And, consequently, small disturbances will increase over time. By analyzing the relation (2), we can draw several important conclusions. First, the mutual induction coefficient $M$ must be positive. In this case, the oscillations coming from the amplifier output are in-phase with the oscillations in the circuit and contribute to their amplification. This feedback is called positive. On the contrary, at $M < 0$ the oscillations are out of phase and mutually suppress each other. The feedback stabilizes the equilibrium condition and is called negative. The second conclusion, which can be drawn from (4), is also quite obvious: the gain, which is characterized by a coefficient $g_0$, must exceed the losses (here the resistance $R$ is responsible). In general, as a rule, for the self-excitation of a generator of any type, it is necessary to fulfill two conditions, which are usually called amplitude and phase conditions. The meanings of these conditions are as follows: a) the source energy, which is converted into oscillation energy, must exceed the losses; b) this energy must enter the oscillatory system in the corresponding phase and contribute to the strengthening of the oscillations.

2.2. Method of electro-acoustic analogies

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 [7, 8]. 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 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 [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:

$$\frac{\partial W}{\partial x} + C_\alpha \frac{\partial \Delta p}{\partial t} + G_\alpha \Delta p = 0$$
$$\frac{\partial \Delta p}{\partial x} + m \frac{\partial W}{\partial t} + R W = 0$$

(3)

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 compressions and rarefactions, which creates pressure changes in relation to the average static pressure $P$. 
Here, $W$ – volumetric flow rate of the coolant in the pipe; $L$ – the length of the pipe; $S$ – the cross section of the pipe; $L_s = \frac{L \cdot S}{k \cdot p}$ – the acoustic compliance of the medium; $\rho_i$ – the density of the two-phase (liquid and vapor) medium; $a$ – the speed of sound; $k$ – the adiabatic factor; $G_w = \frac{1}{k \cdot p} \cdot W \cdot L$ – wave conductivity of the medium $m = \frac{\rho_i \cdot L}{S}$ – the acoustic mass; and $R_a$ – the active acoustical resistance of fluid flow.

These equations are known in the literature under the name of Telegraph equations [9]. The solution of the system of linear differential equations (3) 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 (4) 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 ($R$).

$$\begin{align*}
\frac{\partial i}{\partial x} + C \frac{\partial u}{\partial t} + Gu &= 0 \\
\frac{\partial u}{\partial x} + L \frac{\partial i}{\partial t} + Ri &= 0
\end{align*}$$

Due to the unity of the differential equations of acoustic (3) and electric (4) 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 and voltage ($u$) with distributed constant capacitance ($C$), inductance ($L$), conductivity ($G$) and ohmic resistance ($R$). Thus, the self-frequency of liquid pressure oscillations ($f_{\infty}$) in pipe is determined by formula (5):

$$f_{\infty} = \frac{1}{2\pi \sqrt{mC_a}}$$

For any element $i$ satisfying the conditions in [4, 6]:

$$L_i \ll a_i / f_{\infty}$$

$$C_a = \frac{L_i \cdot S_i}{\rho_i \cdot a_i^2}, \quad m_i = \frac{\rho_i \cdot L_i}{S_i}, \quad f_{\infty} = \frac{a_i}{2\pi \cdot L_i}$$

where $a_i$ – the speed of sound in the liquid in the pipe (m/s); $\rho_i$ – the density of the liquid; $L_i$, $S_i$ – the length, and the cross-sectional area of the $i$-th element, respectively.

For $n$ elements connected in series:

$$C_a = \sum_{i=1}^{n} C_{a_i}, \quad m = \sum_{i=1}^{n} m_i, \quad f_m = \frac{1}{2\pi \sqrt{m \cdot C_a}}$$

The problem of developing acoustic models of coolant motion in the main NPP equipment, its individual components and in a set of structural elements was first solved in reference [4]. Developed methods of modeling and calculation of acoustic waves in the coolant of NPP allowed create an acoustic model of a nuclear reactor and organize its testing and verification at NPP with a light water reactor. The radiation of elastic waves by the coolant flow was investigated in paper [10].

3. Acoustic model of nuclear reactor

In open systems, such as the coolant circulation circuit in NPPs and the reactor itself, chaotic turbulent pulsations and vortices are transformed into ordered oscillations. The frequencies of these oscillations are determined by the Thomson-Kelvin formula and by taking into account that the reactor with cold and hot loops system has the same properties as Helmholtz resonators. Hydraulic systems of NPPs are a chain of interconnected elements of varying complexity, which in general form a sound pipeline [4].
The simplest elements in such systems are pipe devices. Since they are performed with various elements like extensions, chambers, diverting channels, throttles, valves, etc., the general theory of sound propagation in these devices is complex [8, 11, and 12]. However, if the size of the acoustic element is less than the wavelength (6), it can be considered as acoustic elements with concentrated parameters, and the entire sound pipeline as constituting of segments of waveguides with concentrated parameters [8,11,12]. Similar analogies are also true for other seemingly unrelated physical systems [8, 11-14]. The formula for calculating the self-frequency discharge of the Thomson capacitor [2] served as the basis for the development of: acoustic resonator [3]; dynamic analogies [11-13]; acoustic models of the steam generating channel, pressurizer and nuclear reactor [14]. The first circuit of VVER is a branched hydraulic pipeline system containing elements with complex geometry. There are a number of elements, connecting these pipes, and in these connections, there may be coolant flow fluctuations caused by the formation of vortices, and acoustic waves that, along with cyclic loads, lead to vibrations of the equipment and reduce its service life. [15,16]. It is noted in paper [16], that the problem of vibrations at the NPP arose due to the fact that at the design stage of the first reactors, the dynamic effect of the coolant flow, which is an energy source capable of causing mechanical vibrations of the structural elements, did not take into account. However, ensuring the vibration strength of the equipment and pipelines of the reactor plant continues to be an urgent task, even at present. There are several reasons that make it difficult to solve this problem, the main of which, from the author’s point of view, is the impossibility of forecasting exciting vibration effects 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 hyper cycle zone of the fatigue curve, high sensitivity of vibrations to small changes in design, external influences and the environment, the variety of structural forms of equipment elements, the root cause of vibration excitations and their mechanisms. In a nuclear reactor as in a dissipative system, entropy increases and energy decreases over time due to friction or scattering. A nuclear reactor is an acoustic system in which energy increases over time, i.e. it is a system with negative friction (with negative dissipation).

Due to the operation of pumps and heat generation in the reactor, the processes of self-organization occur during the exchange of energy and mass with the environment, i.e., while maintaining the current equilibrium state the dissipation losses are compensated from the outside. Thus, the electrical analogue of the nuclear reactor system with attached pipelines is the Helmholtz resonator, i.e. LC-circuit, with transformer positive feedback, in which, by satisfying condition (2), the system is turned into an oscillator with negative dissipation (negative friction). It should be noted that during the operation of the main circulation pumps in the reactor coolant, in the nozzles (local resistances), which can be considered as acoustic transformers [13], negative friction occurs leading to self-organization of the turbulent process. It is important to note that such self-organization occurs during self-excitation of oscillations as a result of loss of stability of the stationary convective flow during heat supply, and is called "Riike oscillation generator" or "Riike tube" [17].

3.1. Sequence of obtaining new and original results
In works [18-26] the list of works in which for the first time received results and their practical application are specified is given. Sequence of achievement by the author of new and original results served as a scientific basis for the creation of an unparalleled acoustic model of a nuclear reactor which opened the ability to take into account the influence of geometric parameters of equipment and the layout of the coolant circuit on neutron physical, thermal hydraulic and oscillatory processes in equipment and coolant to use it to improve the efficiency of operation service life, safety and security of nuclear power plants from shock and seismic impacts.

Theoretical justification of self-oscillation in a single steam generating channel [18]. Experimental evidence of self-organization of chaotic turbulent process in the self-oscillation threshold value of the negative resistance caused by an increase in heating [19]. Condition for the occurrence of oscillations in the steam-generating channel [20]. The diagnostic sign of boiling of the coolant at VVER and PWR [21] was published shortly before the accident on three miles and could prevent erroneous actions of
personnel when using pressure pulsation sensors. The results of forecasting the frequency of these periodic oscillations in various operating modes of the boiling reactor RBMK-1000 were verified at the Ignalina NPP [22]. The above results are used [23] in the analysis of the processes that led to the destruction of the Chernobyl reactor included in Information about the Chernobyl accident and its consequences, prepared for the IAEA the report [24]. 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. In [25], the influence of gaseous radiolysis products on the vibrations of fuel assemblies and equipment is proved for the first time.

3.2. Scientific basis for creating an acoustic model of a nuclear reactor

The results of the developed methods for calculating the frequency of ASW and determining the sources of their generations are confirmed by the measurement data obtained on experimental facilities and measurements performed at existing NPPs and still are the only way to predict them and identify the prediction of their resonant interaction with the vibrations of the equipment and internal and external sources of wave loads on the equipment.

These results are a convincing proof of the practical value of the scientific direction created by the author in the NRU MPEI. However, the widespread application of these results to date is hindered by the belief that the ASWs are generated by vortex formation in the coolant flows. Due to this misconception and the urgency evolved after the Fukushima accident in the world, to increase the seismic stability of nuclear facilities, it became necessary to characterize additional previously unpublished and therefore unknown acoustic properties of a nuclear reactor by describing its acoustic model [25]. An acoustic system consisting of a nuclear reactor with attached pipelines forming hot and cold threads is showed in figure 2. An acoustic system consisting of a nuclear reactor with attached pipelines forming hot and cold threads is showed in figure 2. On this figure the following symbols are used: 1 - in-core instrumentation detectors; 2 - upper unit; 3 - protective tube unit; 4 - core barrel; 5 - core baffle; 6 - surveillance specimens; 7 - core; 8 - nuclear reactor vessel. Acoustic properties of this system cannot be obtained by a simple superposition of the acoustic properties of its constituent elements. This system is a complex Helmholtz resonator capable of generating multiple ASW simultaneously. To form it, several input and output pipes must be combined by the method of electroacoustic analogies into one equivalent input throat. The three stages (a, b, c) of formation of a complex Helmholtz resonator are shown in figure 3. The complex Helmholtz resonator is the result of a transformation of two reactor models: a) a model combining cold (incoming) pipelines; b) a model combining hot (outgoing) pipelines, in model c) with one throat. In [26], a thermo hydraulic three-dimensional CFD code of the VVER-1200 reactor model was developed and applied, containing ~1 billion cubic meters. 1). The Developed model allows determining the distribution of temperature (figure 2) and coolant pressure (figure 3) in the reactor. The acoustic model of the nuclear reactor was verified at Novovoronezh NPP [25]. It has been established that the number of simultaneously generated acoustic waves corresponds to the number of acoustic particularities in the pipelines connected to the reactor and practically coincides with the results of the predicted computational evaluation carried out using the developed acoustic model of the nuclear reactor. The use of this model, which has no analogues, will allow to optimize design and engineering solutions by creating NPP equipment capable of suppressing unwanted cyclic loads in operational and emergency modes, as well as during seismic and shock impacts. This model can be adapted and applied to VVER reactors regardless of geometric dimension, and for single-phase and two-phase state of the coolant under conditions of forced or natural circulation of the coolant.
Figure 2. Reactor VVER

Figure 3. Reactor VVER CFD model

Figure 4. Formation of complete Helmholtz resonator model

Figure 5. Distribution of static pressure in CFD
4. Conclusions

- The created and verified digital acoustic model of a nuclear reactor is intended for predicting, diagnosing and preventing the occurrence of undesirable self-oscillations of the coolant and resonances with fluctuations of nuclear fuel and equipment in operational and emergency modes.
- A previously unknown property of a reactor with attached pipelines to generate several ASW simultaneously has been established.
- The influence of reactor design and pipeline tracing on vibration, operational efficiency, service life, safety, and seismic resistance of equipment has been proved.
- Potential applications are indicated: design of power plants with large, medium and small power reactors, improvement of operational efficiency, service life, safety and seismic resistance.
- The developed mathematical models are universal, quite simple and, as evidenced by the results of measurements at nuclear power plants, effective for determining the acoustic properties of complex systems with accuracy sufficient to solve a number of important practical problems.
- Requirements for small reactors long-term operation in the switching modes can be achieved by minimizing the dynamic loads on the design of the reactor plant.
- The use of an acoustic model of the reactor allows optimizing design and engineering solutions by designing equipment that can minimize unwanted cyclic loads.

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