CORRELATION ANALYSIS FOR NOISE DIAGNOSTICS OF IN-CORE REACTOR EQUIPMENT

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The brief survey of noise methods of PWR in-core equipment diagnostics is presented. The possibilities of using the standard system of neutron emission sensors and temperature control sensors for registration of noise oscillations of neutron flux and coolant temperature and subsequent study of these signals by spectral methods of analysis are discussed. The new method for the coolant velocity control by the mutual spectrum analysis of noise signals from the neutron and temperature fluxes is offered.

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1. INTRODUCTION

The problem of nuclear energy safety is one of the most urgent problems after the Chornobyl incident. The ways to solving this problem are the development and improvement of control methods and diagnostic techniques for the reactor equipment and energy production process. Now the methods of noise diagnostics are widely discussed and used for the reactor equipment control at many nuclear power plants (NPP).

Powerful pumps (PP) provoke the intensive coolant stream in the primary reactor system. The coolant flowing causes both different oscillations of the in-core equipment and excitation and propagation of acoustic and other types of waves. The interaction of waves is the cause of a stochastic character of oscillations.

Current-technology fission reactors are provided with the in-core system of neutron flux measuring sensors having ability to evaluate the neutron noise oscillations. A stochastic form of neutron fluxes is related with in-core processes and contains information about the coolant parameters and about the in-core equipment oscillations. Spectral methods of analysis of this noise signals are used for diagnostic purposes.

The current methods of noise diagnostics allow us to solve a number of problems concerning the in-core equipment control:

- diagnosis of a primary coolant system component failures;
- detection of real failures and deviations from the normal performance;
- determination of anomalous process increments.

The possibilities of equipment failure control by noise methods are based on the essential dependence of the stochastic processes with different defect. Statistical methods allow obtaining diagnostic information on phase and amplitude characteristics of noise signals, obtained directly from the core or from the primary system pipe.

Methods of noise diagnostics are widely discussed to determine:

- coolant velocity,
- boiling coolant state,
- condition of attachment units of fuel assemblies,
- tendency to deterioration of attachment units in the reactor basket,
- reactor reactivity.

Unfortunately these types of diagnostics do not effectively develop. To solve this problem it is necessary to have special diagnostic equipment: sensors, measuring technique and software. Another problem is the ambiguity of interpretation of measured information because of a large number of degrees of freedom in noise processes.

Many publications are devoted to different problems of noise diagnostics. In the present paper we refer to a small part of papers concerning the problems under discussion [1-18]. Some of them consider theoretical problems of noise diagnosis, others regard the development of diagnostic methods.

2. DIAGNOSTIC MEANS IN WWER-1000

There is a standard system of neutron flux measuring sensors in WWER-1000 reactors. It consists of 64 sensor assemblies with seven sensors in each.

They are placed in one fuel element and distributed uniformly (with equal distances between them) throughout the core.

Besides, there are 95 sensors (thermo-couples), which measure the coolant temperature fluctuations in the upper part of the core. The neutron fluxes from each sensor have a stochastic form (Fig. 1). The abscise axes shows a number of points measured in time, and the Y-axes gives the value of the potential obtained from the sensor in arbitrary units.

For analysis of these signals we used statistical methods. Special software, named "DIALOG", was developed for analysis of noise signals measured in the reactors of the Zaporizhzhya NPP.

The noise signal shown in Fig. 1 is not exactly the neutron noise signal. The signal looks so after elimination of the constant part and normalization of the noise part of the neutron flux. In fact the neutron flux, that puts in the sensor, transforms into an electric signal, then it undergoes some apparatus changing (amplification, digitization and so on). All its changes are described by the transitive function that should be taken into account in the interpretation of diagnostic information.

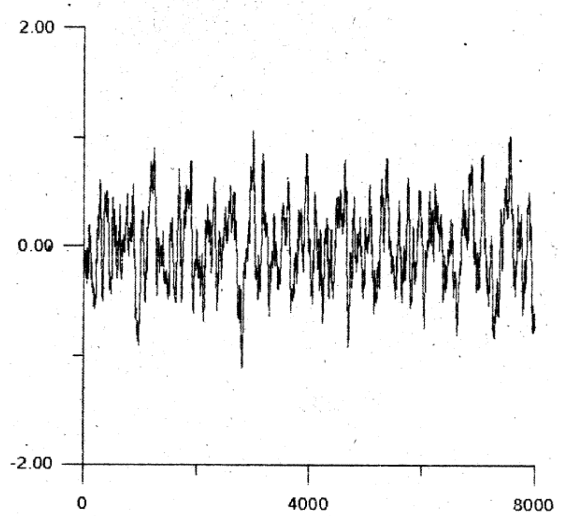

Fig. 1. *Neutron flux signal*

Fig. 2 demonstrates the example of the neutron noise spectra in the "DIALOG" windows obtained by the Fourier expansion of the noise signal. Analysis of such spectrum enables to obtain the information about typical oscillations in the system. There are few well visible peaks in the picture. The frequency of about 16.6 Hz [5] is connected with the pomp rotation. The peak in the vicinity of 9 Hz is the acoustic standing wave frequency [12]. Other peaks have no clear interpretation. They are related with different waves and oscillations inside of the primary system. Their identification is one of the problems of noise diagnostics.

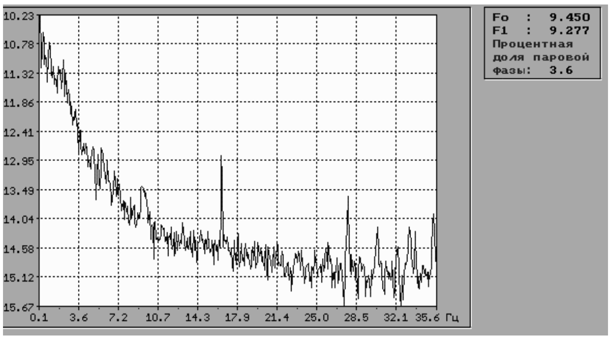

***Fig. 2**. Neutron noise auto spectra*

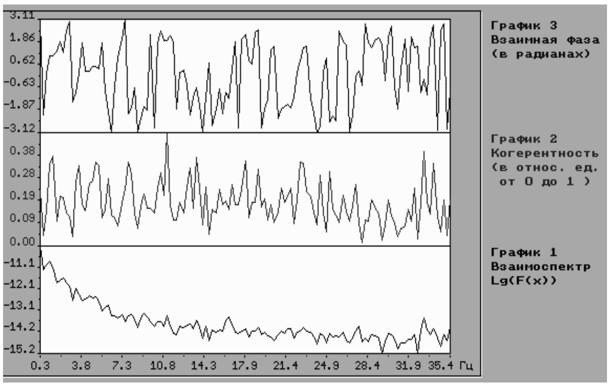

Fig. 3. *Phase bias (above), coherence function (center) and cross spectrum (below)*

Fig. 3 presents similarly [6] the mutual characteristics of noise signals from two sensors: phase shift, coherence function and cross spectrum. The phase shift is in radians, the coherence function and the cross spectrum - in arbitrary units. These functions are usually used to study the mutual characteristics of wave processes. In particular the phase shift is used to determine the coolant velocity.

3. DETERMINING THE COOLANT VELOCITY

The time delay (phase shift) in the neutron flux fluctuations, measured between two sensors placed in one measured channel, allows us to determine the coolant velocity.

The relation between the coolant velocity and the phase shift is determined by the next equation:

$$v_c = \frac{2\pi f \Delta l}{\Delta\varphi}, \tag{1}$$

where f is a perturbation frequency, Δl is the length between sensors, $\Delta\varphi$ is the phase shift. Unfortunately the linear dependence between the phase bias and the frequency is not stable in the core [1,8]. Usually it is valid for small frequency interval from 0.1 to 1.5 Hz (Fig. 4).

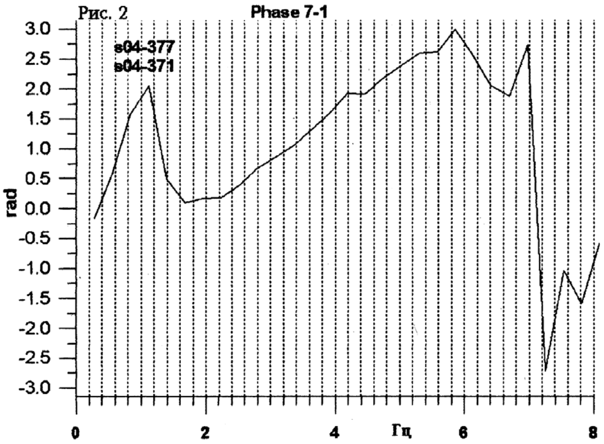

Fig. 4. *Phase shift dependence from frequency*

The linear dependence of the phase shift on the frequency is broken in the region of 1.5 Hz. More high frequencies give other linear dependence, but it does not give the correct results because the scale of perturbation becomes less then the distance between the sensors. It is difficult to determine the phase shift in this case as it exceeds π. Therefore, the interval of 0.1…1.5 Hz was used to estimate the coolant velocity. The estimations are about 5 m/s.

However, this method gives correct results not always. Large disturbances often give wrong results. It was the cause to suggest the new method for the coolant velocity control.

The possibility consists in simultaneous measuring of noise signals from neutrons and of temperature fluctuations by means of different sensors. The phenomenon of thermal inertia gives a phase shift between neutron and temperature oscillations. The coolant velocity can be determined with the help of the transfer function $W_{NT}(\omega)$.

To obtain it we use (as in [1,2]) the following equations of the thermal balance for the fuel and coolant:

$$V_f \rho_f C_f \partial T_f(z,t)/\partial t = Q(z,t)V_f - k(T_f(z,t) - T_c(z,t)), \tag{2}$$

$$V_c \rho_c C_c(\partial T_c(z,t)/\partial t + V_c \partial T_c/\partial z) = k(T_f(z,t) - T_c(z,t)), \tag{3}$$

where V_f and V_c are the fuel and coolant volumes, ρ_f and ρ_c are the fuel and coolant densities; T_f and T_c are temperatures, k is the heat conduction factor between the fuel and the coolant. $Q(z,t)$ is the local specific rate of energy production, v_c is the coolant velocity. Here we suppose that all fission energy dissipated in fuel elements and the energy exchange goes between the coolant and fuel element's surfaces. Further, we write the temperatures and the power output as a sum of non perturbed and fluctuation parts:

$$T_f = T_{0f} + \delta T_f,\ Q(z,t) = Q_0(T_0) + \delta Q(T_c),$$

$$\delta Q(T_c) = G_n \delta N, \tag{4}$$

where G_n is the proportionality factor between the neutron noise flux and energy production. Neutron and temperature fluctuations are connected by transfer function W_{NT}

$$\delta N = W_{NT}(\omega)\delta T_c.$$

After linearization of equations (2,3) we obtain the system:

$$\begin{aligned} &\Lambda_f \frac{\partial \delta T_f}{\partial t} = \delta Q(T_c) S_f - k(\delta T_f - \delta T_c), \\ &S_f Q_0(T_{0e}) - k(T_{0f}(z) - T_{0c}(z)) = 0, \\ &\Lambda_c\left(\frac{\partial \delta T_c}{\partial t} + v_c \frac{\partial \delta T_c}{\partial z}\right) = k(\delta T_f - \delta T_c), \\ &\Lambda_c v_c \frac{\partial T_{0c}}{\partial t} = k(T_{0f}(z) - T_{0c}(z)), \end{aligned} \tag{5}$$

where $\Lambda_j = S_j \rho_j C_j; S_j$ are the squares of the fuel and coolant length unit.

Perturbed parts of the temperatures can be written in the form of harmonic variables:

$$\delta T_j = T_{jz}(z) e^{i((\omega - k_z v_c)t + k_z z + \varphi_j)}, \tag{6}$$

where the index j denotes the coolant and the fuel. Here the multiplier in brackets before t in the exponent has a sense of the frequency in the laboratory system of coordinates. Such perturbations take into account the coolant moving with a velocity v_c and the temperature changing during the coolant moving across the core by z-dependence of the T_{jz} factors.

At such perturbations we obtain from the system (5):

$$i\Lambda_f(\omega - k_z v_c)\delta T_f = G_n W_{NT}(\omega) S_f \delta T_c - k(\delta T_f - \delta T_c) \tag{7}$$

$$i\Lambda_c \omega \delta T_c + \Lambda_c v_c \frac{\delta T_c}{T_{cz}} \frac{\partial T_{cz}}{\partial z} = k(\delta T_f - \delta T_c), \tag{8}$$

where $k = S_f Q_0 / \Delta T, \Delta T = T_{0f} - T_{0c}, \varphi$ are the perturbation phases. The last system gives $W_{NT}(\omega)$:

$$W_{NT}(\omega) = \frac{1}{G_n S_f}\left[i(\omega - k_z v_c)\Lambda_f \frac{\delta T_f}{\delta T_c} + \Lambda_c\left(i\omega + \frac{v_z}{T_{cz}} \frac{\delta T_{cz}}{\delta z}\right)\right]. \tag{9}$$

The temperature fluctuations do not have the wave properties. They are described by the thermal conductivity equation. It allows us to do simplifications in equation (9) by assumption $\omega = 0$. In this case it can be written in the form:

$$W_{NT} = [\Lambda_c \frac{v_c}{T_{cz}} \frac{\partial T_{cz}}{\partial z} - i k_z v_c \Lambda_f \frac{\delta T_f}{\delta T_c}] / G_n S_f. \tag{10}$$

The first term in the brackets is less than the second in the case of perturbations with small k_z values. There are several reasons for such conclusion. The comparative rise of the ground temperature during the flow of the coolant through the core is about 7% ($T_{in} = 550$ K, $T_{out} = 590$ K). The temperature increase due to the perturbations should have the same order of magnitude. There is reason to suppose that $\Lambda_c < \Lambda_f$. It is connected with the large density of the fuel. For large scale perturbations the phase shift between δT_f and δT_c will be not large so their amplitudes have the same order of magnitude.

So for the large scale with the zero frequency fluctuations the phase shift between the temperature and neutron fluxes will be about $\pi/2$. Neutron flux measuring sensors will fix the Doppler frequency shift as the real frequency equals to $k_z v_c$.

According to the obtained results it is possible to measure the coolant velocity by plotting the $\Delta\varphi(f)$ dependency, where $\Delta\varphi$ is the phase shift between the neutron noise and coolant temperature perturbations. Next we can find the points with $\varphi(f) = \pi/2$. The lower of these frequencies corresponds to the lower value of k_z. A relation between these frequencies and the coolant velocity could be written as $f_n = \frac{n v_c}{2H}$, where n is the number of points with phase shift $\pi/2$. In this case the coolant velocity is:

$$v_c = \frac{4H \sum_{j=1}^{n} f_j}{n(n+1)}. \tag{11}$$

4. PART OF THE VAPOR PHASE

Auto spectra analysis shows presence of acoustic standing waves in the primary system. According to [3] a frequency of the standing wave depends on coolant parameters according to formula:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{C_S^2 \rho_m}{\rho l_m l}}\,, \qquad (12)$$

where l is the pipe length, l_m is the length of the pipe parts with vapor phase, ρ and ρ_m are the densities of liquid and mixture phases, C_S is the sound velocity. A vapor phase occurrence diminishes the density of the coolant. As the result it diminishes the wave frequency. Hence, we can calculate the change of the coolant density taking into account the wave frequency change. This possibility was used in the DIALOG software for vapor phase determining. The value of the vapor phase displays in the DIALOG window on the right side of the screen, where F_0 is the wave frequency without a vapor phase, F_1 is the wave frequency in the case of the vapor phase absence (see Fig. 2).

CONCLUSIONS

In spite of the fact that numerous researches are devoted to developing the noise methods for the control of the fission process and the state of internal equipment in the nuclear reactor, the problem stays far from completion. It is connected with difficulties taking place in the interpretation of measured data. In many cases the information obtained leads to doubtful understanding of the processes observed. It is very important to study the wave processes, which take place in the core as well as in the whole primary system of the reactor. Therefore, the paper [18], presented in this issue is interesting, because it studies the problem of interaction between the acoustic and neutron waves in the core.

The present paper contains a brief review of noise methods used for the in-core diagnostics. Parts of these methods were developed in the software system for WWER-1000 reactors at the Zaporizhzhya NPP. Here also, a new method of determination of the coolant velocity is proposed.

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КОРЕЛЛЯЦИОННЫЙ АНАЛИЗ ШУМОВОЙ ДИАГНОСТИКИ ВНУТРИРЕАКТОРНОГО ОБОРУДОВАНИЯ

В.А. Рудаков

Приведен краткий обзор шумовых методов диагностики внутриреакторного оборудования водо-водяных реакторов. Рассмотрены возможности использования стандартной системы датчиков нейтронного излучения и температурного контроля для регистрации шумовых колебаний нейтронного потока и температуры теплоносителя с последующей обработкой этих сигналов методами спектрального анализа. Предложен новый метод контроля скорости теплоносителя с помощью анализа взаимных спектральных характеристик шумовых сигналов нейтронного потока и температуры теплоносителя.

КОРЕЛЯЦІЙНИЙ АНАЛІЗ ШУМОВОЇ ДІАГНОСТИКИ ВНУТРІШНЬОРЕАКТОРНОГО ОБЛАДНАННЯ

В.А. Рудаков

Приведено стислий огляд шумових методів діагностики внутрішньореакторного обладнання водо-водяних реакторів. Розглянуто можливості використання стандартної системи датчиків нейтронного випромінювання і температурного контролю для реєстрації шумових коливань нейтронного потоку і температури теплоносія з наступною обробкою цих сигналів методами спектрального аналізу. Пропонується новий метод контролю швидкості теплоносія за допомогою аналізу взаємних спектральних характеристик шумових сигналів нейтронного потоку і температури теплоносія.