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ZJE - 263 1982

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1. INTRODUCTION

The neutron noise analysis has gone through a stormy development during the last 5 - 8 years. This development is reflected in the ever-increasing number of published works. While at the first conference of the specialists in the field of noise diagnostics, SMORN-1, which took place in Roma at 1974, the majority of papers has been devoted to the problems of noise monitoring in the research reactors, three years later at the conference in Gatlinburg (SMORN-2) nearly all papers have been already devoted to noise analysis in power reactors.

The neutron noise analysis can be classified at present as a special field of nuclear engineering. The research works studied in this area of the applied research can be divided into two basic groups:

1. Experimental and theoretical studies of the content of the noise signal of the neutron flux density.
2. Direct application of the noise methods for increasing the safety and reliability of nuclear power installations - the methods of neutron noise diagnostics.

Both groups are of course mutually tied up and the successes in the application of the neutron noise analysis for the operational diagnostics of power reactors are conditioned by sufficient progress in the research of the information content of the noise signal. This area represents a wide range of theoretical and experimental effort covering the area of the theoretical models formulation, the verification calculations, the numerical experiments, the simulated experiments in the research reactors with isolated sources of excitation forces including the verification of relevant interpretation models.

2. MODEL OF ONE-POINT APPROXIMATION

The simplest theory of the neutron noise in a reactor is the model of the one-point approximation. In accordance with this model the fluctuation of the thermal neutron flux density in the frequency zone can be expressed by the following relation

$$\delta\phi(\omega,r) = G_0(\omega)\cdot\delta\varrho(\omega)\cdot\phi(r) \qquad /1/$$

where ω..... circular frequency
r ..... coordinate
$\phi(r)$... neutron flux density in point r in the critical reactor
$\delta\phi(\omega,r)$ neutron flux density fluctuation in point r
$G_0(\omega)$... transfer function of the zero power reactor.

The transfer function of the zero power reactor can be expressed in the following way

$$G_0(\omega) = \frac{1}{i\omega\left(l + \frac{\beta}{\bar{\lambda}+i\omega}\right)} = \frac{1}{\beta}\,\frac{1}{\frac{i\omega}{\alpha_{CR}} + \frac{1}{1+\frac{\bar{\lambda}}{i\omega}}} \qquad /2/$$

where l...... life time of prompt neutrons
β...... effective fraction of delayed neutrons
$\bar{\lambda}$...... medium value of the decay constant (for one group of delayed neutrons $0.1\ s^{-1} = 0.016$ Hz)

$$\alpha_{CR} = \frac{\beta}{l} = 100\ s^{-1} = 16\ \text{Hz}$$

For small frequencies ($\omega \ll \bar{\lambda}$), $G_0(\omega) \rightarrow \infty$ while for high frequencies ($\omega \gg \alpha_{CR}$) $G_0(\omega) \rightarrow 0$.

In the "plateau" area of transfer function ($\lambda \ll \omega \ll \alpha_{CR}$) it is possible to express $G_0(\omega)$ in a simplified form

$$G_0(\omega) \doteq \frac{1}{\beta} \qquad /3/$$

In the one-point model the fluctuations of the neutron flux density are excited only by the reactivity fluctuations in the active zone. $\delta\varrho(\omega)$ are the reactivity fluctuations of the active zone including the corresponding effect of the feedback depending only on the excitation frequency. Therefore, the one-point model of the neutron noise is called the "space-independent model". Expressed more precisely, the density fluctuations of the neutron flux $\delta\phi(\omega,r)$ depend upon the space coordinate, but this space dependence does not reflect the space dependence of the excitation force. Analogically in the validity region of the one-point kinetics the space independent characteristics of the random process are:

- the output spectral density of the normalized fluctuation
NAPSD $\delta\phi_r(\omega) = |G_0(\omega)|^2 \cdot$ APSD $\delta\varrho(\omega)$, where APSD is the spec- /4/
tral density of the output power of the reactivity $\delta\varrho(\omega)$

- the reciprocal output density of the normalized fluctu-
tions NCPSD $\delta\phi_{r_1,r_2}(\omega) = G_0(\omega)\cdot$ APSD $\varrho(\omega)$. /5/

The coherence between the fluctuations $\delta\phi(t,r_1), \delta\phi(t,r_2)$ is then independent on the frequency

$$\mathrm{COH}\,\delta\phi_{r_1,r_2}(\omega) = 1$$ /6/

and the phase shift between the fluctuations measured in two different levels is zero. Simplifying it, it is possible to say that in accordance with the one-point kinetics the neutron field in the reactor "is breathing in the same rhythm" in the whole volume of the active zone.

The experimental works leading to the explanation of the driving force - neutron noise tranfer and to the verification of the first interpretation models were carried out mostly on experimental reactors with active zone of small dimensions and with highly enriched fuel. The result of these studies /1 - 4/ was the conclusion that for the studies of the neutron noise in the small and highly enriched zones it is possible to use the theory of the one-point kinetics. But simulteneously the need of the space dependent model for neutron noise study in geometrically large active zones of power reactors has been predicted /5 - 9/.

Fig. 1 presents NPSD in the reactor VVER-440 of the nuclear power station NORD, as measured by two SPN detectors and the Rh emitter from the system of the in-reactor instrumentation and by one ionisation chamber located outside the pressure vessel (schematic arrangement shown in the left part of fig. 1). The spectrum measured by the detector E 58 differs from that measured by the detectors E 38 and IK 3 which are similar. Consequently, the output spectral density depends on the measuring position. By means of accelerometers located on the channels for the control rods drive the vibration frequencies of the rods S 14 = 1.46 Hz and S 18 = 1.46 Hz can be distinctly seen in the spectrum of the detector E 58. With increasing distance from the vibrating rod the peak is less distinct. The resonance of the frequency of 2.75 Hz which is distinct in the spectrums of the detectors E 38 and IK 3 is absent in the spectrum of the detector E 58. The coherent functions are displaying evident deviations from the conclusions of the one-point geometry.

3. SPACE-DEPENDENT MODEL

In the space dependent theory the noise excited by the reactivity is only one component of the noise field. The second component is the direct local influencing from the fluctuations of the effective cross-section. The neutron flux density in the frequency zone is expressed by the relation

$$\delta\phi(\omega,r) = \frac{G_0(\omega)\,\delta\rho(\omega)\,\phi(r)}{\delta\phi_g(\omega,r)} + \delta\phi_\ell(\omega,r) \qquad /7/$$

The particular noise components are called

$\delta\phi_g(\omega,r)$ = the global effect

$\delta\phi_\ell(\omega,r)$ = the local effect.

The global effect is determined by the reactivity fluctuations and its space dependence is determined by the neutron flux distribution in the critical reactor.

The local effect is the function of the space dependence of the appropriate noise on the excitation force.

Consequently, when the defect causing the noise is independent on the space coordinates the neutron fluctuations are described by the global component. When the volume in which the disturbance occurs is much smaller than the volume of the active zone, then it is possible to characterize the disturbance as a local one. A decision whether the noise caused by this disturbance can be considered as global, i.e. following the model of the one-point kinetics, or spatial, is dependent on the dimensions of the active zone.

4. THE INFORMATION CONTENT OF THE OUT-OF-CORE DETECTOR

It is evident from fig. 1 that there is no substantial difference between the information content of the noise signal in case of the in-core detector and the out-of-core one. Unlike the in-core detector reacting only to the changes of the neutron field in the active zone, the out-of-core detector is sensitive also to changes in the attenuation of the medium between the active zone and the detector.

With regard to the fact that the typical mean free path of the fast neutrons is some 10 cm, it is evident that the out-of-core detector detects only the neutrons from the outer fuel assemblies. The calculations carried out have shown that 91% of the out-of-core response in the direction of the coordinates x-y originate from the nearest five fuel assemblies. The physical model drafted on the basis of these data /11/ is schematically illustrated in fig. 2.

The main contribution to the signal of the ionization chamber located out of core in the position defined by a distance $\ell(\theta)$ from the periphery and by angle θ (between the line connecting the centre of the active zone with the chamber, and the axis x) originates from the zone whose width is proportional to the size of the mean free path of the fission neutrons in the active zone.

The current of the ionization chamber located out of the active zone is approximately equal to

$$I(t,\theta) \cong \phi_f(t,\theta)\cdot T(t,\theta) \qquad /8/$$

where $\phi_f(t,\theta)$ is neutron flux density with the mean fission energy integrated over the area R, and $T(t,\theta)$ is the attenuation factor.

The normalized fluctuation of the current is the sum of two chambers representing successively the noise contribution of the active zone and the noise attenuation which is related to changes of properties of the medium between the active zone and the out-of-core detector in the manner as follows

$$\frac{I(t,\theta)}{I(\theta)} = C(t,\theta) + A(t,\theta) \qquad /9/$$

The noise of the active zone

$$C(t,\theta) = \frac{\delta\phi_f(t,\theta)}{\phi_f(\theta)} \qquad /10/$$

is represented by the neutron flux density fluctuations in the active zone and its contribution to the information content of the out-of-core detector signal is the same as in case of the in-core detector.

The attenuation noise

$$A(t,\theta) = \frac{\delta T(t,\theta)}{T(\theta)} \qquad /11/$$

is characterized by the fluctuations of the attenuation factor $T(t,\theta)$ which is the function of the detector distance from the active zone

$$T(t,\theta) = T(\ell(t,\theta)) \qquad /12/$$

where $\ell(t,\theta) = \ell(\theta) + \delta\ell(t,\theta)$ /13/

The distance fluctuations $\delta\ell(t,\theta)$ can be expressed by the relation

$$\delta\ell(t,\theta) = \varepsilon(t)\cdot\cos[\phi_K(t) - \theta] \qquad /14/$$

where $\varepsilon(t)$ is the vector of the instantaneous displacement of the active zone centre.

The attenuation noise is then

$$A(t,\theta) = \mu \cdot \delta\ell(t,\theta) \qquad /15/$$

where

$$\mu = \frac{1}{T} \cdot \frac{dT}{d\ell} \qquad /16/$$

is the linkage coefficient of the mechanical displacement of the component to the normalized neutron noise. The typical value of this coefficient is 0.15 cm^{-1} /12/.

Combining /14/ and /15/ gives

$$A(t,\theta) = \mu \cdot \varepsilon(t) \cdot \cos \theta_K(t) - \theta \qquad /17/$$

At the same time it is valid that

$$A(t,\theta + 180^\circ) = -A(t,\theta) \qquad /18/$$

so that the signal fluctuations of the opposite detectors are in the phase opposition.

5. VIBRATION DIAGNOSTICS OF REACTOR INTERNAL PARTS

A typical example of the noise attenuation is the neutron noise excited by pendulum movement of the supporting cylinder. Its movement changes the distance of the supporting cylinder from the ionization chamber. When we neglect the active zone noise, secondarily excited by the vibrations of the assemblies, the noise of the ionization chamber can be described by equation /17/.

In fig. 3 are the measured results of the neutron noise excited by the oscillatory movement of the supporting cylinder in the nuclear power plant Stade /13/. The vibration frequency of the supporting cylinder of about 13 Hz is distinctly differentiated in the spectrum of the ionization chamber SOR. The coherence between the chambers SOR mutually shifted by 180° indicates quite explicitly the vibrations at the frequency of 13 Hz, as well as the phase displacement of 180°. The phase shift of 180° alone is not the satisfactory prove of the supporting cylinder, because also the vibrations of further reactor internal parts are displayed by phase displacement of 180° for opposite chambers.

The supporting cylinder movement has very often a preferred direction of movement or, better said, preferred directions of movements in different frequency zones.

When the detector is located in the direction of the prevailing movement direction, i.e. $\theta_K = \theta$, then $A(t,\theta) = \max$. When there is $\theta_k \neq 0$ then the detector noise signal is decreasing and the relative contribution of other noise sources increases.

When the opposite detectors are colinear with the prevailing movement direction in a definite frequency zone, the coherence between both detectors approaches 1 /14/. The coherence between detectors which are not centrally symmetrical is always smaller than the coherence between the opposite detectors located in the movement direction.

The space behaviour of the coherence function for typical pendulum movements of the supporting cylinder is shown in fig. 4 for the detectors shifted mutually by 60° and 180° in the frequency zone 1 Hz - 15 Hz. The coherence between the opposite detectors in the frequency zone of 7 Hz - 11 Hz is approaching 1, while in case of detectors shifted by 60° it is in the mentioned frequency zone by 0.1 Hz less. This suggests that the zone of 7 - 11 Hz is the zone where the side amplitude of the supporting cylinder is prevailing. For frequencies of 17 Hz, the coherences of both pairs of detectors show peaks. This response is typical for the shell vibration of the supporting cylinder as well as for the thermal shielding.

Fig. 5 compares the NPSD signals of the in-core and the out-of-core sensors in the nuclear power plant Fessenheim 2. All in-core detectors display a resonance at the frequencies of 3.2 Hz and 7.1 Hz caused by the vibrations of the internal parts of the reactor. Comparison with the measurements in the nuclear power plant Fessenheim 1 with similarly located sensors is in fig. 6. The NPSD signals show a displacement of frequencies from the 11.5 Hz (Fessenheim 1) to 7.5 Hz in Fessenheim 2 /15/. This difference is caused by the change of the supporting cylinder bearing. The basic shape of the supporting cylinder oscillation of the active zone in Fessenheim 1 corresponds to a solution of the system dynamics with a boundary condition "fixing - support" and in Fessenheim 2 to a solution with a condition "fixing - free". Fig. 7 shows the coherence between the in-core and the out-of-core detectors of the nuclear power plant Fessenheim 2 at the 3.2 Hz and at 7 Hz (the value is given in parenthesis). The phase displacement of 180° is marked with a solid line, and the phase displacement 0° with a dashed line. Table 1 compiles the characteristic causes corresponding to the definite resonances in the spectrum of the neutron noise.

Table 1

Frequency (Hz)	The characteristic cause
3	transverse vibrations of fuel assemblies
11.5	basic shape of the internal parts oscillation
19	toroidal shape of the supporting cylinder oscillation, $n = 2$
20	toroidal shape of the supporting cylinder oscillation, $n = 4$
24.8	frequency of the main circulation pumps
32	shell shape of the oscillation of the thermal shielding, $n = 2$
42	shell shape of the oscillation of the thermal shielding, $n = 4$

So, by the method of the noise analysis it is possible to identify not only the basic shape of the oscillation of the internal reactor parts, but also the shell shapes of oscillations of the components (for example the supporting cylinder or the thermal shielding).

6. THE DIAGNOSTICS OF BOILING CRISIS

It can be expected that the boiling in one fuel assembly, i.e. produced boiling in the diagnostic fuel assembly, will not influence the low frequency part of the spectrum, where the dominating noise source is the global effect of the reactivity. Consequently, influenced will be the part of the spectrum with higher frequencies where the origin of new high frequency components can be expected resulting from local fluctuations of the cavity reactivity coefficient analogically as in boiling reactors.

Taking into account the space dependence of the two phase flow effect it is advantageous to arrange the detectors in a probe because this offers a possibility of carrying out mutual spectral analysis of signals of detectors located at different heights and in principle also in a medium with differently progressed boiling.

Supposing the detectors are placed in the probe at the coordinates (x,y,z_1) and (x,y,z_2) it is possible to express, according to the noise theory of the boiling reactors, the mutual power spectral density of detectors by a relation

$$\mathrm{CPSD}^{m}_{xyz_1,\ xyz_2}(\omega) = C_{1,2}\cdot H_{1,2}(\omega)\cdot d_1(\omega)\cdot d_2(\omega)\cdot e^{-i\omega T_{1,2}}\ \cdot \mathrm{APSD}^{m}_{xyz_1}(\omega) \qquad /19/$$

where $C_{1,2}$ - the proportion constant depending on the group constants

$H_{1,2}(\omega)$ - the frequency-dependent transfer function of the reactor expressing the characteristic of the low band filter with regard to neutron noise

$d_i(\omega)$, $i = 1, 2$ - the frequency-dependent factor expressing the sensitive length of the detector

$T_{1,2}(S)$ - the time of bubble passage between two detectors

$\mathrm{APSD}^{m}_{xyz_1}(\omega)$ - the power spectral density measured by detector at coordinates x,y,z_1

$\mathrm{CPSD}^{m}_{xyz_1,xyz_2}(\omega)$ - mutual power spectral density of the two detectors at the coordinates x,y,z_1 and x,y,z_2

$\omega\,(\mathrm{sec}^{-1})$ - angular frequency.

The power spectral density of the detector located at the coordinate x,y,z_1 is defined by the expression

$$APSD^{m}_{xyz_i}(\omega) = \frac{\alpha(x,y,z_i)}{v_m(x,y,z_i)} \qquad /20/$$

where $\alpha(x,y,z_i)$ - local volume of the steam bubbles in the point of the detector

$v_m(x,y,z_i)$ - local velocity of steam bubbles in the point of the detector

The sensitivity factor of the detector in dependence on the angular frequency can be expressed as

$$d_i(\omega) \cong \frac{\sin\left(\frac{\omega \ell}{2v_m}\right)}{\frac{\omega \ell}{2v_m}} \qquad /21/$$

By means of equation /21/ it is possible to define the characteristic frequency of the detector by a relation

$$f_i = \frac{v_m}{\ell} \qquad /22/$$

where $k(\omega)$ is the sensitive length of the detector .

$$APSD^{m}_{xyz_i}(\omega) = k(\omega)\frac{\alpha(x,y,z_i)}{v_m(x,y,z_i)} \qquad /23/$$

$k(\omega)$ is the frequency dependent constant.

The power spectral density $APSD^{m}_{xyz_i}(\omega)$ increases with the increase of the steam bubble volume and, in the application in the diagnostic fuel assembly, with increasing z. On the basis of the fact that an increase of the boiling intensity is represented by an increase of the high frequency part of the spectrum it is possible to decide whether there exists a boiling in the fuel assembly or not. Characteristic spectrum of the neutron noise caused by the boiling is in fig. 8. At the present time the possibilities of the quantitative determination of the steam bubbles content using the neutron noise analysis are experimentally verified.

7. CONCLUSIONS

The neutron noise diagnostics is for its passivity (i.e. it does not require any additional interference into the system) a suitable method for the diagnostics of both the mechanical vibrations of internal parts, and the boiling in the pressurized water reactors, complementing thereby other methods of finding the instantaneous state of the installation.

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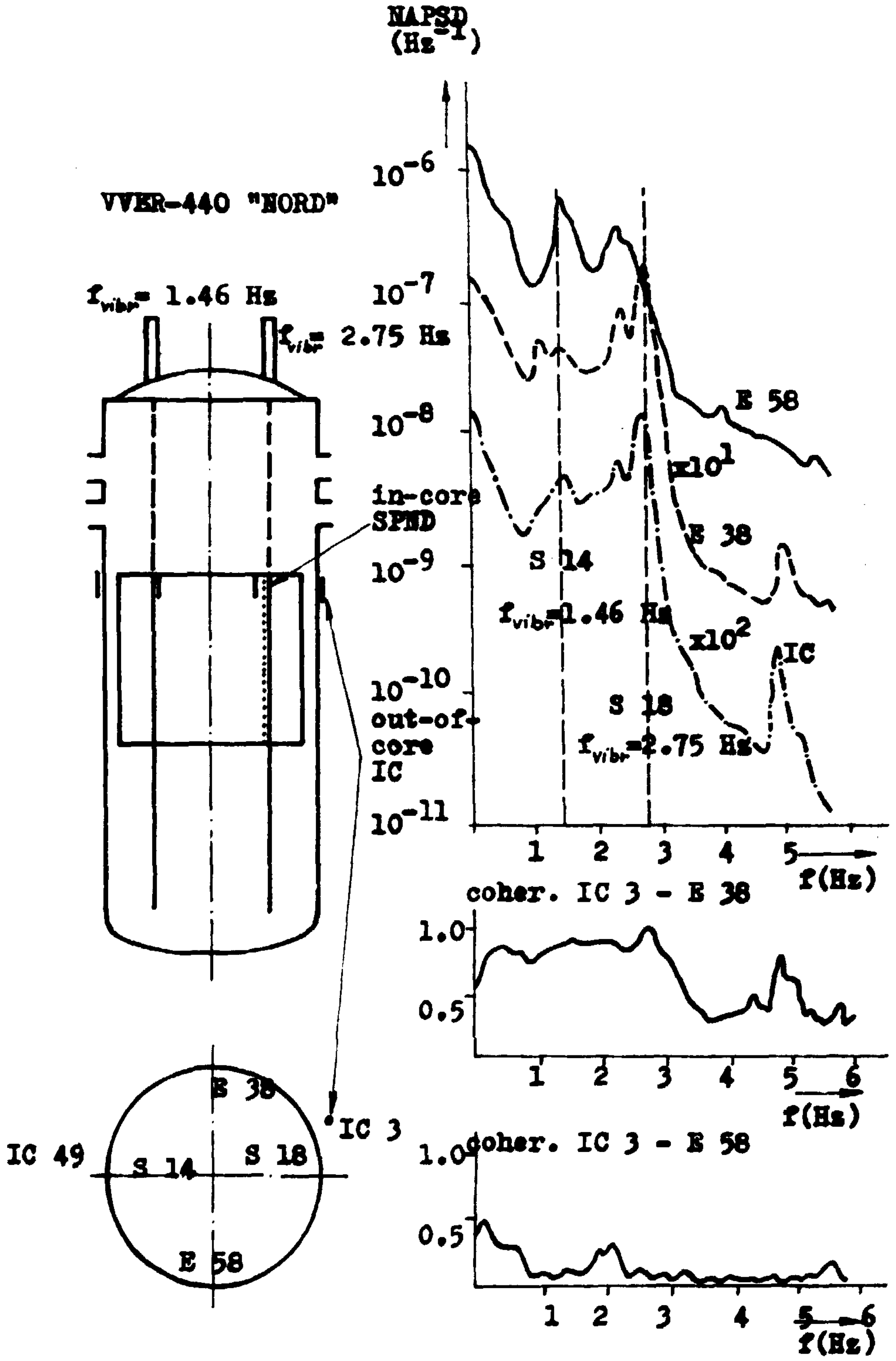

Fig. 1. Noise measurement in NORD nuclear power plant

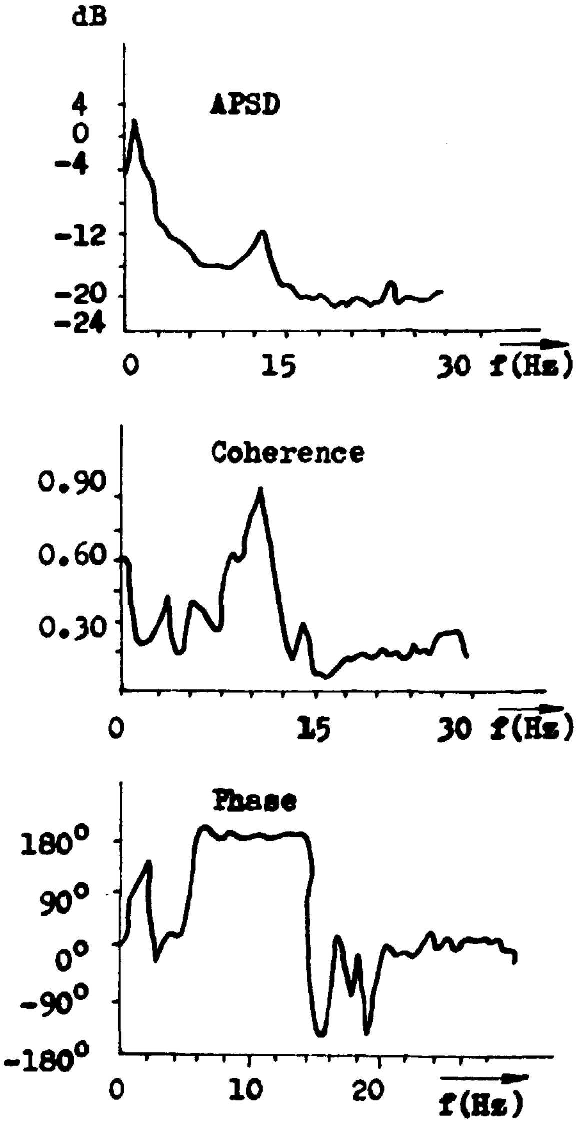

Fig. 3. Neutron noise excited by the supporting cylinder movement in the Stade nuclear power plant

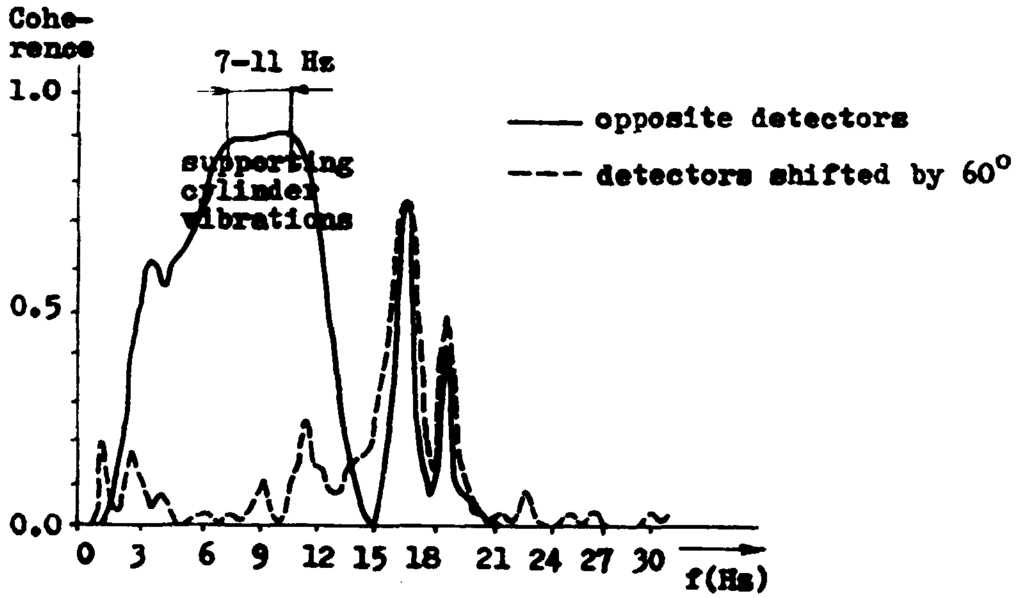

Fig. 4. Space behaviour of the coherence function for the typical pendulum movements of the supporting cylinder

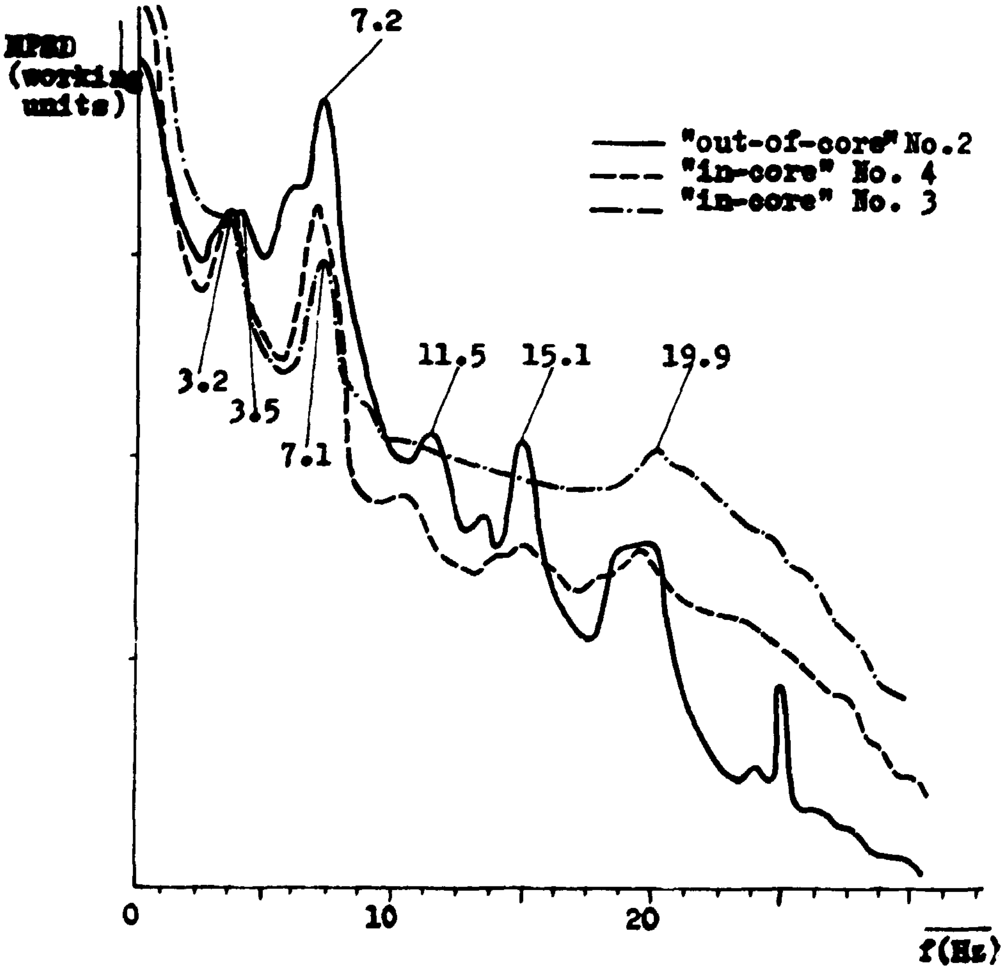

Fig. 5. Comparison of signal power spectral densities of the "out-of-core" and "in-core" detectors in Fessenheim 2 nuclear power station

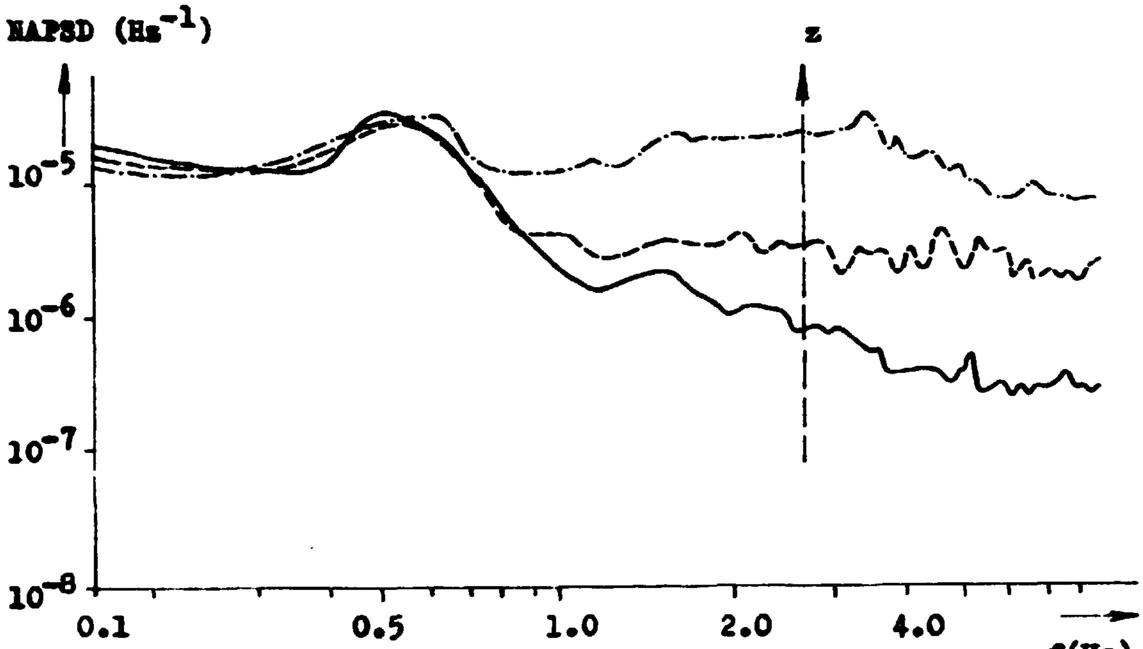

Fig. 8. The characteristic spectrum of the neutron noise at different heights of the active zone caused by the boiling of the coolant

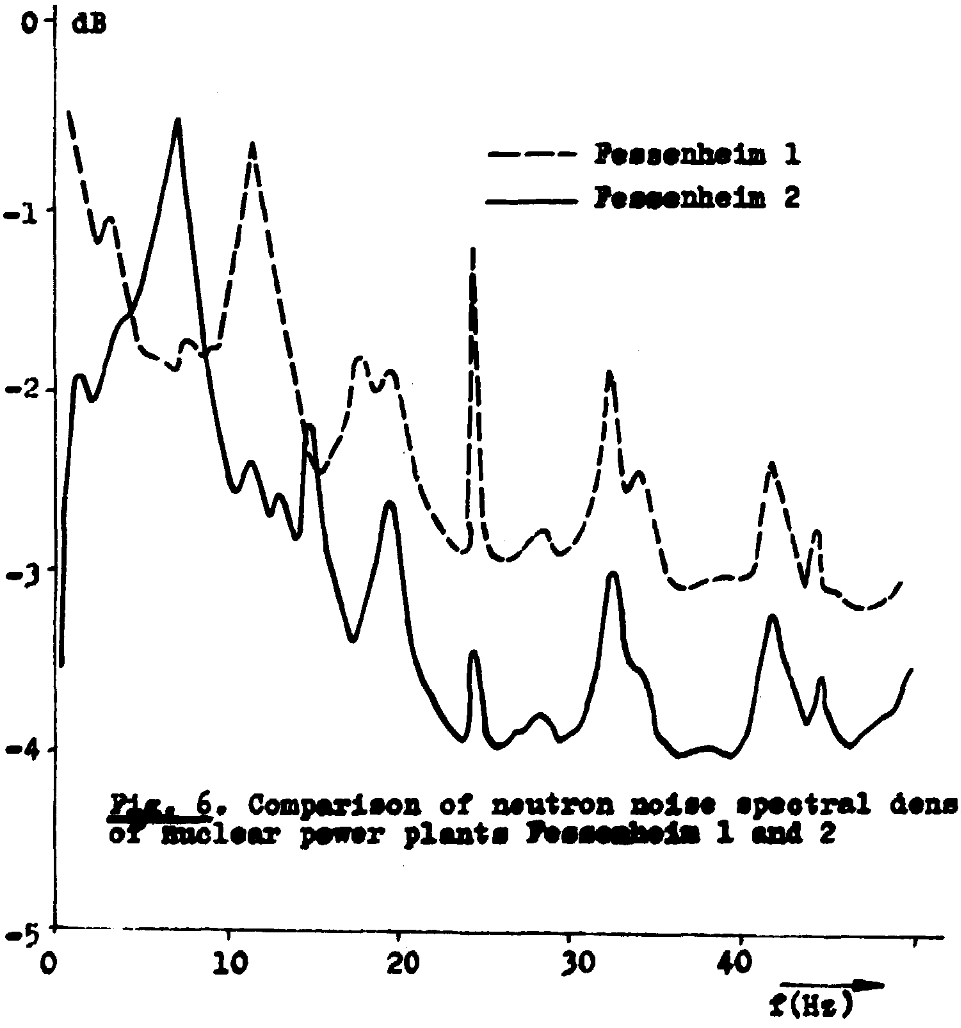

Fig. 6. Comparison of neutron noise spectral densities of nuclear power plants Fessenheim 1 and 2

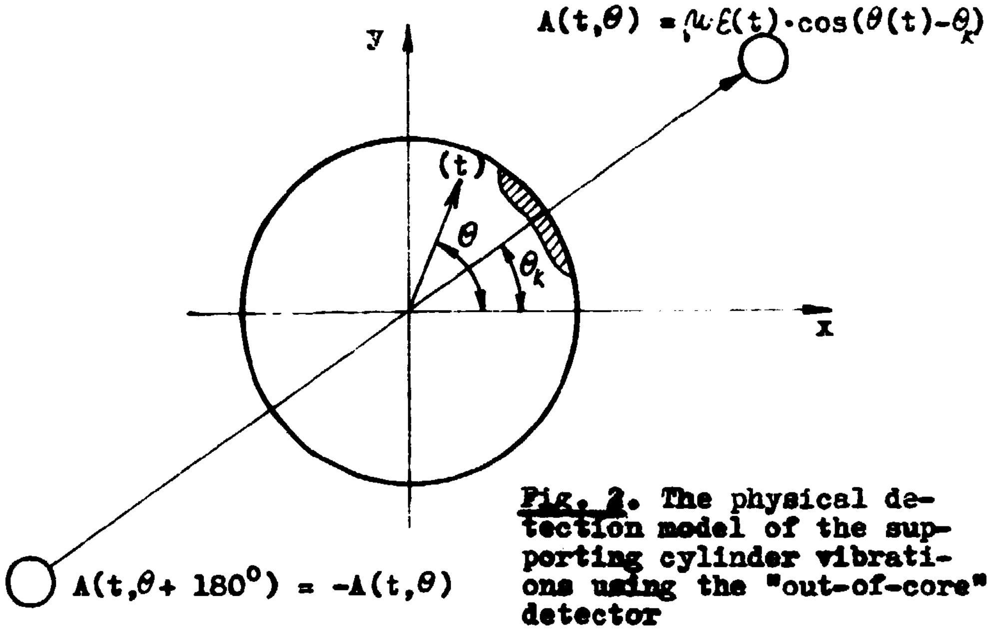

Fig. 2. The physical detection model of the supporting cylinder vibrations using the "out-of-core" detector

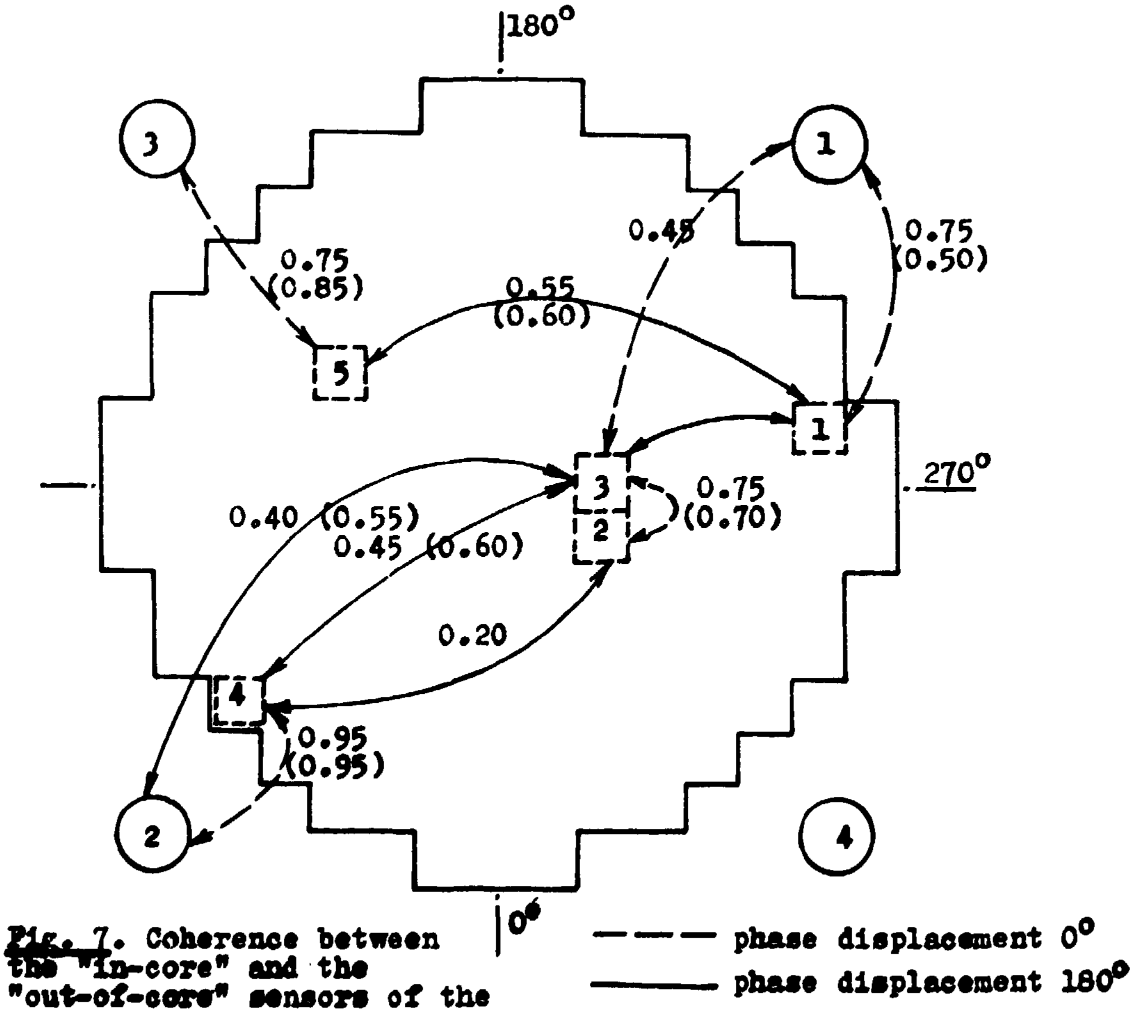

Fig. 7. Coherence between the "in-core" and the "out-of-core" sensors of the Fessenheim 2 nuclear power station