NEW NEUTRON-TEMPERATURE NOISE METHODS AND THEIR EXPERIMENTAL CHECK ON THE REACTOR VVER-1000

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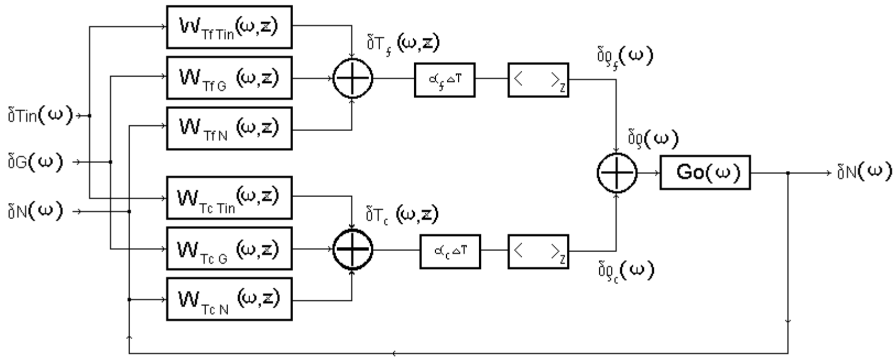
Abstract

The analytical relationships explaining the typical features of experimental spectral characteristics of in-core detector signal have been obtained on the basis of physically substantiated simplifications. New methods of moderator temperature reactivity coefficient measurement have been developed. Characteristics of global and local core energy release field nonuniformity are proposed.

Initial model

The model with axial space dependence is taken as the original neutron-temperature reactor model. The model is based on temperature balances in the fuel-coolant system and neutron kinetics equations with power feedback through moderator temperature reactivity coefficient (MTC) [1,2,3]. The linearised model written with variations in the frequency field is shown in Figure 1.

Figure 1. The full intercommunications scheme of neutron-temperature fluctuations

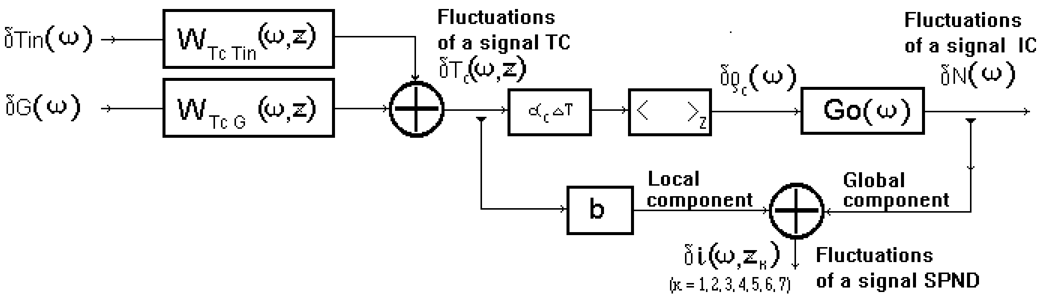


Transfer functions Wxy in Figure 1 play a part of a space-dependent filters at point sources ($\delta T_{in}(\omega)$, $\delta N(\omega)$, $\delta G(\omega)$), where $\delta T_{in}(\omega)$, $\delta N(\omega)$, and $\delta G(\omega)$ are normalised fluctuations of coolant inlet temperature, reactor power and coolant flow rate respectively.

$\delta\rho(\omega)$	reactivity fluctuations
$G_0(\omega)$	transfer function from reactivity to neutron flux for the reactor of null power
α_c	MTC
$\delta Tc(\omega)=\langle\delta Tc(z,\omega)\rangle_z$	coolant averaged temperature fluctuation
$\langle\ldots\rangle_z$	space average operation (average over z)

Neglecting the temperature fluctuations contribution to reactivity fluctuations and ignoring the power feedback (this is valid for frequencies more than 0.2 Hz) lead to the simplification of the model as shown in Figure 2.

Figure 2. Simplified scheme for frequencies more than 0.2 Hz



The transfer functions in explicit form are written as follows:

$$W_{TcTin}(z,\omega) = exp\left\{[H_c(\omega)^{-1} + H_f(\omega)](z/\tau_c w_0)\right\} \qquad (1)$$

$$W_{TcG}(z,\omega) = -W_{TcTin}(z,\omega)[0.2 + 0.8 \cdot H_f(\omega)](1/H)\int_0^z \Im(\xi)W_{TcTin}(\xi,\omega)d\xi \qquad (2)$$

where H_c=$(1+j\omega\tau_c)^{-1}$, H_f=$(1+j\omega\tau_f)^{-1}$, τ_c, τ_f are time constants of coolant and fuel respectively, and $\Im(z)$ is vertical reactor neutron power distribution.

For power fluctuations and coolant temperature fluctuations

$$\delta N(\omega) = \delta G(\omega)\Re_{NG}(\omega) + \delta T_{in}(\omega)\Re_{NT_{in}}(\omega) ,$$

$$\delta T_c(z,\omega) = \delta G(\omega)\Re_{TcG}(z,\omega) + \delta T_{in}(\omega)\Re_{TcTin}(z,\omega) ,$$

transfer functions are approximately written as:

$$\Re_{NTin}(\omega) \approx (\alpha_c \Delta T)/\beta)\langle exp[-j\omega(z/w_0)]\rangle_z$$

$$\Re_{NG}(\omega) \approx (\alpha_c \Delta T)/\beta)\left\langle -0.2 exp(-j\omega z/w_o)(1/H)\int_0^z F(\xi)exp(-j\omega\xi/w_o)d\xi \right\rangle_z$$

$$\Re_{TcTin}(z,\omega) \approx W_{TcTin}(z,\omega) \approx exp\left\{-\left[j\omega\tau_c + 1/\omega\tau_f\right]\cdot z/w_0\tau_c\right\} \approx exp\left(-j\omega\tau_0 z/H\right)$$

$$\Re_{TcG}(z,\omega) \approx W_{TcG}(z,\omega) \approx -0.2 \cdot exp(-j\omega z/w_0)\cdot(1/H)\int_0^z \Im(\xi)exp(-j\omega\xi/w_0)d\xi ,$$

where τ_0=H/w_0 is the time period for coolant to pass through the core.

The following assumptions are made: the IC signal fluctuations coincide with $\delta N(\omega)$ fluctuations; thermocouple signal fluctuations at point *z* coincide with $\delta Tc(z,\omega)$; SPND signal fluctuations are of the form $\delta i(z,\omega)=\delta N(\omega)+b\delta Tc(z,\omega)$, i.e. they consist of two components: global neutron noise – $\delta N(\omega)$ and local neutron noise – $b\delta Tc(z,\omega)$, where *b* is the SPND efficiency [4]. Unlike BWR, global and local components in VVER correlate each other because they both depend on the point sources $\delta G(\omega)$,$\delta Tin(\omega)$. As a result there is an analytical relation between G- and L-components: $\delta N(\omega)=\alpha_c \Delta T G_0(\omega)\langle\delta T_c(\omega,z)\rangle_z$.The sources $\delta G(\omega)$,$\delta Tin(\omega)$ are both transported along the channel, i.e. the delay effects are inevitably observed in G-L- (IC-SPND) and L1-L2- (SPND-SPND) correlation.

Sink-structures analysis

Sink structures are periodic local minimums of spectral characteristic which are described in the form of summands or cofactors of the following type $|\sin\pi af|$, $|\sin\pi af|/\pi af$, $(\sin\pi af/\pi af)^2$. They carry no less information than spectral characteristic resonance and are easily identified because of periodicity. The following sink-structures' features develop their interference protectability and insensitivity due to the effect of various unconsidered factors. If any spectral function $F(f)$ involves sink-structures, their location will not change during the conversion $A(f)F(f) + B(f)$, where $A(f)$ and $B(f)$ are monotonic frequency functions. If functions $F_1(f)$, $F_2(f)$ involve sink-structures which do not coincide in frequency the product $F_1(f)F_2(f)$ involves the union of sink-structures. Thus if the initial theoretical model is not completely adequate, i.e. if it describes only one sink-structure and ignores others or if the functions $A(f)$ and $B(f)$ are not taken into account this theoretical sink-structure can nevertheless be revealed through experimental spectral characteristics.

The transfer function at $\Im(z)\equiv 1$ can be written in explicit analytical form. This makes it possible to obtain any auto- and cross-spectral characteristics of neutron-temperature fluctuations in the scheme shown in Figure 2.

APSD of SPND is of the form:

$$
\begin{aligned}
S_{\delta_i}(z,\omega) = S_{\delta G}(\omega)\cdot 0.16\cdot\Bigg\{ & \left(\frac{\alpha_c\Delta T}{\beta}\right)^2\cdot\left(\frac{\sin\frac{\omega\tau_0}{2}}{\frac{\omega\tau_0}{2}}\right)^4 + b^2\left[\frac{\sin(\frac{\omega\tau_0 z}{2H})}{\omega\tau_0}\right]^2 - \\
& -2b\frac{\alpha_c\Delta T}{\beta}\left(\frac{\sin\frac{\omega\tau_0}{2}}{\frac{\omega\tau_0}{2}}\right)^2\frac{\sin(\frac{\omega\tau_0 z}{2H})}{\omega\tau_0}\cdot\cos\left[\omega\tau_0\left(1-\frac{3}{2}\frac{z}{H}\right)\right]\Bigg\} + \\
& + S_{\delta Tin}(\omega)\cdot\left\{\left(\frac{\alpha_c\Delta T}{\beta}\right)^2\cdot\left(\frac{\sin\frac{\omega\tau_0}{2}}{\frac{\omega\tau_0}{2}}\right)^2 + b^2 + 2b\frac{\alpha_c\Delta T}{\beta}\left(\frac{\sin\frac{\omega\tau_0}{2}}{\frac{\omega\tau_0}{2}}\right)\cdot\cos\left[\omega\tau_0\left(\frac{1}{2}-\frac{z}{H}\right)\right]\right\}
\end{aligned}
\qquad (3)
$$

The initial model involves unknown parameters (α_c,τ_0,b) and unmeasurable source-functions $S_{\delta G}$(f),$S_{\delta Tin}$(f). APSD of SPND consists of global, space independent sink-structures: $[\sin(\omega\tau/2) / (\omega\tau_0/2)]^2 = A(\omega)$, $A(\omega)^2$, local sink-structures depending upon z as: $\{[\sin(\omega\tau_0 z/H]/\omega\tau\}^2 = B(z, \omega)$ and functions of z which modulate the sink-structures. Only global sink-frequencies coincide with the frequency series k/τ_0, the local sink-structure being essentially dependent on the parameters α_c, b, z.

The local component of flow rate fluctuations is very small in magnitude at the horizon of the first SPND ($z = H/8$) but the distance between sink-frequencies is very long at this point. The most intensive slashness by sink-structures due to the local component is observed at the seventh-level SPND, its amplitude being maximum at this location. One also should not neglect the effect of one factor with respect to another in wide range of frequencies when analysing sink-structures in the case of arbitrary co-ordinates "*z*". There are local minimums in both contributions where the effect of corresponding factor is of zero or near zero value.

The following relationship corresponds to the first of global sink-frequency ($f = 1/\tau_0$):

$$S_{\delta i}(z,1/\tau_0) = b(z)^2\left\{0.16 \cdot S_{\delta G}(1/\tau_0)\left[sin(\pi z/H)/2\pi\right]^2 + S_{\delta T_{in}}(1/\tau_0)\right\} \tag{4}$$

Thus if at this frequency APSD (4), is a sine function of *z* it is impossible to neglect the flow rate fluctuations with respect to coolant inlet temperature fluctuations. This is a test whose purpose is to discover which source predominates at frequency $f = 1/\tau_0$, when the efficiency of all SPNDs are equal. APSD of thermocouple (TC) is of the form

$$S_{\delta T}(\omega,z) = S_{\delta G}(\omega) 0.16 \cdot \left(\left[sin\, \omega\tau_0 z/2H\right]/\omega\tau_0\right)^2 + S_{\delta T\, in}(\omega) \tag{5}$$

This formula is another test which reveals the proportion of the sources $S_{\delta G}(\omega)$ and $S_{\delta Tin}(\omega)$: if there are sink-structures in thermocouples APSD one should not neglect the effect of flow rate because the cofactor $B(z,\omega)$ exists only at $S_{\delta G}(\omega)$.

CPSD TC-IC is of the form:

$$S_{\delta T\delta N}(\omega,z) = (\alpha_c \Delta T/\beta)\left(sin\frac{\omega\tau_0}{2}\bigg/\frac{\omega\tau_0}{2}\right)\times$$
$$\times\left\{\left[-0.16 S_{\delta G}(\omega)\cdot\left(sin\frac{\omega\tau_0}{2}\bigg/\frac{\omega\tau_0}{2}\right)\cdot\frac{sin(\omega\tau_0 \frac{z}{2H})}{\omega\tau_0}\cdot e^{j\omega\tau_0\left(1-\frac{3z}{2H}\right)}\right] + S_{\delta Tin}(\omega)\cdot e^{j\omega\tau_0\left(\frac{1}{2}-\frac{z}{H}\right)}\right\} \tag{6}$$

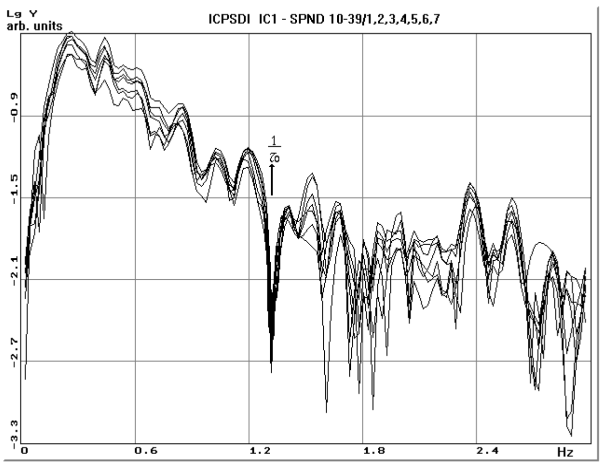
It is postulated in the majority of the works in which the MTC sign is estimated that TC signal fluctuations and IC signal fluctuations are contraphase because of the MTC negativity. This is true when the source $S_{\delta Tin}(\omega)$predominates, i.e. when one can neglect the square bracket in last formula. However, if $S_{\delta G}(\omega)$ predominates the TC-signal and IC-signal will be in phase for frequencies $f < 1/\tau_0$, the MTC sign is negative. At $z = H$ and for $1/\tau_0 < f < 2/\tau_0$ the sign of CPSD IC-TC is again negative.

The value of τ_0 can be reliably obtained from the CPSD IC-SPNDi (i = 1,2,...,7). Since

$$S_{\delta\delta N}(\omega,z)=\frac{\alpha_c\Delta T}{\beta}\cdot\left(\frac{\sin\frac{\omega\tau_0}{2}}{\frac{\omega\tau_0}{2}}\right)\times\left\{0.16\cdot S_{\delta G}(\omega)\cdot\left(\frac{\sin\frac{\omega\tau_0}{2}}{\frac{\omega\tau_0}{2}}\right)\cdot\left[\frac{\alpha_c\Delta T}{\beta}\cdot\left(\frac{\sin\frac{\omega\tau_0}{2}}{\frac{\omega\tau_0}{2}}\right)^2-b\cdot\frac{\sin\frac{\omega\tau_0 z}{2H}}{\omega\tau_0}\cdot e^{j\omega\tau_0\left(1-\frac{3}{2}\frac{z}{H}\right)}\right]+\right.$$
$$\left.+S_{\delta Tin}(\omega)\cdot\left[\frac{\alpha_c\Delta T}{\beta}\cdot\left(\frac{\sin\frac{\omega\tau_0}{2}}{\frac{\omega\tau_0}{2}}\right)+b\cdot e^{j\omega\tau_0\left(\frac{1}{2}-\frac{z}{H}\right)}\right]\right\} \quad (7)$$

the global term $(\alpha_c\Delta T/\beta)\cdot\left(\sin\frac{\omega\tau_0}{2}\Big/\frac{\omega\tau_0}{2}\right)$ is a common cofactor for both sources. That is, the global nulls k/τ_0 always exist in CPSD SPND-IC for any proportion between the global and local components. A family CPSD IC-SPND is shown in Figure 3. In proximity to the designed value $1/\tau_0$ = 1/0.7 = 1.43 Hz, a single sink-frequency 1.272 Hz exists on all curves.

Figure 3. A CPSD IC-SPNDi module family



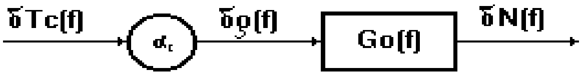
MTC estimation by sink-structures

Noise methods make it possible to measure MTC without introducing any disturbances into reactor. This is usually accomplished through the use of the formula [5]:

$$\alpha_c=(1/|G_0|)\cdot\int_{\Delta f}|S_{\delta N\delta T}(f)|df\Big/\int_{\Delta f}S_{\delta N}(f)df \quad (8)$$

Formula (8) is obtained from the simplified point model shown in Figure 4.

Figure 4. A point model scheme for MTC-estimation according to Eq. (8)

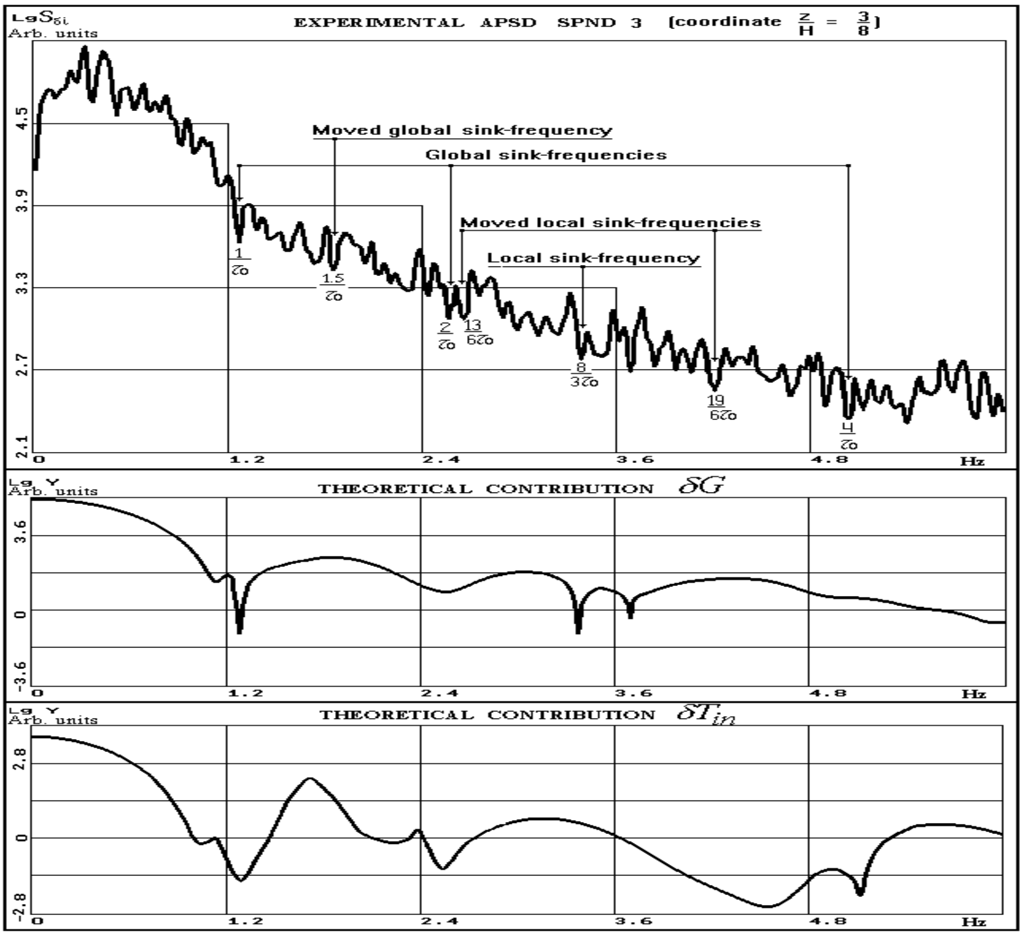


It follows from the scheme in Figure 2 that all of APSD and CPSD except APSD TC depend upon MTC. That is the case if the signal-to-noise ratio is good and frequency range choice is optimum MTC can be obtained from APSD IC, APSD SPND as well as from CPSD IC-TC, IC-SPND, SPND-TC. The most simple relationships are $\sqrt{S_{\delta N}(f)}\,F_1(f) = \alpha_c$, $|S_{\delta N\delta T}(f)|\,F_2(f) = \alpha_c$. It follows from the first formula that nonabsolute measurements MTC can be carried out by single channel with recording only ex-core neutron noise $\delta N(t)$ [6]. Two-channel nonabsolute measurements according to the second formula exclude errors due to the existence of noncorrelared components. Neutron-temperature noise method of MTC-measurements is nonabsolute due to the function F_2(f). This function can not be excluded by any conversion of various in-core signal spectral estimates. For example it is not difficult to extract the ratio $S_{\delta N\delta T}(f,z)/S_{\delta T}(f,z)$ from formulas (5) and (6). It is clear from the ratio that formula (8) within rough assumptions is true up to a constant. Thus the change from the elementary point model to one-dimensional space model proves that the MTC-estimation method according to (8) is not absolute.

The foundation of the new method lies in conforming the theoretical spectral characteristics to experimental ones at the locations of sink-frequencies. The MTC value does not influence the sink-structures locations traditionally used for MTC-estimation characteristics, i.e. for APSD IC, CPSD IC-IC, CPSD IC-TC. MTC exists only as a cofactor in these characteristics, their sink-structures depending only on τ_0 (global ones) or on τ_0 and z (local ones). The MTC-variation for in-core neutron detectors signals leads to variations in the sink-structures' location. This applies to all spectral characteristics obtained from the SPND-signal, i.e. to APSD SPND, CPSD SPND-SPND, CPSD SPND-IC, CPSD SPND-TC. All of these characteristics simeltaneously include an unknown MTC and unknown SPND efficiency b. Two of the parameters (α_c, b) are indivisible because the extremums locations of the above listed spectral characteristics on frequency axis depend upon the dimensionless parameter $X = (b\beta)/(\alpha_{\tilde{n}}\Delta T)$. All of the analytical sink-frequencies X-relationships are transcendental equations which can only be numerically solved. By varying a single model parameter X one can strive for a coincidence of experimental and theoretical sink-frequencies (Figure 5).

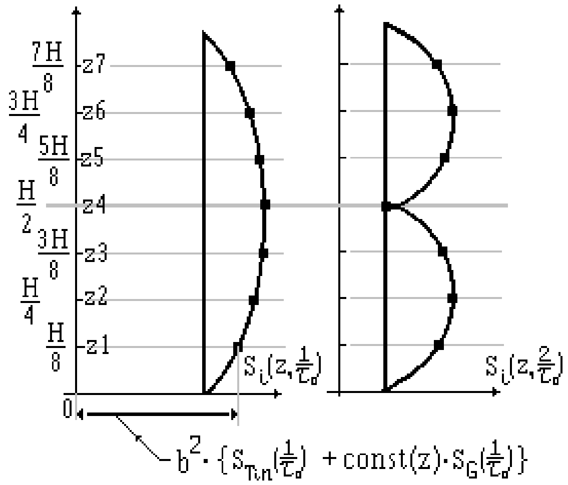
After bringing theoretical and experimental minimums of seven APSD SPND into coincidence one gets seven equations $X_i = (b_i\beta)/(\alpha_c\Delta T)$ (i = 1,2,...,7) in eight unknowns. Now the knowledge of any single SPND efficiency is enough to calculate all other unknown parameters (α_c, bi) from these equations. If there is one mobile in-core neutron detector instead of seven SPND or if all of the seven SPND are identical the MTC estimation can be simplified. For equal SPNDs efficiencies (b (z) ≡ b) the equation for APSD SPND (4) for sink-frequency $1/\tau_0$ acquires the explicit form of "z". Formula (4) can be approximated in the form of $S_{\delta i}(z,1/\tau_0) = A[\sin(\pi z/H)]^2 + B$ through the least-squares technique. Afterward, parameters $A = 0.16b^2 S_{\delta Gi}(1/\tau_0)$ and $B = b^2 S_{\delta Tin}(1/\tau_0)$ can be obtained from this expression.

Figure 5. Experimental APSD SPND and results of fitting by sink-structures



If signal-to-noise ratio is not good for the main sink-frequency $1/\tau_0$ the similar least-squares technique can be applied to the second harmonic $2/\tau_0$ (Figure 6). For this case the relation of "z" will acquire the form $S_{\delta i}(z,2/\tau_0) = A1[\sin(2\pi z/H)]^2 + B_1$. For VVER with nonmeasurable δT_{in} the parameter $S_{\delta Tin}(1/\tau_0)$ is obtained from APSD TC (5): $S_{\delta T}(1/\tau_0,H) = S_{\delta Tin}(1/\tau_0)$ for $z = H$ and $f = 1/\tau_0$. Now the efficiency "b" is calculated from "A", and from Xi - MTC- α_c. Seven values of MTC calculated from the equations Xi coincide only in the ideal case. Therefore this series of values is used for rejecting the poor minimums in fitting to experimental APSD. After that MTC-series is averaged in order to decrease statistical error. MTC measurements are also possible for stationary location of neutron detectors in the reactor core. But it is necessary to meet a certain condition in this case, i.e. SPND is required to be at the location $z = H/2$. $z = H/2$ is the location where SPND No. 4 is installed in VVER-1000. The flow rate contribution of this SPND at sink-frequency $2/\tau_0$ is zero only for APSD: $S_{\delta i}(2/\tau_o, H/2) = b_4^2 \cdot S_{\delta Tin}(2/\tau_o)$. Further operations are similar to those described in previous sections. Parameter $S_{\delta Tin}(2/\tau_0)$ is obtained from APSD TC at $z = H$; then, the efficiency of the fourth SPND is calculated and finally all other efficiencies and absolute MTC values are calculated from the Xi -equations.

Figure 6. Vertical APSD SPND distribution for the first and second sink-frequencies



Sink-structures caused by nonuniformity of energy releasing field

The real vertical neutron flux intensity distribution is $\Im(\xi) \neq const$. Its first space harmonic up to a constant is of the form $\sin(\pi\xi/H)$. The $\Im(\xi)$ function appears in the local component in the form of $\frac{1}{H}\int_0^z \Im(\xi)\exp(-j\omega\tau_0 \frac{\xi}{H})d\xi$, and is displayed in the global component as $\frac{1}{H}\int_0^H \Im(\xi)\exp(-j\omega\tau_0 \frac{\xi}{H})d\xi$. At $\Im(\xi) = \sin\pi\frac{\xi}{H}$ one obtains:

$$\frac{1}{H}\int_0^z \sin\pi\frac{\xi}{H}\exp(-j\omega\tau_0\frac{\xi}{H})d\xi =$$

$$= -\frac{j}{\pi}\exp\left(-\frac{j\pi z f\tau_0}{H}\right)\left\{\frac{\sin\left[\frac{\pi z}{2H}(1-2f\tau_0)\right]}{1-2f\tau_0}\cdot\exp\left(\frac{j\pi z}{2H}\right) - \frac{\sin\left[\frac{\pi z}{2H}(1+2f\tau_0)\right]}{1+2f\tau_0}\exp\left(-\frac{j\pi z}{2H}\right)\right\}$$

At z=H this expression is simplified to:

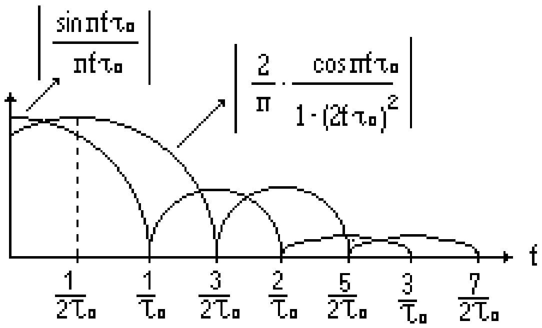
$$\frac{1}{H}\int_0^H \sin\pi\frac{\xi}{H}\exp(-j\omega\tau_0\frac{\xi}{H})d\xi = \frac{2}{\pi}\cdot\exp(-j\pi f\tau_0)\frac{\cos\pi f\tau_0}{1-(sf\tau_0)^2}$$

If compared to the case of $\Im(\xi) = 1$

$$\frac{1}{H}\int_0^H \exp(-j\omega\tau_0\frac{\xi}{H})d\xi = \exp(-j\pi f\tau_0)\cdot\left(\frac{\sin\pi f\tau_0}{\pi f\tau_0}\right)$$

it can be seen that the linear phase / frequency relationship did not change, sink-frequencies having moved by the value of $1/2\tau_0$ (Figure 7). Thus the amount of sink-structures had increased essentially due to “z” variancy of the reactor energy releasing field.

Figure 7. Global and shifted global sink-structures



The control over moved global sink-frequencies $(k+1/2)(1/\tau_0)$, (k=1,2,...) relays information about energy releasing field nonuniformity for the whole core region in an axial direction. As in the previous case the local component of flow rate contribution (the function $\left(\sin\frac{\omega\tau_0 z}{2H} \Big/ \omega\tau\right)^2 = B(z,\omega)$) including sink-frequencies $F_{\sin ê} = H/z\tau_0$ at $\Im(\xi) \neq const$ will also include the moved series of sink-frequencies $F_{\sin k}{}^{*} = \frac{1}{\tau_0}(\frac{H}{z} - \frac{1}{2})$.

The integral (global) energy releasing field nonuniformity for the whole core can be characterised numerically by the ratio $\chi_{global} = \sqrt{S_{\delta i}(15/\tau_0)/S_{\delta i}(1/\tau_0)}$. The local energy release nonuniformity in channel can equally be characterised by the ratio $\chi_{local} = \sqrt{S_{\delta_i}\left[\frac{1}{\tau_0}(\frac{H}{z}-\frac{1}{2})\right] \Big/ S_{\delta_i}(\frac{1}{\tau_0}\cdot\frac{H}{z})}$. It should be particularly noted that proposed coefficients are calculated from the signal of a single SPND.

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