Nuclear Mathematical and Computational Sciences: A Century in Review, A Century Anew
Gatlinburg, Tennessee, April 6-11, 2003, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2003)

A PHENOMENOLOGICAL MODEL FOR THE EXPLANATION OF A STRONGLY SPACE-DEPENDENT DECAY RATIO

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ABSTRACT

It is commonly believed that the Decay Ratio (DR), a parameter characterizing the stability of Boiling Water Reactors (BWRs), is a space-independent parameter of the reactor, i.e. it is independent of which Local Power Range Monitor (LPRM) is used in the core to perform the evaluation. This paper shows that the presence of several simultaneous types or sources of instability with different stability properties and different space dependence renders the DR also space-dependent, and even strongly space dependent. Two cases were investigated: the case of a local instability (i.e. one induced by a local noise source) coexisting with a global instability (in-phase oscillations), and the case of two local instabilities (noise sources). The results of these calculations were compared to the Forsmark-1 channel instability event, where strongly space-dependent decay ratios had been found in the measurements. Good adequacy was found between the DR model applied to the Forsmark-1 event and the corresponding measured DR. The fact that one single noise source in the core does not allow explaining a non-homogeneous DR suggests that in the case of Forsmark-1, at least two types or sources of instability had to be present in the core at the same time. According to the results obtained in this paper, these could be either a local and a global instability, or two local ones.

Key Words: Decay Ratio, neutron noise, core calculations, measurement

1. INTRODUCTION

During a measurement campaign performed during the fuel cycle 16 in the Forsmark-1 Boiling Water Reactor (BWR) in order to study BWR stability, it was noticed that the so-called Decay Ratio (DR) was strongly radially space-dependent [1]. The DR, which characterises the stability of a BWR, was always assumed until that moment to be a space-independent parameter of the core. This space-dependent character of the DR could not be understood.

A phenomenological model suggested by Pázsit in [2] was applied to the Forsmark-1 case. Originally, this model was derived to explain the discontinuous character of the DR when the operating point was changed smoothly on the power-flow map. Such a behaviour was found in the Swedish BWR Ringhals-1, where dual oscillations (local and regional) appeared simultaneously. In the study reported in [2], the space dependence of the decay ratio was not investigated, only its dependence on the operating point. However, the model takes into account the space dependence of the different oscillations, hence it was used in this study to show that the coexistence of two types or sources of instability with different DRs and space dependence can make the DR strongly space-dependent. Two cases were investigated in this study: the case of a local noise source coexisting with a global noise source (in-phase oscillations), and the case of two local noise sources. In order to use this phenomenological model in these two cases, the calculation of the spatial structure of the neutron noise induced by the aforementioned noise sources is required.

In the following, the Forsmark-1 measurement is first described in detail. The different models used to estimate theoretically the DR are thus explained, namely the DR model is recalled and the neutron noise simulator is briefly explained. As will be seen later on, the calculation of the neutron noise in case of the global-type of oscillations is identical to the estimation of the static flux, so that a static core simulator is also required and presented in this paper. Both simulators rely on the 2-group diffusion approximation, and are able to handle 2-D heterogeneous cores. Finally, the space-dependence of the DR is estimated from the phenomenological model and compared to the measured DR.

2. DESCRIPTION OF THE FORSMARK-1 CASE

In 1996, during the start-up tests of the Forsmark-1 BWR for the fuel cycle 16, instability conditions were detected at reduced power and reduced core-flow. Forsmark-1 is a BWR of the Westinghouse Atom design (previously ABB Atom AB, or ASEA-Atom AB) built in 1980 and has a thermal core-rated power of 2700 MWth and a nominal core flow of 10450 kg/s. Although BWRs are known to become less stable at reduced power/core flow, the appearance of this instability could not be understood and was not predicted by the stability calculations. The corresponding operating point in the power/flow map was therefore avoided. In January 1997, at approximately Middle Of Cycle conditions (MOC), stability measurements were carried out in order to study the instability discovered previously. The core was thus brought to 63.3% of power and to a core flow of 4298 kg/s. Again instability conditions were encountered, at a frequency of roughly 0.5 Hz.

During this stability measurement the lower plane of the core was rather well equipped with Local Power Range Monitors (LPRMs), where signals from 27 of the 36 available detector strings were actually recorded at a sampling frequency of 12.5 Hz. One parameter that is relevant for characterizing the stability of BWRs is the DR, which is defined as the ratio between two consecutive maxima A_i and A_{i+1} of the Auto-Correlation Function (ACF) of the normalized neutron density, or alternatively two consecutive maxima of the Impulse Response Function (IRF) as calculated by using an Autoregressive Moving-Average (ARMA) or an Autoregressive model (AR) to fit the behaviour of the system. These methods are illustrated in Fig. 1. The DR gives therefore a measure of the inherent damping properties of the system. Using each detector separately allows estimating the Decay Ratio (DR) according to the following standard method [3]:

$$DR = \frac{A_{i+1}}{A_i}, \forall i \qquad (1)$$

Although the DR was always assumed to be a 0-D parameter of the core, i.e. independent of the position where the DR is estimated in the core, the Forsmark-1 measurement revealed that the DR was actually strongly space-dependent, as can be seen on the following Fig. 2. This Figure shows that one half of the core exhibits a DR close to instability (higher than 0.9) and the other half has a DR close to 0.6.

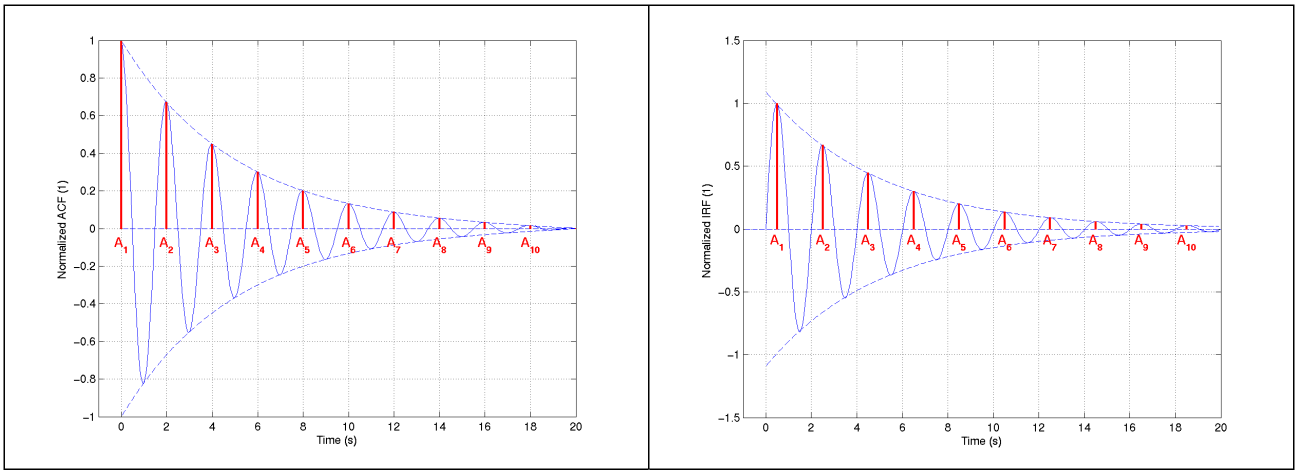

Figure 1. ACF and IRF of a second-order system (on the left-hand side and the right-hand side respectively).

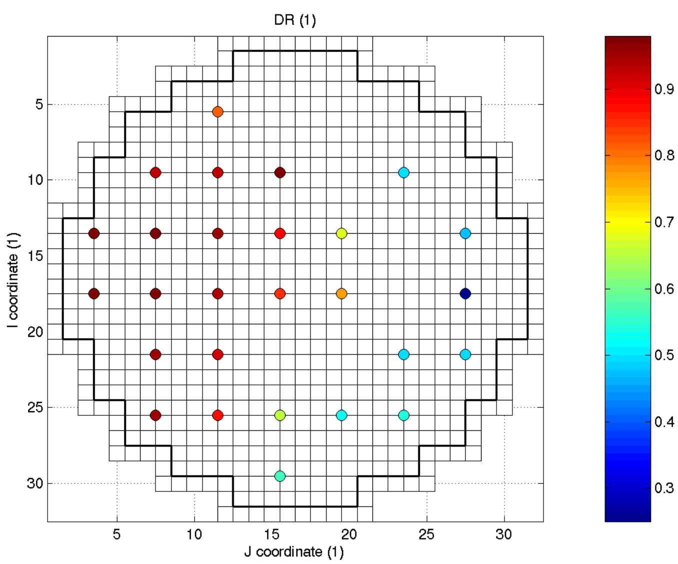

Figure 2. Measured radial space-dependence of the Decay Ratio in Forsmark-1 (derived from [4]).

A closer look at the phase of the measured flux noise indicated that the neutron noise was driven by a local noise source, similar to the effect of an absorber of variable strength (reactor oscillator). As a matter of fact, more detailed analyses of this instability event revealed that the reason of this instability was due to the presence of one or more likely two noise sources [5], [6]. In these aforementioned analyses, even a localisation of these noise sources was carried out, and one of the noise sources pointed out by the localisation algorithm was close to a fuel assembly which was found to be unseated during the fuel outage following the fuel cycle 16. As pointed out by [7], when a fuel element is unseated, some of the coolant flow bypasses the fuel element and this might render the channel thermal-hydraulically unstable (self-sustained Density Wave Oscillation or DWO [8]).

3. DESCRIPTION OF THE MODELS

The fact that the observed DR in the Forsmark-1 case exhibits a strong space-dependence suggests that two types or sources of instability are present at the same time in the core. If there was only one type or one source of instability, the DR would not be space-dependent, and would roughly be the same whatever LPRM is used to perform the DR evaluation. In the following, an analytical model that allows estimating the DR resulting from two types/sources of instability is presented and its application to the Forsmark-1 case is explained.

3.1. Analytical model of the Decay Ratio

An analytical model to calculate the DR in case of dual oscillations was proposed by Pázsit in [2]. This model was developed to explain the discontinuous character of the DR when the operating point was changed smoothly on the power-flow map, and relied on dual oscillations according to which the DR was calculated. Although the model is rather simple in order to facilitate analytical calculations with the goal of facilitating insight and understanding, its domain of validity was confirmed also in detailed core calculational models [9]. The same model will be used in this paper to study the space-dependence of the DR. The only difference with the previous investigation is the type or source of instability investigated. In Pázsit 's paper, only the case of a regional (out-of-phase) type of oscillations coexisting with a global (in-phase) type of oscillations was investigated. This model was extended here to any type or source of instability existing simultaneously in the core. More specifically, two cases are presented: the case of a local noise source coexisting with a global type of oscillations, and the case of two local noise sources. In the following, the main characteristics of the model proposed by Pázsit are recalled.

The starting point is to write that the flux fluctuations can be written as a sum between the contribution of two noise sources, each of them being factorized into a temporal part only and a spatial part only as follows:

$$\delta\phi(\boldsymbol{r},t) = \delta\phi_1(\boldsymbol{r},t) + \delta\phi_2(\boldsymbol{r},t) = \delta\psi_1(t)\varphi_1(\boldsymbol{r}) + \delta\psi_2(t)\varphi_2(\boldsymbol{r}) \tag{2}$$

where the amplitudes $\delta\psi_i(t)$ (i=1, 2) are second-order processes, with the same resonance frequency ω_0, but different damping properties. As will be shown later, for the case of local instability, the factorisation does not hold in a strict sense; nevertheless, it is quite well applicable in the frequency range considered. At any rate, this study relies on this basic assumption. If one further assumes that the aforementioned second-order processes are driven by the driving forces $f_i(t)$ (i=1, 2), the amplitudes $\delta\psi_i(t)$ (i=1, 2) will obey the following Eq. (3):

$$\delta\ddot{\psi}_i(t) + 2\xi_i\omega_0\delta\dot{\psi}_i(t) + \omega_0^2\delta\psi_i(t) = f_i(t) \tag{3}$$

For simplicity, we will neglect the cross-term between the two noise sources, i.e. we will assume that:

$$CPSD_{f_1,f_2}(\omega) = CPSD_{f_2,f_1}(\omega) \approx 0 \tag{4}$$

If one further assumes that the DR of any of the two types or sources of instability is larger than 0.4, the second-order terms in ξ can be neglected, and Pázsit in [2] showed that the ACF of any LPRM signal would then be given by:

$$ACF(\boldsymbol{r},\tau) = \cos(\omega_0\tau)\sum_{i=1}^{2} a_i(\boldsymbol{r}).e^{-\xi_i\omega_0\tau} \tag{5}$$

with

$$a_i(\boldsymbol{r}) = \frac{1}{1 + \frac{APSD_{f_j}}{APSD_{f_i}} \cdot \frac{\varphi_j(\boldsymbol{r})}{\varphi_i(\boldsymbol{r})} \cdot \frac{\ln(DR_i)}{\ln(DR_j)}}, \; i \neq j \tag{6}$$

Eq. (5) does not correspond to a pure second-order system, and therefore the definition of its DR is not unique. From a measurement viewpoint, it is practical to define the DR as the ratio between the first and the second maxima of the ACF, i.e.:

$$DR(\boldsymbol{r}) = \sum_{i=1}^{2} a_i(\boldsymbol{r}) \cdot e^{-2\pi\xi_i} = \sum_{i=1}^{2} a_i(\boldsymbol{r}).DR_i \tag{7}$$

where

$$DR_i = e^{-2\pi\xi_i} \tag{8}$$

As explained by Pázsit in [2], the cross-term can be explicitly accounted for. In such a case the expressions that we would obtain would be more complicated, but the model of the DR presented previously would be essentially the same, only the weighting coefficient $a_i(\boldsymbol{r})$ between the two types or sources of instability would be different. Furthermore, Eq. (8) allows verifying the other hypothesis used in this model, i.e. that neglecting ξ^2 besides unity is justified for any DR larger than 0.4.

3.2. Numerical estimation of the neutron noise

In order to calculate the space-dependence of the DR when two types or sources of instability coexist in the core, one needs to estimate the $a_i(\boldsymbol{r})$ coefficients used in Eq. (7), i.e. one needs to define the f_i parameters and to calculate the functions $\varphi_i(\boldsymbol{r})$. The f_i parameters (or more exactly their ratio) can be chosen freely. The functions $\varphi_i(\boldsymbol{r})$, which represent the spatial dependence of the induced neutron noise, depend on the type or source of instability.

In case of a global-type of oscillations, it is well known that the induced neutron noise is spatially distributed according to the static flux $\phi_0(\boldsymbol{r})$, i.e. is given in the frequency domain by:

$$\delta\phi(\boldsymbol{r},\omega) = \phi_0(\boldsymbol{r}) \cdot G_0(\omega)\,\delta\rho(\omega) \tag{9}$$

where $G_0(\omega)$ and $\delta\rho(\omega)$ are the zero-power reactor transfer function and the reactivity noise (noise source) respectively, so that:

$$\varphi_i(\boldsymbol{r}) = C_i \phi_0(\boldsymbol{r}) \tag{10}$$

where C_i is a scaling coefficient.

In case of a local noise source, the induced neutron noise is given in the frequency domain by:

$$\delta\phi_i(\boldsymbol{r},\omega) = G(\boldsymbol{r},\boldsymbol{r}_0,\omega) \cdot S_{r_0}(\omega) \tag{11}$$

where $S_{r_0}(\omega)$ and $G(\boldsymbol{r},\boldsymbol{r}_0,\omega)$ are the noise source localised at the position $\boldsymbol{r}_0$ and the corresponding Green's function (transfer function) of the noise equations, respectively [5]. Eq. (11) shows that, in general, for the local oscillations, the space and frequency (or space and time) dependence of the neutron fluctuations does not factorise. However, one can make use of the fact that the transfer function $G(\boldsymbol{r},\boldsymbol{r}_0,\omega)$ depends on frequency only through the zero-power reactor transfer function $G_0(\omega)$. This latter, on the other hand, depends very weekly on the frequency in the so-called plateau region, roughly between 0.05 and 15 Hz. Since the oscillation frequency of the local instability was about 0.5 Hz, one can use the values of $G(\boldsymbol{r},\boldsymbol{r}_0,\omega)$ at the resonance frequency ω_0. Hence, one can write:

$$\varphi_j(\boldsymbol{r}) \approx C_j \left|G(\boldsymbol{r},\boldsymbol{r}_0,\omega_0)\right| \tag{12}$$

where C_j is another scaling factor. Since it is only the ratio of the scaling factors in Eqs. (10) and (12) that counts, we shall assume $C_j = 1$ in Eq. (12).

Consequently, one needs to estimate both the static flux and the neutron noise induced by the localised noise source(s) in order to use the phenomenological model given by Eqs. (6) and (7). Since this study investigates the case of the Forsmark-1 BWR, i.e. a strongly heterogeneous core, the static flux was calculated by a 2-D 2-group static core simulator and the neutron noise by a 2-D 2-group noise simulator. In the following, the basic properties of these two simulators, which were developed at the Department of Reactor Physics, Chalmers University of Technology, are briefly presented.

The static core simulator solves the following matrix equation in the two-group diffusion approximation:

$$\left[\overline{\overline{D}}(\boldsymbol{r})\nabla^2 + \overline{\overline{\Sigma}}(\boldsymbol{r})\right] \times \begin{bmatrix} \phi_1(\boldsymbol{r}) \\ \phi_2(\boldsymbol{r}) \end{bmatrix} = 0 \tag{13}$$

where

$$\overline{\overline{D}}(\boldsymbol{r}) = \begin{bmatrix} D_1(\boldsymbol{r}) & 0 \\ 0 & D_2(\boldsymbol{r}) \end{bmatrix} \tag{14}$$

$$\overline{\overline{\Sigma}}(\boldsymbol{r}) = \begin{bmatrix} \dfrac{\nu\Sigma_{f,1}(\boldsymbol{r})}{k_{eff}} - \Sigma_{a,1}(\boldsymbol{r}) - \Sigma_{rem}(\boldsymbol{r}) & \dfrac{\nu\Sigma_{f,2}(\boldsymbol{r})}{k_{eff}} \\ \Sigma_{rem}(\boldsymbol{r}) & -\Sigma_{a,2}(\boldsymbol{r}) \end{bmatrix} \tag{15}$$

All the notations have their usual meaning. Finite differences were used to carry out the 2-D spatial discretization of the system according to the so-called “box-scheme” [10]. Eq. (13), which is a homogeneous equation, was solved by using an iterative scheme, more exactly the power iteration method [10], [11]. This static core simulator was successfully benchmarked against SIMULATE-3 [12] (after axial homogenization) for both PWR [13] and BWR [14] cases.

The neutron noise simulator solves the following matrix equation in the 2-group diffusion approximation at a given frequency ω, for fluctuations of the macroscopic removal cross-section[1]:

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[1] The neutron noise simulator is actually able to handle any type of noise sources (namely fluctuations in the fast or thermal macroscopic absorption cross-section, fluctuations in the macroscopic removal cross-section, fluctuations in the fast or thermal macroscopic fission cross-section). In the case of DWO, the fluctuations of the macroscopic removal cross-section are the most relevant ones, and therefore the neutron noise simulator in this study only calculates the corresponding induced neutron noise. We refer to [6] for the derivation of Eq. (16) in the most general case.

$$\left[\bar{\bar{D}}(\boldsymbol{r})\nabla^2+\bar{\bar{\Sigma}}(\boldsymbol{r},\omega)\right]\times\begin{bmatrix}\delta\phi_1(\boldsymbol{r},\omega)\\ \delta\phi_2(\boldsymbol{r},\omega)\end{bmatrix}=\bar{\phi}_{rem}(\boldsymbol{r})\,\delta\Sigma_{rem}(\boldsymbol{r},\omega) \tag{16}$$

where the matrix and vector are given as:

$$\bar{\bar{\Sigma}}(\boldsymbol{r},\omega)=\begin{bmatrix}-\Sigma_1(\boldsymbol{r},\omega) & \nu\Sigma_{f,2}(\boldsymbol{r},\omega)\\ \Sigma_{rem}(\boldsymbol{r}) & -\Sigma_{a,2}(\boldsymbol{r},\omega)\end{bmatrix} \tag{17}$$

$$\bar{\phi}_{rem}(\boldsymbol{r})=\begin{bmatrix}\phi_1(\boldsymbol{r})\\ -\phi_1(\boldsymbol{r})\end{bmatrix} \tag{18}$$

and the different coefficients are defined as:

$$\Sigma_1(\boldsymbol{r},\omega)=\Sigma_{a,1}(\boldsymbol{r})+\frac{i\omega}{v_1}+\Sigma_{rem}(\boldsymbol{r})-\nu\Sigma_{f,1}(\boldsymbol{r})\left(1-\frac{i\omega\beta_{eff}}{i\omega+\lambda}\right) \tag{19}$$

$$\nu\Sigma_{f,2}(\boldsymbol{r},\omega)=\nu\Sigma_{f,2}(\boldsymbol{r})\left(1-\frac{i\omega\beta_{eff}}{i\omega+\lambda}\right) \tag{20}$$

$$\nu\Sigma_{a,2}(\boldsymbol{r},\omega)=\nu\Sigma_{a,2}(\boldsymbol{r})+\frac{i\omega}{v_2} \tag{21}$$

As for the static core simulator, finite differences were used to carry out the 2-D spatial discretization of the system according to the so-called “box-scheme” [10]. Eq. (16), which is an inhomogeneous equation, was solved by direct matrix inversion. The neutron noise simulator is thus able to calculate the spatial distribution of the neutron noise induced by any localized (or even spatially distributed) noise sources. This neutron noise simulator was successfully benchmarked against analytical solutions in case of homogeneous cores with a central noise source [6].

The only data required in order to use the static core simulator and the neutron noise simulator are the 2-D 2-group material constants, and the point-kinetic parameters of the core. In the case of the Forsmark-1 BWR, these data were obtained from calculations performed by Vattenfall Fuel AB with the SIMULATE-3 code. The data were homogenized from 3-D to 2-D by preserving the reaction rates according to the following formulae:

$$XS_{G,I,J}=\frac{\sum_K XS_{G,I,J,K}\phi_{G,I,J,K}V_{I,J,K}}{\sum_K \phi_{G,I,J,K}V_{I,J,K}} \tag{22}$$

and

$$\phi_{G,I,J} = \frac{\sum_K \phi_{G,I,J,K} V_{I,J,K}}{\sum_K V_{I,J,K}} \tag{23}$$

with XS_G having a broad meaning, i.e. being D_G, $\Sigma_{a,G}$, Σ_{rem}, or $\nu\Sigma_{f,G}$. All the other symbols have their usual meaning with $V_{I,J,K}$ representing the volume of the node (I,J,K) and G being the group index. In order to get a 2-D system equivalent to the 3-D system, the leakage rate of the 3-D system in the axial direction was added to the absorption cross-section in the 2-D system, both in the fast and thermal groups. The neutron noise simulator requires itself the static fluxes and the corresponding eigenvalue. Although these data are directly available after homogenization from SIMULATE-3, they have to be obtained from the 2-D 2-group static core simulator that is compatible with the neutron noise simulator. Otherwise using the SIMULATE-3 results, i.e. results that were calculated using a discretization scheme different from the one used in the neutron noise simulator – nodal methods for SIMULATE-3 and finite differences for the 2-D 2-group static core and neutron noise simulators –, would be equivalent to make the system non-critical.

4. RESULTS

In the following, the results of the previous phenomenological model applied to Forsmark-1 are presented. Two cases are investigated: the case of a local noise source coexisting with a global noise source, and the case of two local noise sources.

4.1 The case of a local noise source and a global noise source

The results corresponding to the case of a local noise source coexisting with a global noise source (in-phase oscillations) are presented in Fig. 3. The DR corresponding to the local noise source was set to 0.99, whereas the DR corresponding to the in-phase oscillations was set to 0.4. The local noise source was located at the position pointed out by a noise source localization algorithm applied previously in [6] to the case of the Forsmark-1 channel instability event. Finally, as explained earlier, the ratio f_2 / f_1 can be chosen freely and was determined so that the DR calculated throughout the core matched the measured DR. As can be seen on Fig. 3, the DR calculated by using the phenomenological model given by Eqs. (6) and (7) in case of a local noise source and a global noise source is strongly spatially dependent, and reproduces quite well the behavior of the measured DR in Forsmark-1. The reason for the relatively sharp boundary between the two values of the DR is the fast spatial decay of the local oscillations. Thus there are two different regions in the core, one in which the local oscillations dominate, and one in which the global ones dominate, with a relatively narrow transition region. Such a case would not occur with concurrent global and regional oscillations, only when at least one local component is involved.

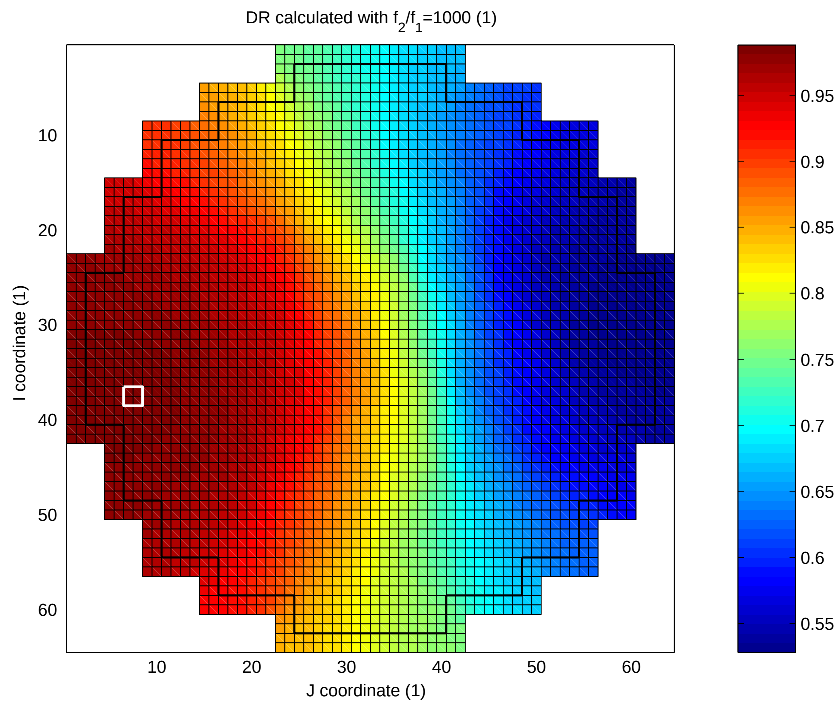

Figure 3. Simulated radial space-dependence of the Decay Ratio in Forsmark-1 in case of a local noise source and a global noise source (the white square represents the location of the local noise source).

4.2 The case of two local noise sources

The results corresponding to the case of two local noise sources are presented in Fig. 4. The local noise source with a DR of 0.99 was located at the position pointed out by the noise source localization algorithm applied previously in [6] to the case of the Forsmark-1 channel instability event. The noise source with a DR of 0.4 was positioned on the opposite side from the other noise source. The ratio f_2 / f_1 was chosen so that the DR calculated throughout the core matched the measured DR. As can be seen on Fig. 4, the DR calculated by using the phenomenological model given by Eqs. (6) and (7) in case of two local noise sources is strongly spatially dependent, and reproduces again rather well the behavior of the measured DR in Forsmark-1. Again, the reason of the sharp boundary between the two stability regions is the fast spatial decay of the amplitude of the local oscillations.

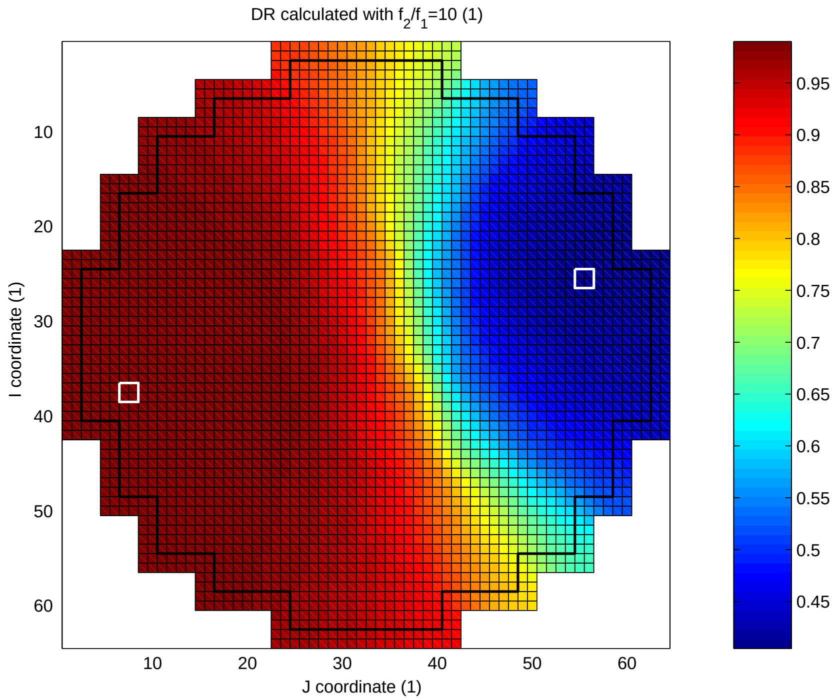

Figure 4. Simulated radial space-dependence of the Decay Ratio in Forsmark-1 in case of two local noise sources (the white squares represent the location of the local noise sources).

5. CONCLUSIONS

The purpose of this paper was to construct a simple model, with the help of which the experimentally found space-dependence of the Decay Ratio (DR) is possible. In the early cases of BWR instability, the DR appeared to be a space-independent parameter of a BWR core, characterizing its global stability. Nevertheless, it was noticed during the Forsmark-1 channel instability event (January 1997) that the DR measured throughout the core using LPRM signals was radially strongly space-dependent, ranging from 0.6 on the right-hand side of the core to values higher than 0.9 on the left-hand side of the core, i.e. values close to limit-cycle oscillations.

The phenomenological model of the DR developed by Pázsit in [2] was used in this paper in order to calculate the space-dependence of the DR in case of several types or sources of instability, each of them having different stability properties and space dependence. More specifically, two cases were investigated: a local noise source coexisting with a global noise source (in-phase oscillations), and two local noise sources. It was shown, via the use of a 2-D 2-group static core simulator and a 2-D 2-group neutron noise simulator applied to realistic data corresponding to the Forsmark-1 instability event, that the space-dependent character of the measured DR could be reproduced. This therefore confirms our original idea that in case of dual oscillations with different space-dependence, i.e. when several types or sources of instability coexist at the same time in the core, the DR itself becomes necessarily space-dependent. In the case when at least one local oscillation is involved, the DR may appear as discontinuous in space, which is the case that was observed in Forsmark.

ACKNOWLEDGMENTS

This work was supported by the Swedish Nuclear Power Inspectorate (SKI – Statens Kärnkraftinspektion), research contract 14.5-010892-01161, and CEA-Cadarache, France (CEA/DEN/DER), research contract V. 315 8001. Ewa Kurcyusz-Ohlofsson, from Vattenfall Fuel AB, is acknowledged for the delivery of the SIMULATE-3 output data.

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NOMENCLATURE

ACF	Autocorrelation Function
APSD	Auto-Power Spectral Density
AR	Autoregressive (model)
ARMA	Autoregressive Moving-Average (model)
BWR	Boiling Water Reactor
CEA	Commissariat à l’Energie Atomique
DR	Decay Ratio
DWO	Density Wave Oscillation
IRF	Impulse Response Function
LPRM	Local Power Range Monitor
MOC	Middle Of Cycle
SKI	Swedish Nuclear Power Inspectorate (Statens Kärnkraftinspektion)