LOCALISATION OF A CHANNEL INSTABILITY IN A BWR VIA NEUTRON NOISE METHODS

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Abstract

A special type of instability occurred in the Swedish BWR Forsmark 1 in 1996. In contrast to the better known global or regional (out-of-phase) instabilities, the decay ratio appeared to be very high in one half of the core and quite low in the other half. A more detailed analysis showed that the most likely reason for the observed behaviour is a local perturbation of thermohydraulic character, e.g. a density wave oscillation (DWO), induced by the incorrect positioning of a fuel assembly (an "unseated" assembly). In such a case it is of large importance to determine the position of the unseated assembly already during operation such that it can be easily found during reloading.

The subject of this paper is to report on development and application of methods by which the position of such a local perturbation can be determined. Two different methods that support and complement each other were used. First a visualisation technique was elaborated which expedites a very good qualitative comprehension of the situation and which can be useful for the operators. It also gives an important basis for the application of the localisation algorithm. Second, a quantitative (algorithmic) localisation method, suited for this type of perturbation, was elaborated. This latter takes noise spectra from selected detectors as input and yields the perturbation position as output. The method was tested on simulated data, and then applied to the Forsmark measurements. The location of the disturbance, found by the algorithm, is in accordance with independent judgements for the case, and close to a position where an unseated assembly was found during refuelling.

1. INTRODUCTION

A special type of instability occurred in the Swedish BWR Forsmark 1 in 1996. This event has been described and analysed in several reports previously (Refs. [1] and [2]). We will only briefly summarize the findings that led to the present study.

The phenomenon was discovered as a half-core instability phenomenon in the start-up measurements after refuelling in 1996. To investigate the phenomenon, measurements were made with several in-core detectors in early 1997 in a position of the power-flow map where the instability was fully developed. It was found that in one half of the core the decay ratios, as well as the noise rms values, were much higher than in the other half. Some results from the most characteristic measurement, referred to as measurement M2 in the continuation, are shown in Figs 1 and 2 below as an illustration.

Further analysis of the measurements (Refs [1]- [3]) made it likely that the reason for the behaviour shown in these figures is a localised perturbation, such as a density wave oscillation in one or a few fuel assemblies. In such a case, the position of the instability is of large

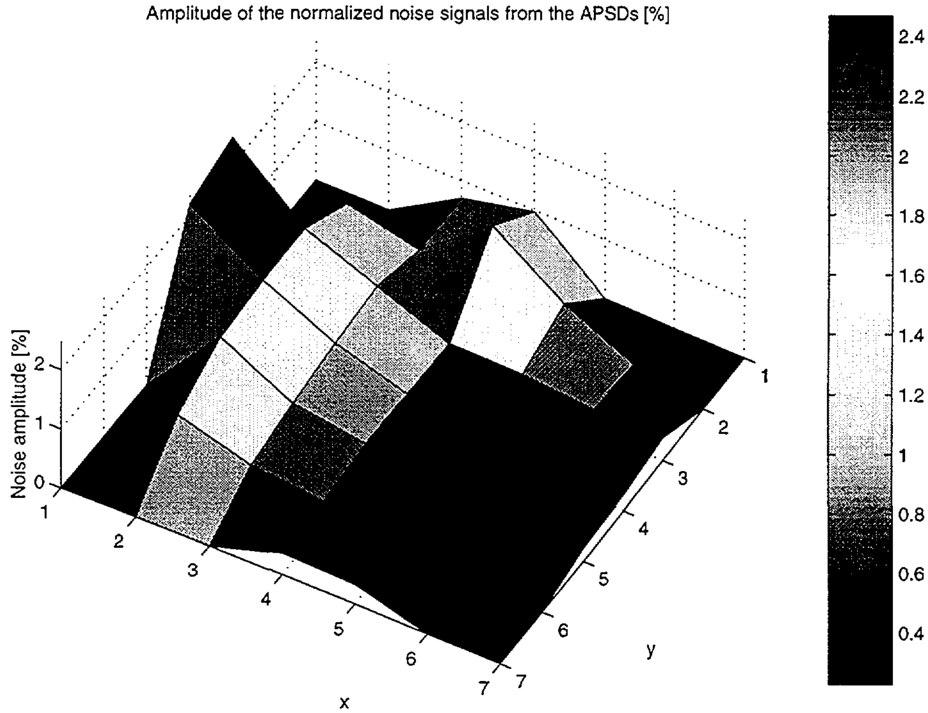

Fig. 1. Distribution of the noise amplitudes in a horizontal cross section of the core in measurement M2 in Forsmark-1

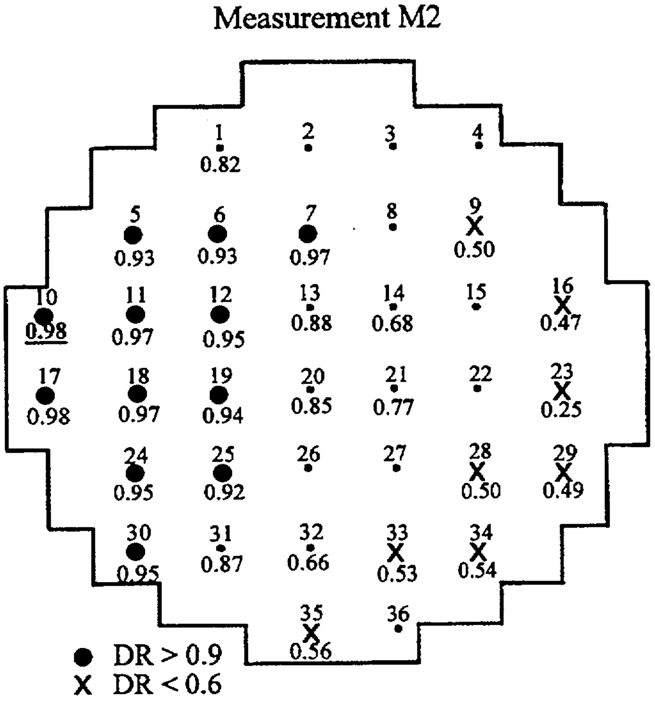

Fig. 2. Distribution of the decay ratios (DR) of the various LPRMs in measurement M2 in Forsmark-1 (from Ref. [2]). Upper line: LPRM number. Lower: DR

diagnostic interest, because an inspection of the fuel assembly or assemblies in which the instability occurred may reveal the reason of its appearance. One hypothesis is that the instability arose due to an improper "seating" of the assembly. Without having a qualified guess about the approximate position of the instability, it is practically not possible to find a reason because there is no possibility to check every fuel assembly, due to time constraints.

Hence, it is of large importance to determine the position of the unseated assembly already during operation such that it can be easily found during reloading.

Local perturbations can be localised from neutron noise measurements. One possibility is to use the noise contribution ratio or signal transmission path analysis methods (Refs. [2] and [3]). In these methods a multivariate analysis of several LPRM signals is used and one of them is pointed out as the driving force for the other detector signals. The position of the perturbation is then assumed to lie either at the position of the LPRM or in its neighbourhood.

There exists however another method by which the location of the perturbation can be determined. One can utilize the fact that any localised perturbation induces a space-dependent neutron noise. The noise amplitude and the phase decay with increasing distance from the source, thus the space dependence carries information on the position of the source. By modelling the noise source in some functional form, and calculating the reactor physical dynamic transfer function of the core, the induced neutron noise can be expressed via formulas, either analytical or numerical, in which the position of the perturbation is included as an argument. By the use of such relationships or formulas, a method of localisation can be elaborated, by which the position of the perturbation can be found from the measured neutron noise and the calculated transfer function of the system. Such a strategy was used in the past for the localisation of an excessively vibrating control rod in a VVER-type pressurized water reactor (Refs. [4] and [5]). The purpose of the present investigation was to elaborate and test a similar method for the channel instability, which formally corresponds to the case of an absorber of variable strength.

The advantage of such a method is that it uses reactor physics knowledge on the spatial attenuation of the neutron noise from a source. Due to this fact, the spatial resolution of the localisation procedure is high; it can in principle point out any position in the core, and not only the discrete detector positions. In practice, of course, the accuracy of the method can be low for various reasons that will be discussed later on. The important point at this stage is that there is no principal limitation involved in the spatial resolution of the method.

A localisation method, suited for this type of perturbation, was elaborated. The method was tested on simulated data, and then applied to the Forsmark measurements. The location of the disturbance, found by the algorithm, is in accordance with independent judgements for the case, and close to a position where an unseated assembly was found during refuelling.

2. VISUALISATON OF THE NOISE AS AN OPERATOR AID AND AS A QUALITATIVE INVESTIGATION OF THE NOISE SOURCE

An algorithmic method for locating a localised perturbation is based on an expression for the induced neutron noise. In this expression a functional form of the noise source is used. There exist different types of localised perturbations. One of them is the so-called "reactor oscillator" (Ref. [6]) which is conceptually equal to a localised absorber of variable strength. The second type is represented by the lateral vibrations of an absorber rod. These noise sources have different representations, and also the spatial structure of the neutron noise induced by a vibrating absorber and an absorber of variable strength is rather different. This means that for each different perturbation type one has to use a different algorithm. There exists an algorithm for the vibrating rod, but not for the absorber with variable strength.

Intuitively, it is expected that a channel instability is equivalent to a reactor oscillator, i.e. an absorber of variable strength. For its localisation a new algorithm needs to be elaborated. This will be reported in Section 3. However, before this assumption is actually used, one must assure that the assumption on the type of the noise source is correct. This is only possible by an investigation of the spatial structure of the noise, i.e. the LPRM detector signals.

The need for this investigation led us to a method which has a significant diagnostic value itself, even if it only yields qualitative information. This method consists of a visualisation of the joint space-time behaviour of the noise in the core directly in the time domain. An animation or motion picture of the space- and time-dependent neutron noise was constructed using computer codes written as scripts in the package MATLAB. In Fig. 3 a sequence, showing one cycle of the instability oscillation in measurement M" in Forsmark, is shown from this movie.

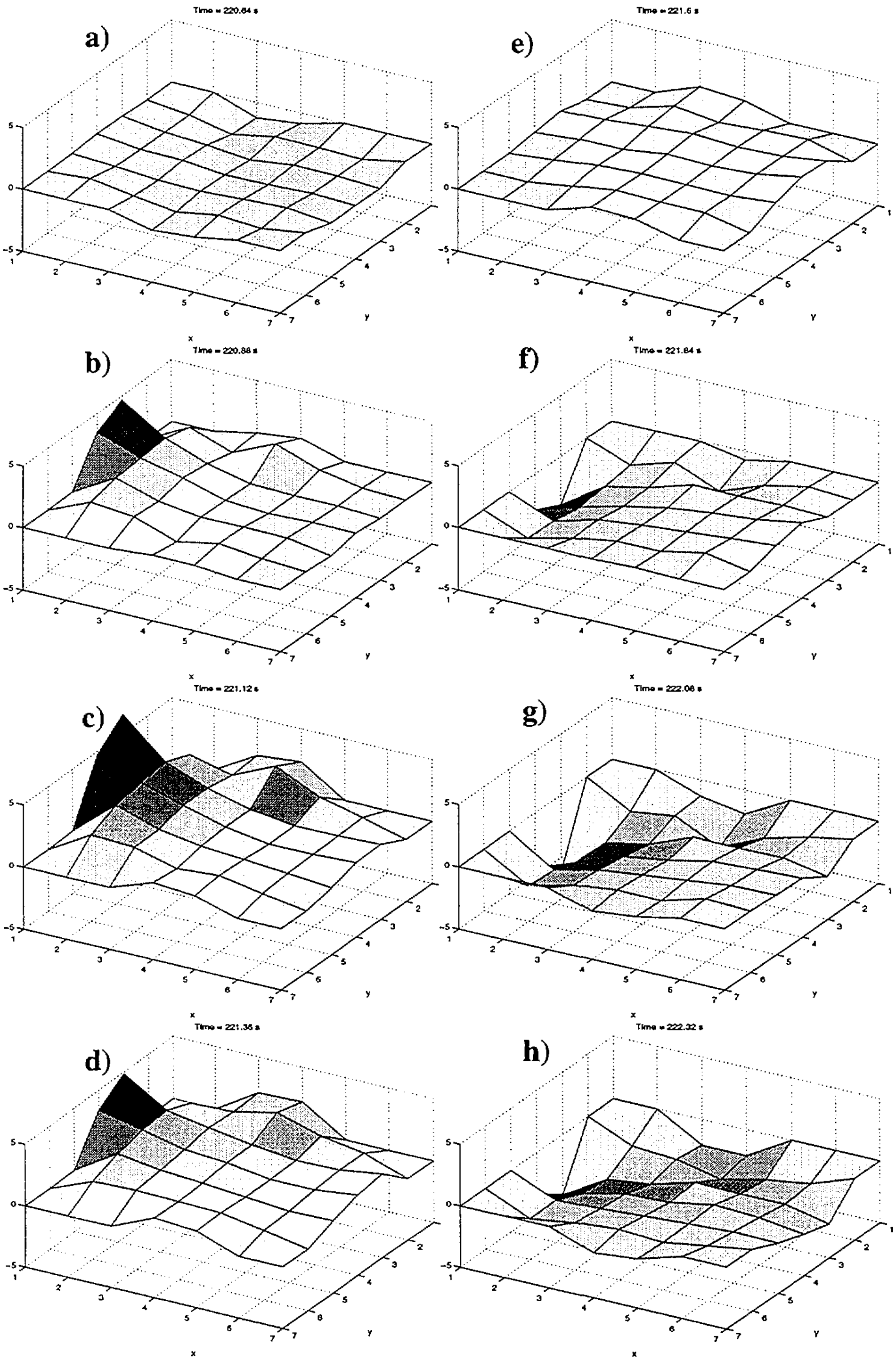

Fig. 3. The figure shows the amplitude of the flux in the x-y plane for a single cycle.

The advantages of this method are as follows:

- it shows raw signals, in contrast to processed ones such as power spectra, thus they can be interpreted without expert signal processing knowledge and used by people with reactor physics or operating experience;
- since it contains only minimal signal processing, it can be used on-line;
- it can be used to confirm the existence of a few, spatially separated noise sources, which is a pre-requisite for using the algorithmic localisation method;
- finally, it gives information on the selection of the detectors for the algorithmic method.

An analysis of a few minutes of the display yields the following conclusions on the perturbation in the concrete case of the Forsmark measurements M2:

- the spatial peaks in the noise field are all generated by an absorber of variable strength rather than by a perturbation corresponding to lateral vibrations. (This latter could be the case for instance if two adjacent channels oscillated in opposite phase);
- there is one primary spatial peak (i.e. localised perturbation) and one secondary peak of smaller amplitude than the primary. Further, there are also perturbations at other positions that appear and vanish in a non-stationary way;
- the oscillations are not stationary in time, not even for the two principal peaks. However, for these latter, one may assume approximate stationarity such that spectral analysis methods can be applied;
- the principal individual perturbations (spatial peaks) are quite well separated in space.

Based on the above, it was assumed that the perturbation consists of a single oscillation of the variable strength absorber type. The spatial separation between any two perturbations appearing concurrently was large enough (larger than the attenuation length of the noise, see later) such that two different perturbations that occur simultaneously can be localised separately, by using a suitably selected set of detectors in the Forsmark measurement.

3. THE ALGORITHMIC LOCALISATION METHOD

The starting point is an expression of the noise in the frequency domain as a convolution of the transfer function (Green's function) of the unperturbed system, and the noise source (Ref. [7]):

$$\delta\phi(\boldsymbol{r}, \omega) = \int G(\boldsymbol{r}, \boldsymbol{r}', \omega)\, S(\boldsymbol{r}', \omega)\, d\boldsymbol{r}' \tag{1}$$

Here, $G(\boldsymbol{r}, \boldsymbol{r}', \omega)$ is the transfer function, discussed later, and $S(\boldsymbol{r}', \omega)$ is the noise source, or perturbation, that induces the noise. It consists of the fluctuations of the macroscopic cross sections which appear in the time-dependent diffusion equations.

A noise source of variable strength at a fixed position $\boldsymbol{r}_p$ can be represented functionally as

$$S(\boldsymbol{r}', \omega) = \gamma(\omega)\, \delta(\boldsymbol{r}' - \boldsymbol{r}_p) \tag{2}$$

In reality, the noise source is not a δ-function, rather it has a finite volume. This fact can be easily accounted for, and will not be discussed here. Applying (2) in (1), the noise, as measured by a detector at position $\boldsymbol{r}_i$, is given as

$$\delta\phi(\boldsymbol{r}_i, \omega) = \gamma(\omega)\, G(\boldsymbol{r}_i, \boldsymbol{r}_p, \omega) \tag{3}$$

In this expression, $\delta\phi(\boldsymbol{r}_i, \omega)$ is known from measurement, and $G(\boldsymbol{r}_i, \boldsymbol{r}_p, \omega)$ can be calculated as a function of its arguments. However, $\gamma(\omega)$ and $\boldsymbol{r}_p$ are noise source properties, and they are not known in a practical case. Since the main interest lies in the determination of the source position (localisation), we will use the notation $\boldsymbol{r}$ as the argument for the position of the source in the algorithm. Thus, we have succeeded in the localisation procedure when we obtain $\boldsymbol{r} = \boldsymbol{r}_p$.

To this order we consider an expression for the ratio of two detector signals, which will be given as

$$\frac{\delta\phi(\boldsymbol{r}_i, \omega)}{\delta\phi(\boldsymbol{r}_j, \omega)} = \frac{G(\boldsymbol{r}_i, \boldsymbol{r}, \omega)}{G(\boldsymbol{r}_j, \boldsymbol{r}, \omega)} \tag{4}$$

In this expression, the source strength $\gamma(\omega)$ is eliminated. The l.h.s. is known from measurement, and the unknown perturbation position $\boldsymbol{r}$ can in principle be obtained as the value (more precisely, one of the values) which, when substituted into (4), satisfies the equation. Using only one pair of detectors, in general there will be a whole line on the 2-D plane, in which the search for $\boldsymbol{r}$ is made, each point of which satisfies (4). Such a line was called a "localisation curve" in Ref. [4]. One needs at least one more detector to obtain one or two more localisation curves, such that the intersection of such lines gives the true perturbation position. Besides, in practice one uses power spectra instead of Fourier-transforms of the signals.

Thus the method goes as follows. Having access to n detectors, one can select $n(n-1)/2$ pairs and corresponding ratios of the type (4). Then, for pair r_i and r_j, one defines the quantities

$$\delta_{ij}(\boldsymbol{r}) = \frac{APSD_i}{APSD_j} - \left|\frac{G(\boldsymbol{r}_i, \boldsymbol{r}, \omega)}{G(\boldsymbol{r}_j, \boldsymbol{r}, \omega)}\right|^2 \tag{5}$$

and

$$\delta_{ijkl}(\boldsymbol{r}) = \frac{CPSD_{ij}}{CPSD_{kl}} - \frac{G^*(\boldsymbol{r}_i, \boldsymbol{r}, \omega)\, G(\boldsymbol{r}_j, \boldsymbol{r}, \omega)}{G^*(\boldsymbol{r}_k, \boldsymbol{r}, \omega)\, G(\boldsymbol{r}_l, \boldsymbol{r}, \omega)}; \qquad i \neq j,\, k \neq l \tag{6}$$

where, in general, $\delta_{ijkl}(\boldsymbol{r})$ is complex. Clearly, theoretically $\delta_{ij}(\boldsymbol{r})$ and $\delta_{ijkl}(\boldsymbol{r})$ are zero in an ideal case if $\boldsymbol{r} = \boldsymbol{r}_p$. This would be the case if no background noise, no measurement error existed etc. In practice however all these exist, thus in general (5) and (6) will deviate from zero for all $\boldsymbol{r}$ values. It can however be expected that the deviation from zero will be minimum for the true rod position. Thus, we define an optimization function as

$$g(\boldsymbol{r}) = \sum_{\substack{i,j,k,l \\ i \neq j;\, k \neq l}} \left|\delta_{ijkl}(\boldsymbol{r})\right|^2 + \sum_{i,j} \delta_{ij}^2(\boldsymbol{r}) \tag{7}$$

The position of the perturbation is then given as the value $\boldsymbol{r} = \boldsymbol{r}_p$ for which g is minimum:

$$\min g(\boldsymbol{r}) \Rightarrow \boldsymbol{r} = \boldsymbol{r}_p \tag{8}$$

The localisation method, as described above, can be extended to localize several concurrent noise sources. However, the complexity of the method increases somewhat and the amount of computational effort needed increases significantly. However, as long as the noise sources are not over-lapping each other substantially, the multiple source method does not necessarily improve the localisation but it does still increase the complexity. Because of the above reasons, we have only applied and tested the single source method by using a suitably selected set of detectors for the few individual perturbations.

The calculation of the transfer function will not be described in detail here, we refer to references [7] and [8]. We have used one-group diffusion theory, one group of delayed neutrons and a bare, homogeneous cylindrical reactor in 2-dimensional $r - \phi$ geometry. This model is essentially the same as the one used in the study and application of the method of localising a vibrating control rod (Ref. [4]). The transfer function in this model is given as

$$G(\mathbf{r}, \mathbf{r}_p, \omega) = \frac{1}{4}\left[Y_0(B|\mathbf{r} - \mathbf{r}_p|) - \sum_{n=0}^{\infty} \frac{(2-\delta_{n,0})\,Y_n(BR)\,J_n(Br_p)}{J_n(BR)} J_n(Br)\cos(n(\alpha - \alpha_p))\right] \tag{9}$$

This transfer function was used both in the simulation tests and in the concrete application with Forsmark data.

4. TEST OF THE ALGORITHM WITH SIMULATED DATA

To get some hands-on experience with the algorithm, and to get some estimate of its performance, it was first tested in simulation tests. These tests were conceptually similar to those performed in the study of the algorithm for the localisation of a vibrating control rod. The starting point is the selection of the position of the source, $\mathbf{r}_p$, and a few detector positions $\mathbf{r}_i$, $i = 1, 2, 3$. To simplify the simulations, we have selected the minimum possible number of detectors, which is three. Then the induced noise at these detector positions is calculated by (3), after which the calculated noise values were used in the localisation algorithm (5) and (7). The minimisation procedure was performed in the whole 2-D plane, yielding an absolute minimum. Since the perturbation position is known in advance in these tests, the correctness of the result, and thus the performance of the algorithm, can be judged.

The significance of the test is motivated among others also by the fact that expression in (7) may have several minima, and there is no prior proof of the hypothesis that the perturbation position yields the absolute minimum. Especially in the case of “disturbed” or “not clean” detector signals, such a proof may not exist at all since the deviations between the assumption of the model and reality are not known in exact quantitative terms. Thus the only way of finding the answers to such questions is to perform numerical simulations with both “clean” and “contaminated” signals (the contamination is also simulated). Another goal of the test is to check the sensitivity of the algorithm to disturbing effects such as background noise, statistical measurement error etc. Even if the existence of these does not lead to the occurrence of a global minimum at a position completely different from that of the true perturbation position, it will lead to deteriorated accuracy of the method. The simulation of the perturbed signals is achieved by adding a random number of a few percent to each calculated detector signal before performing the localisation step (7).

A layout of the selected source position and detector positions is seen in Fig. 4. The absolute value and phase of the induced neutron noise are shown in Fig. 5 over the whole cross-section of the core, i.e. not only in the three detector positions (which are indicated in Fig. 4) that will be used in the localisation algorithm. It is seen how the amplitude of the noise decreases and the phase delay increases with increasing distance from the source. From the quantitative results an attenuation length, i.e. a distance within which most of the noise amplitude change takes place, can be extracted. This attenuation length is about half of the radius of the core. The space-dependence also agrees qualitatively with the one seen in Fig. 3. The magnitude of the attenuation length is also in agreement with the fact that the oscillations are felt in about one half of the core.

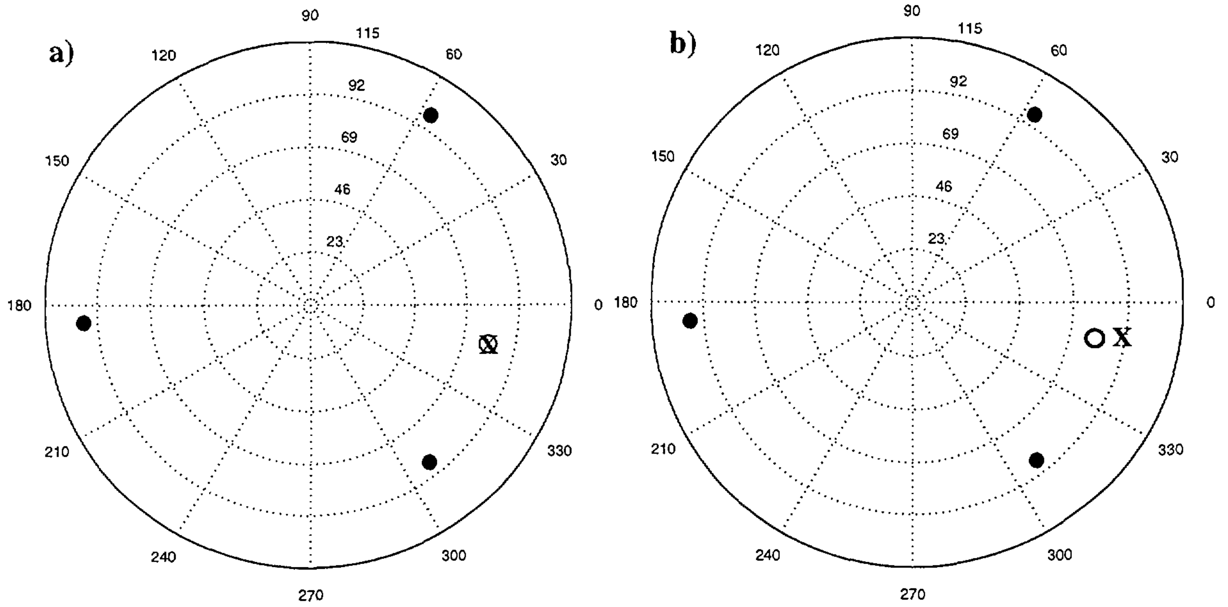

Fig. 4. The localised source position is marked by 'X'. The detectors used in the localisation are indicated by '●' and the actual source position by 'O'. In Fig. 4b the localisation algorithm was disturbed by the addition of extraneous random noise to the detector signals.

Expression (7) whose absolute minimum is to give the source position, is shown in Fig. 6. It is seen that it has a relatively simple structure, with only one minimum which is very well discernible, and it also coincides with the source position. This is reassuring, although the smoothness of the function $g(\mathbf{r})$ depends partly on the use of a homogeneous reactor model. In an inhomogeneous reactor model it may not be as simple; this question will be investigated in the future.

The results of the algorithm for one case are shown in a different way in Fig. 4, where a direct estimation on the precision can be visually made. The figure shows the results of the algorithm both for the case when pure (unperturbed) signals were used in the localisation step (Fig. 4a), and the case when perturbed signals were used (Fig. 4b). In the latter case a random number with a variance of 5% of the mean value of each signal was added to all three detector signals. It is seen that in the latter case the precision of the algorithm deteriorates, as expected. For perturbations of this magnitude, the deterioration is not large.

5. APPLICATION OF THE METHOD TO FORSMARK DATA

The layout of the core, with all detectors available in the measurement, is shown in Fig. 7. The number of detectors is much larger than the required minimum of 3 detectors, which was used in the simulation tests. Actually, it was not practical to use all detectors at a

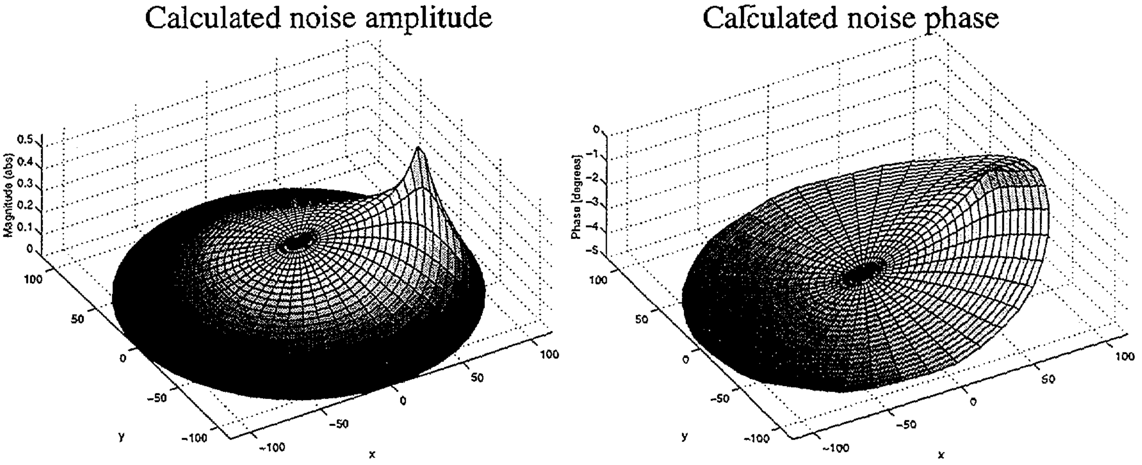

Fig. 5. The spatial distribution of the calculated noise amplitude and its phase

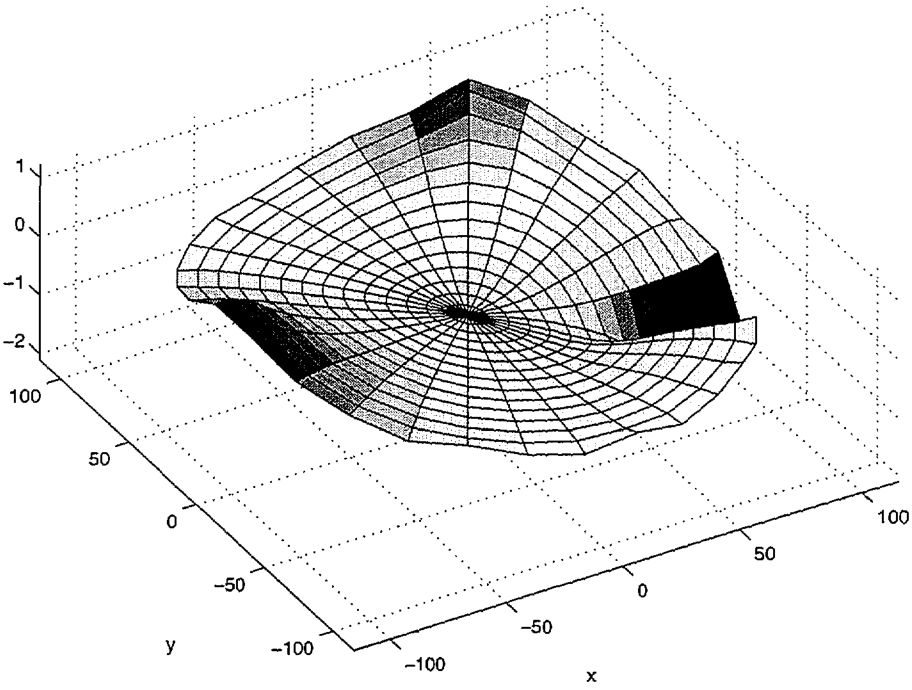

Fig. 6. The minimization surface in logarithmic scale.

time in a localisation run, only a limited set. There are two reasons why a limited set of detectors is more efficient than using all of them. First, as both the measurement "movie" (Fig. 3) and the simulated results (Fig. 5) show, the amplitude of the noise diminishes relatively fast away from the source, with a relaxation length smaller than the core radius. Since the background noise (i.e. noise from sources other than the instability) can be expected to be a smooth function of core position, e.g. follow the space dependence of the static flux, the relative weight of the useful noise is low in the signal of detectors that are far away from the source. Thus, the localisation is more accurate if only detectors from the same half or quadrant of the core are used where the source position is situated. The second reason for why using detectors around the suspected source position is effective is that the present algorithm is based on the assumption of one single source being active at a time. The measurement movie, on the other hand, makes it likely that at least one or two noise sources are acting, even if not stationarily, only in a sporadic manner. Fortunately, these potential sources are all separated from each other by a distance comparable with or larger than the noise attenuation length. By selecting groups of detectors around each potential source, the effect of other sources is minimised and the various source positions can be determined separately by applying the single-source algorithm individually. It is this strategy that has been used in the present work.

Selecting a group of detectors is of course a somewhat subjective moment. Since the result of the localisation depends on the detectors used in the localisation algorithm, the selection of a set of detectors introduces an element of arbitrariness into the procedure. This kind of influencing the outcome of the results is justified by the fact that the conditions in a practical case do not exactly correspond to the idealised conditions assumed in the algorithm. The selection of a "most suitable" set of detectors is made in order to minimize the consequences of this deviation between practice and theory, and is performed by using reactor physics expertise.

We have tried to locate two noise sources, primarily the principal one close to LPRM 10, and a secondary one close to LPRM 7 (for the poistions of the different LPRMs, see Fig. 2). The results of the first case, concerning the primary source, are shown in Fig. 7. The figure also shows the detectors that were selected in this localisation procedure. The result of the localisation is also shown in Fig. 8, where it is seen that the identified position is neighbouring to a position (18,3) where an unseated fuel assembly was found after revision 1997.

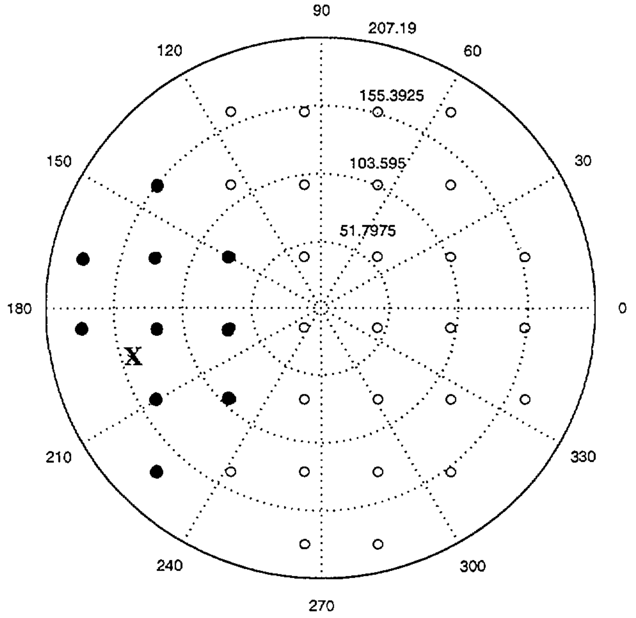

Fig. 7. The position of the source (X) as obtained by the localisation method using the detectors (●).

Varying the number and position of the detectors used in the procedure will naturally affect the result of localisation. This was also investigated by choosing various detector sets. As long as detectors are taken mostly from the west half of the core, the variation of the result is quite moderate. Choosing detectors from the other half of the core will lead to significantly different results. This is in accordance with the previous reasoning on the selection of the most suitable set of detectors above. At any rate, the result shown in Figs. 7 and 8 is the one that appears to be most plausible.

Results of the localisation of the secondary source, including the position of the detectors used is shown in Fig. 9. This position too corresponds quite well to the local oscillations seen in the movie. Hence it is also demonstrated that the two noise sources could

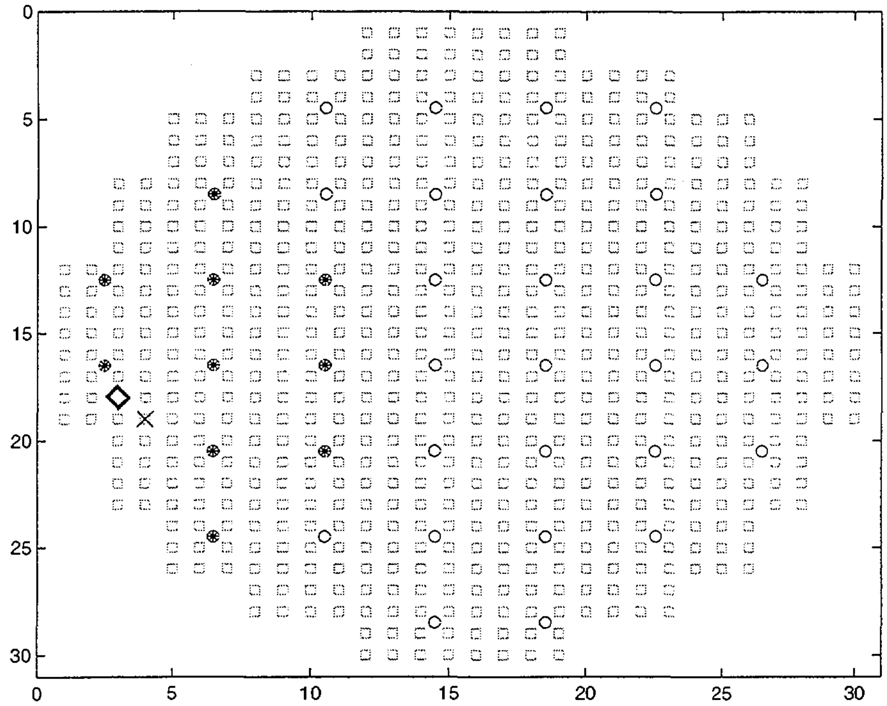

Fig. 8. The position of the source as obtained by the localisation method and the position of the unseated fuel element is indicated by a cross (x) and a diamond character (◇), respectively.

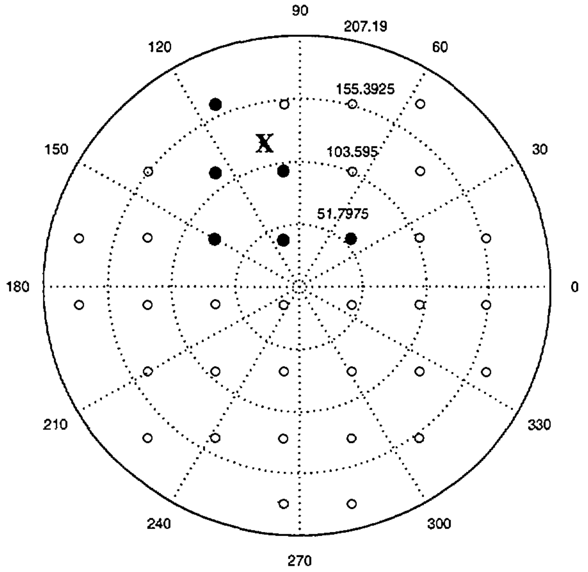

Fig. 9. The position of the secondary source as obtained by the indicated detectors (●) in the localisation method.

be identified separately by the use of suitably selected detector sets, and by applying the single source localisation algorithm.

6. CONCLUSIONS AND FUTURE WORK

The main purpose of this study was to test the applicability of the localisation technique in a practical case, using the Forsmark measurements. Such an algorithm has not been used and tested before. The study, both in simulations and with measured data, showed that the algorithm works satisfactorily. It was demonstrated that the resolution of the method is higher than the distance between the detectors in the core. It was also seen that two or three sources can be localised individually if they are separated sufficiently well in space, with applying the single source localisation algorithm by using suitable selected sets of detectors.

One weakness of the method in its present form is the very simple core model used in the calculation of the transfer function. Besides of using one-group theory, the most important restriction is the use of a homogeneous bare reactor model. Core inhomogeneities, reflector, and most important, control rod patterns cannot be taken into account in the present model. The most important task in the further development of the method is to extend it to two energy groups, include a reflector, and take into account the inhomogeneous core structure. This will require fully numeric methods, and perhaps parallel computing techniques due to the large complexity of the calculational task.

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