Progress in Nuclear Energy 70 (2014) 98–111

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Qualitative and quantitative investigation of the propagation noise in various reactor systems

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ARTICLE INFO

Article history:
Received 4 May 2012
Received in revised form
2 July 2013
Accepted 21 July 2013

Keywords:
Neutron noise
Propagating perturbations
Space-dependent noise
Local and global components
Two-group theory

ABSTRACT

The space-dependent neutron noise, induced by propagating perturbations (propagation noise for short) is investigated in a one-dimensional homogeneous model of various reactor systems. By using two-group theory, the noise in both the fast and the thermal group is calculated. The purpose is to investigate the dependence of the properties of the space-dependent fast and thermal propagation noise on the static neutron spectrum as well as on the presence of the fluctuations of several cross sections. The motivation for this study arose in connection with recent work on neutron noise in molten salt reactors (MSR) with propagating fuel of various compositions. Some new features of the induced noise were observed, but it was not clear whether these were due to the propagating perturbation alone, or to the propagation of the fuel and hence that of the delayed neutron precursors. The present study serves to clarify the significance of the spectral properties of the different cores through calculating the propagation noise in four different reactor systems, as well as considering the influence of the perturbation of the various cross sections. By comparing the results with those obtained in MSR, the effect of the moving fuel on the propagation noise is clarified. It is shown that in fast systems the noise in the fast group is much larger than in the thermal group and hence can gain diagnostic importance. It is also shown that the co-existence of several cross section fluctuations leads to qualitatively and quantitatively new characteristics of the noise, hence it is important to model the effect of e.g. temperature fluctuations of the coolant in a proper way.

1. Introduction

The space-dependent behaviour of the neutron noise in power reactors was investigated intensively in a variety of papers for the last 40 years (for an overview, see (Williams, 1974; Kosály, 1980; Pázsit and Demazière, 2010)). Somewhat remarkably, however, as noted recently (Pázsit and Dykin, 2010), the in-core noise in PWRs and BWRs, induced by propagating perturbations (inlet temperature fluctuations and two-phase flow, respectively), has remained an exception. The reasons for this are also discussed in Pázsit and Dykin (2010). The space dependence here refers to the axial dependence of the induced noise, i.e. its space dependence in the same direction as the flow/propagation itself. The radial dependence of the neutron noise induced by a local (channel-type) instability was investigated in the past (Karlsson and Pázsit, 1999); however, in this case, the axial structure and hence the propagating character of the noise source does not play a role.

The space dependence of the neutron noise induced by propagating perturbations (for which the shorthand notation "propagation noise" will be used further in this paper) received interest recently due to investigations of the neutron noise in molten salt reactors (MSR). In such reactors the circulation of the fuel is likely to induce propagating perturbations due to inhomogeneities in the density/temperature, fuel concentration in the salt, locally slightly varying burnup in the fuel etc. The propagation noise induced by such perturbations was investigated in some recent publications (Pázsit and Jonsson, 2010; Jonsson and Pázsit, 2011).

In the second of the above references the neutron noise was calculated in a two-group approach, in three different systems with different material properties which lead to different neutron spectra. The motivation came from the fact that the MSR, being one of the six selected Gen-IV systems, can be built either with a fast or with a thermal spectrum, dependent on the moderator and the fuel used. Hence three different systems were selected, one with a very soft thermal spectrum, representing a graphite moderated thorium fuelled MSR, a Gen-II light water reactor (BWR) and a high conversion fast system operating with MOX fuel, with fast spectrum. Even these two latter systems were assumed to contain moving fuel

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0149-1970/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.pnucene.2013.07.014

in liquid form, representing models of possible MSRs, only the group constants were taken from the corresponding traditional systems. By selecting these three systems, the significance of the spectral properties of the core on the spatial and frequency properties of the induced propagation noise, including the relative significance of the local component of the noise, could be investigated.

The above mentioned investigation was the first of its kind because the spectral properties of the neutron noise, and the significance of the spectral properties of the core on the characteristics of the neutron noise have not been investigated before. All quantitative studies were made in thermal LWRs, and only the influence of the system size and the frequency on the thermal neutron noise was of interest. The investigation of the characteristics of the noise in systems with different spectral properties yielded some new features and tendencies regarding the induced noise. However, it was a somewhat unfortunate circumstance that these novel studies were not performed in traditional systems with stationary fuel, rather directly on MSR-type systems with moving fuel, i.e. with moving delayed neutron precursors. Hence it was not possible to say whether these new properties were due to the effect of the propagating perturbations and/or the spectral properties alone, or to the propagation of the fuel and hence that of the delayed neutron precursors. In other words, it was not clear if the same properties would be observed in traditional systems with stationary fuel.

Hence we decided to make a thorough investigation of the noise properties in various traditional systems (i.e. with stationary fuel) with widely differing spectral properties. Four different systems were selected:

- a fast reactor with MOX fuel
- a BWR
- a PWR
- a heavy water core (representing a CANDU).

By selecting these four different systems, a wider range of spectral properties could be covered. This way the present study can also be considered as the first attempt to study the applicability of noise analysis to systems significantly different from the LWR cores dominating in quantitative studies of noise diagnostics so far, as well as the first attempt to study the spectral properties of the induced neutron noise in a two-group model. The present study also serves to clarify the significance of the core properties and that of the fuel propagation, through calculating the propagation noise in cores with static fuel in the four different reactor systems ranging from Gen-II to GEN-IV characteristics and comparing it with the results obtained in the MSR study of Jonsson and Pázsit (2011). One result of these investigations is that in fast systems the neutron noise in the fast group (the “fast noise”) has a much larger amplitude than that of the thermal noise, and hence it can be utilised in fast system for diagnostic purposes.

Another novelty of the present investigations is the modelling of the noise source. In the past studies of the propagation noise, the perturbation was modelled by the fluctuations of one single macroscopic cross section:either the thermal absorption cross section (in case of inlet coolant temperature fluctuations in PWRs), or the removal cross section (for the void fluctuations in BWRs). This is because it was considered that the main features of the problem can be described sufficiently well by considering the fluctuations of a “dominating” cross section. The validity of this assumption is investigated in this paper by considering the noise source as temperature fluctuations of the coolant, and calculating the relative weight of the fluctuations of all cross sections. It turned out that the effect of the aggregate of the cross section fluctuations has qualitatively and quantitatively different properties than in the case of a single cross section fluctuation. This underlines the need for proper modelling of noise sources at least for calculating the neutron noise induced by propagating temperature and density fluctuations.

2. Basic considerations

The investigation of the neutron noise induced by various perturbations is usually performed through the Green’s function method. This has the practical advantage that it is more straightforward to obtain analytical results, as well as that the Green’s function itself, representing the dynamic transfer function of the system, gives insight into the properties of the system which are not dependent on the perturbation. Hence in the final result it is easier to identify if a certain feature can be attributed to the system properties or to the perturbation.

In a two-group approach, there is an alternative possibility due to the fact that the two-group equations are not self-adjoint. Hence, as was suggested by van Dam (1975, 1976), one can use the dynamic adjoint function instead of the Green’s function (Pázsit and Demazière, 2010). Actually, due to some differences between the direct and the adjoint Green’s function, in most works the dynamic adjoint was used. One reason is that in the two-group case, where both the noise source and the induced neutron noise appear both in the fast and the thermal group, the transfer function is actually a 2 × 2 matrix. Although the noise source appears in both groups, in traditional systems one only measures the thermal noise, and hence the calculations were also aimed at only this quantity. In that case, the adjoint approach has the advantage over the direct Green’s function that it is sufficient to use the second column of the adjoint matrix, which can be determined from a vector equation. This two-component quantity was called the adjoint function, with a fast and a thermal component, similarly to the flux. Using the direct Green’s matrix, to calculate the thermal noise induced by perturbations in both the fast and the thermal group, one would need the second row of the Green’s matrix, which cannot be determined from one single vector equation, rather the whole Green’s matrix needs to be calculated.

In the present study, given the fact that fast systems will also be investigated, it will be interesting to calculate not only the thermal noise (neutrons with energies below 1 eV), but also the fast noise (neutrons with energies above 1 eV). Indeed, in Gen-IV systems with a fast spectrum, it may be either advantageous, or simply necessary, to use the fast noise, or both the fast and the thermal noise, for maximum performance. In that case the advantage of the dynamic adjoint disappears. Hence in the paper both the adjoint function (adjoint matrix) and the Green’s matrix will be used, and in all cases both the fast and the thermal neutron noise will be calculated and compared.

The formulae used are as follows. The static equations for the direct flux read as:

$$\begin{pmatrix} D_1\nabla^2 - \Sigma_{a1} - \Sigma_R + \nu\Sigma_{f1} & \nu\Sigma_{f2} \\ \Sigma_R & D_2\nabla^2 - \Sigma_{a2} \end{pmatrix} \begin{bmatrix} \phi_1(z) \\ \phi_2(z) \end{bmatrix} = 0, \tag{1}$$

where all symbols have their usual meaning. In the above it was assumed that the system is critical, i.e. $k_{\text{eff}} = 1$. The notation $\Sigma_1 = \Sigma_{a1} + \Sigma_R - \nu\Sigma_{f1}$ will also be employed. Zero flux conditions will be used at the extrapolated boundaries, i.e. $\phi_i(0) = \phi_i(H) = 0$ for a one-dimensional system lying between $z = 0$ and $z = H$.

The static fluxes are given as:

$$\phi_1(z) = \sin B_0 z, \tag{2}$$