Available online at www.sciencedirect.com

ScienceDirect

Progress in Nuclear Energy 51 (2009) 67–81

PROGRESS IN NUCLEAR ENERGY
An International Review Journal

www.elsevier.com/locate/pnucene

Review

Numerical tools applied to power reactor noise analysis

Christophe Demazière*, Imre Pázsit

Chalmers University of Technology, Department of Nuclear Engineering, SE-412 96 Göteborg, Sweden

---

Abstract

In order to be able to calculate the space- and frequency-dependent neutron noise in real inhomogeneous systems in two-group theory, a code was developed for the calculation of the Green's function (dynamic transfer function) of such systems. This paper reports on the development as well as the test and application of the numerical tools employed. The code that was developed yields the space-dependence of the fluctuations of the neutron flux induced by fluctuating properties of the medium in the two-group diffusion approximation and in a two-dimensional representation of heterogeneous systems, for both critical systems and non-critical systems with an external source. Some applications of these tools to power reactor noise analysis are then described, including the unfolding of the parameters of the noise source from the induced neutron noise, measured at a few discrete locations throughout the core. Other concrete applications concern the study of the space-dependence of the Decay Ratio in Boiling Water Reactors, the noise-based estimation of the Moderator Temperature Coefficient of reactivity in Pressurized Water Reactors, the modeling of the beam- and shell-mode core-barrel vibrations in Pressurized Water Reactors, and the investigation of the validity of the point-kinetic approximation in subcritical systems driven by an external source. In most of these applications, calculations performed using the code are compared with at-power plant measurements. Power reactor noise analysis applications of the above type, i.e. core monitoring without disturbing plant operation, is of particular interest in the framework of the extensive program of power uprates worldwide.

Keywords: Noise analysis; Code development; Numerical methods; Modeling; Analysis of measurements

---

1. Introduction

It is well known that the neutron noise, i.e. the deviation between the time-dependent neutron flux and its expected (time-averaged) value (assuming that all the processes are stationary and ergodic in time), allows the determination of important parameters and operational state of the core. The neutron noise can be used either for diagnostic purposes, when an abnormal situation is suspected, or for estimating a dynamical core parameter, when the reactor is at steady-state conditions (Thie, 1963, 1981; Uhrig, 1970; Williams, 1974). Examples of the first category are the detection of flow blockage in fuel assemblies by estimating the flow velocity in the corresponding fuel channel by cross-correlation between two neutron detectors, the estimation of core-barrel vibrations, or the detection of the appearance and localization of a noise source such as an unseated fuel assembly or an excessively vibrating control rod. For the second category, namely the determination of global dynamical core parameters, the Decay Ratio in Boiling Water Reactors (BWRs) and the Moderator Temperature Coefficient of reactivity in Pressurized Water Reactors (PWRs) are probably the two most significant applications.

Noise diagnostics has the obvious advantage that it can be used on-line without disturbing reactor operation. Such a monitoring technique received further attention in the past few years due to the extensive program of power uprates worldwide. Some of the main issues/concerns related to the operation of the plants at the uprated power level are the reduction of the safety margins, such as the margins to instability for BWRs, and increased vibrations (flow induced vibrations).

The strategy of neutron noise diagnostics is to represent the induced neutron noise as a spatial convolution of the noise source, i.e. the cross-section fluctuations, with the frequency-dependent transfer function of the core. This factorisation is possible because linear theory is used, due to the smallness

---

* Corresponding author. Tel.: +46 31 772 3082; fax: +46 31 772 3079.
E-mail address: demaz@nephy.chalmers.se (C. Demazière).

0149-1970/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pnucene.2008.01.010

of the perturbation. The transfer function is only dependent on the parameters of the unperturbed core, hence it can be calculated in advance, irrespective of the (unknown) perturbation. In possession of the measured neutron noise, and the calculated transfer function, the unknown noise source can be determined by an inversion of the convolution integral. This process is therefore often called "spatial unfolding". In practice, the inversion is not possible for arbitrary unknown noise sources, since the noise is only measured in a few discrete spatial locations. Therefore a simple analytical model of the noise source is constructed which only contains a few unknown parameters ("noise source modeling"), which can then be determined by unfolding.

In the early days of neutron noise diagnostics all noise unfolding methods were based on simple analytical core models, i.e. calculating the transfer function in homogeneous cores with one-group theory, and sometimes in a two-region homogeneous model or in two-group theory. The reason for this is twofold. First, inverse methods, such as unfolding, have no routine solution methodology, and an analytical solution is, as a rule, much more amenable for unfolding. The second reason is that a numerical solution for the transfer function for real inhomogeneous cores with two-group theory was out of reach with the computer power and computing algorithms available at the time. This is because calculation of the transfer function requires, as opposed to the calculation of the static flux, the handling of complex coefficients. Further, the dimensions of the spatial co-ordinates are doubled, due to the simultaneous handling of source and detector positions.

However, with the development of computer power and computing algorithms, neither of the above two aspects represent real restrictions. For the unfolding, powerful non-parametric inversion procedures were developed, such as neural networks, for which pure numerical values of the calculated noise are completely satisfactory. Second, the transfer function can readily be calculated for heterogeneous cores in two-group theory by numerical methods such as finite difference or nodal methods.

It is remarkable that, except of two notes addressing the need and possibility of the efficient numerical calculation of the transfer function (van Dam, 1975; Pázsit, 1992), this possibility has largely escaped the attention of the noise community. Up to date, except the one described in this paper, no work was reported in the systematic development and application of the dynamic transfer function of real inhomogeneous cores. It is the development and application of such a code, performed at the Department of Nuclear Engineering, Chalmers University of Technology, which is the subject of the present paper.

Chalmers University of Technology has long been active in the field of reactor noise analysis. Based on this expertise, a program of core surveillance was started in collaboration with the Ringhals Nuclear Power Plant, in order to give a fingerprint of the status of the different units before and after the power uprates. Simultaneously, a program of method development was pursued with support from the Swedish Nuclear Power Inspectorate (SKI). In the frame of this work, the development of a tool, usually referred to as a "neutron noise simulator" (Demazière, 2004), for the calculation of the dynamic transfer function of realistic cores, was incorporated. This simulator is able to calculate the response of a nuclear core to perturbations expressed as fluctuations of the macroscopic nuclear cross-sections or of the possible external neutron source, assuming that the operating conditions of the reactor are stationary. The main features of this simulator are as follows:

- its ability to model any kind of perturbation in the core, either localized or spatially-distributed, either of the type "absorber of variable strength" (reactor oscillator) or of the type "vibrating absorber";
- a two-dimensional representation of the core and reflector;
- the use of the frequency-domain instead of the time-domain for performing the calculations;
- its ability to model a wide range of reactor types, both for critical systems [Pressurized Water Reactors (PWRs), Boiling Water Reactors (BWRs), others] and subcritical systems (Accelerator Driven Systems), as long as the fuel assemblies have a rectangular cross-sectional shape; and
- its coupling to the major static code systems in use for in-core fuel management, in order to get a set of realistic steady-state data (group constants).

Using the frequency-domain allows avoiding performing lengthy calculations in the time-domain for accurately describing the effect of a given perturbation. Furthermore, the problem of properly choosing a time discretization is eliminated, and the convergence/stability of the calculations is thus automatically guaranteed. Once the frequency of interest (i.e. the frequency of the perturbation) is known, the simulator estimates the space-dependence of the neutron flux through the reactor at this given frequency, i.e. the so-called Green's function. It is also possible to perform the calculations at several frequencies in order to determine the space-dependent spectrum of the neutron flux, from which the space- and time-dependence of the neutron flux can be determined by inverse Fourier-transform.

This paper presents the main characteristics of the noise simulator in more detail, and briefly gives an overview of some of its main applications so far and the methodology used for solving these practical examples.

2. Features of the noise simulator

Although, as described in Section 1, the primary goal is to calculate the dynamic transfer function which is independent of the perturbation, this goal has to be modified when numerical methods are applied. This is because due to the spatial discretization, also the analytical model of the noise source needs to be discretized. In addition, the discretization applied in the calculation of the transfer function represents certain restrictions on how the noise source can be numerically represented. For this reason, instead of calculating the transfer function completely independently of the noise source, as in the case of analytical methods, a "hybrid" approach is necessary. Namely, the transfer function is calculated for a few basic