Annals of Nuclear Energy 94 (2016) 272–278

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

The least-squares method based on coupling coefficients for reactor power distribution reconstruction

Xingjie Peng [a,b,*], Yun Cai [a,b], Qing Li [b], Kan Wang [a]

[a] Department of Engineering Physics, Tsinghua University, Beijing, China
[b] Science and Technology on Reactor System Design Technology Laboratory, Nuclear Power Institute of China, Chengdu, China

ARTICLE INFO

Article history:
Received 25 November 2015
Received in revised form 11 March 2016
Accepted 21 March 2016

Keywords:
Least squares method
Coupling coefficient
Power distribution reconstruction

ABSTRACT

The least-squares method based on three-dimensional coupling coefficients (LS-3DCC) was tested to determine its capability for replacing the three-dimensional coupling coefficients (3DCC) method for reconstructing the power distribution of ACP-100 which is a kind of small modular reactor (SMR). In the LS-3DCC method, the power distribution reconstruction problem is regarded as an inverse problem, and the Tikhonov regularizing operator constructed by coupling coefficients is used to alleviate the ill-posedness. Some power distribution pairs are generated to compare the LS-3DCC method and the 3DCC method, and the comparison results show that the LS-3DCC method performs better than the 3DCC method.

1. Introduction

Core power distribution monitoring in operating power reactors is very important in core surveillance, the 3-D power distribution is one of the basic operation parameters which can determine many other important parameters such as power peaking factor, enthalpy rising factor and quadrant tilt ratio used to evaluate the operation condition of reactor and the safe margin. The economy of reactor could be optimized if the real time 3-D power distribution is well obtained and used for surveillance and regulation. Most commercial power reactors in operation are equipped with fixed or movable in-core neutron detectors to obtain power distribution information. Many kinds of on-line monitoring systems, such as BEACON (Boyd and Miller, 1996) and GNF-ARGOS (Tojo et al., 2008), have been developed to estimate in-core power distributions using fixed in-core detectors. The detector results at certain locations reflect the actual reactor flux or power can be applied to improve the results of the only diffusion calculations.

Several computational methods have been proposed for power or flux mapping. The CANDU on-line flux mapping system (Tang and et al., 1978) converts the 102 vanadium detector signals to thermal fluxes at the detector sites and then maps out the 3D flux distribution by a process of least-squares fitting of the measured thermal fluxes to a linear expansion of pre-calculated flux modes. Combustion Engineering (CE) nuclear power plants use the coupling coefficient (Karlson, 1995) (CC) method to estimate the power distributions, and the pre-calculated two-dimensional coupling coefficients are used. Jang (Jang and et al., 2004) proposed a 3-Dimensional coupling coefficient (3DCC) method and Webb (Webb and Brittingham, 2000) proposed a Lagrange multiplier method, which both can be regarded as an improved version of the CC method. Lee and Kim (2003) proposed a least-squares method by combining the coarse mesh finite difference (CMFD) form of the fixed-source diffusion equation and the detector response equation to form an over-determined linear equation. The idea of least-squares method is intuitive, and the reconstruction results of this method are accurate. But there is a drawback of this method that it can be used only with neutronics design codes based on finite difference method or CMFD method while many neutronics design codes are based on nodal methods without CMFD acceleration.

In this study, the least squares 3-Dimensional coupling coefficient (LS-3DCC) method is proposed which can be used with any neutronics design code. The detector response equations are formed into matrix form and the power reconstruction problem is regarded as an inverse problem which is ill-posed. The Tikhonov regularization technique (Tarantola, 2005) is used to solve this ill-posed problem, and the regularizing operator is constructed by coupling coefficients. This new method is compared with 3DCC, and some useful results are obtained.

* Corresponding author at: Department of Engineering Physics, Tsinghua University, Beijing, China.
E-mail address: pengxingjiets@gmail.com (X. Peng).

http://dx.doi.org/10.1016/j.anucene.2016.03.018
0306-4549/

2. Methodology description

The purpose of this paper is to discuss the research investigating the LS-3DCC method for estimating power, and how it compares to the 3DCC method. Both methods are based on coupling coefficients, and these two methods are introduced sequentially.

2.1. 3DCC method

In 3DCC method, each node power is determined from the power coupling coefficients. Usually, one axial detector box may include a few neutronics calculation nodes. The height of one detector is much larger than that of a neutronics node and the heights of neutronics nodes can be adjusted to make sure the height of one detector is the sum of the heights of neutronics nodes exactly. And in 3DCC method, the power of each single neutronics calculation node belonging to a detector box is utilized. The power of a neutronics node belonging to a detector box can be reproduced from the corresponding detector box power using a power sharing factor as shown in Eq. (1):

$$P^M_{l,k} = F_{l,kk'} D^M_{l,k'} \tag{1}$$

where k' and k are axial indices for the detector box and the neutronics node separately, l is the radial index for the assembly, the superscript "M" means the measured power, $P^M_{l,k}$ = measured power of neutronics node (l, k), $D^M_{l,k'}$ = measured power of detector box (l, k'), and $F_{l,kk'}$ = power sharing factor from detector box (l, k') to neutronics node (l, k). Fig. 1 shows the indexing rule of the neutronics node and detector box using a small reactor as an example under an assumption that assembly No. 1 is instrumented, and one detector box occupies two neutronics node in this example.

In-core detector signals can be converted into detector box power through the following equation using the "signal to power" conversion factor:

$$D^M_{l,k'} = I^M_{l,k'} W_{l,k'} \tag{2}$$

where $I^M_{l,k'}$ = measured detector signal of detector box (l, k'), $W_{l,k'}$ = signal to power conversion factor of detector box (l, k'). The signal to power conversion factor $W_{l,k'}$ can be calculated from fine-mesh, multi-group diffusion theory (Webb and Brittingham, 2000).

The power sharing factor can be approximated by:

$$F_{l,kk'} \approx F^C_{l,kk'} = \frac{P^C_{l,k}}{D^C_{l,k'}} = \frac{P^C_{l,k}}{\sum_{k\in \mathrm{K}(k')} P^C_{l,k}} \tag{3}$$

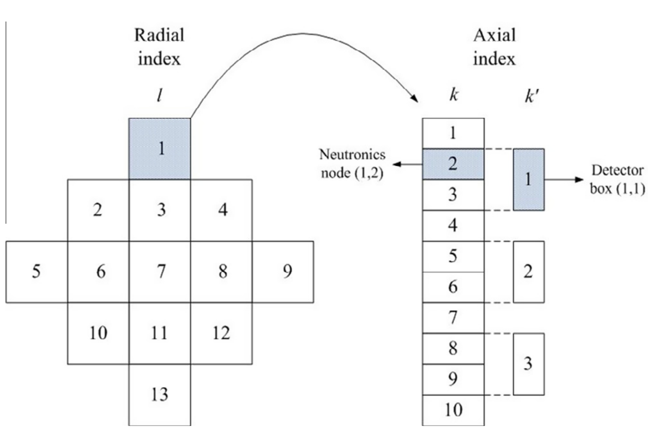

Fig. 1. Indexing rules of neutronics node and detector box.

where $F^C_{l,kk'}$ = approximated power sharing factor, $P^C_{l,k}$ = node power calculated by the neutronics code, $D^C_{l,k'}$ = detector box power calculated by neutronics code, $\mathrm{K}(k')$ = axial index groups of neutronics nodes occupied by detector box (l, k'), and the superscript "C" means calculated. The power of detector box can be defined as the summing powers of neutronics nodes if one detector box occupies several neutronics nodes as shown in Fig. 1.

A non-instrumented node power can be determined using the neighboring powers and the 3D coupling coefficients which are defined by the ratio of the sum power of the face adjacent neighboring nodes to the power of a node (l, k) as Eq. (4):

$$C_{l,k} = \frac{1}{P_{l,k}} \left(\sum_{i=1}^{N_{Rl}} P_{l(i),k} + \sum_{j=1}^{N_{Ak}} P_{l,k(j)} \right) \tag{4}$$

where $C_{l,k}$ = power coupling coefficient at node (l, k), N_{Rl} = number of radial neighboring nodes to node (l, k), N_{Ak} = number of axial neighboring nodes to node (l, k), $l(i)$ = radial index of the ith radial neighboring nodes to node (l, k), and $k(j)$ = axial index of the jth axial neighboring nodes to node (l, k). The power coupling coefficient can be determined using 3D neutronics calculation as Eq. (5) by assuming that there isn't difference between real 3DCCs and calculated 3DCCs:

$$C_{l,k} = C^C_{l,k} = \frac{1}{P^C_{l,k}} \left(\sum_{i=1}^{N_{Rl}} P^C_{l(i),k} + \sum_{j=1}^{N_{Ak}} P^C_{l,k(j)} \right) \tag{5}$$

Because the calculated 3DCCs can be provided by the neutronics calculation beforehand, the power of the non-instrumented node can be solved by Eq. (6):

$$C^C_{l,k} P_{l,k} - \sum_{(l(i),k)\in U(l,k)} P_{l(i),k} - \sum_{(l,k(j))\in U(l,k)} P_{l,k(j)} = \sum_{(l(i),k)\in I(l,k)} P^M_{l(i),k} + \sum_{(l,k(j))\in I(l,k)} P^M_{l,k(j)} \tag{6}$$

Groups $U(l, k)$ and $I(l, k)$ mean the non-instrumented and instrumented neighboring node groups of node (l, k), respectively. If node (l, k) doesn't have instrumented neighbor, then $I(l, k)$ is a null set and right hand side of Eq. (6) is zero. Eq. (6) is applied to all the nodes and can be expressed as the following matrix–vector form:

$$AP^U = S^I \tag{7}$$

where A = coupling coefficient matrix, P^U = vector of non-instrumented node powers, and S^I = source vector from detected node powers or zero.

2.2. LS-3DCC method

In LS-3DCC method, instead of using Eq. (1) to get the relationship between the measured node power and the measured detector power, a more accurate and direct relationship can be utilized as Eq. (8):

$$\sum_{k\in \mathrm{K}(k')} P^M_{l,k} = D^M_{l,k'} \tag{8}$$

where $\mathrm{K}(k')$ means the set of axial indexes of neutronics nodes which belong to the k' th axial detector box. The usefulness of Eq. (1) depends on the accuracy of the estimated $F^C_{l,kk'}$ because Eq. (3) is an approximation equation, while Eq. (8) is accurate unconditionally due to the definition of power of detector box. To check the usefulness of Eq. (1), Eq. (1) can be transformed into:

$$\frac{P^M_{l,k}}{D^M_{l,k'}} \approx \frac{P^C_{l,k}}{D^C_{l,k'}} \tag{9}$$