Spectral Rehomogenization of Nodal Cross-Sections via Proper Orthogonal Decomposition

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Abstract - Industrial reactor-core calculations mostly resort to the nodal-diffusion methodology, relying on the homogenization paradigm for the generation of few-group assembly cross-sections. The incapability of cross-sections condensed with the infinite-medium spectrum to model core-environment spectral effects is one of the major limitations in the numerical simulation of current- and next-generation reactor cores, characterized by strongly heterogeneous geometrical layouts. AREVA NP has recently proposed a spectral-correction method to reproduce the variation of the neutron spectrum between environmental and infinite-lattice conditions by means of a modal expansion approach, which is solved for by Galerkin or Petrov-Galerkin projection of the local fine-group neutron balance equation over a set of weighting operators. The accuracy of this method significantly depends on the choice of the basis and test functions. Purely analytical modes turn out to be often inadequate to reproduce the strongly varying shape of the spectrum deformation in the reactor core. The present paper investigates an alternative strategy building upon the Proper Orthogonal Decomposition (POD). This approach relies on the calculation of the optimal (in a least-square sense) orthonormal basis functions for the space spanned by a set of snapshots of the reference spectrum variation. In our work, we test the capability of the POD modes to contain characteristics of the spectral interactions between fuel-assemblies in the reactor core. It is shown that the POD-Galerkin-based spectral rehomogenization can reconstruct very accurately the spectrum in the real environment.

1. INTRODUCTION

Few-group cross-sections used in nodal diffusion codes for 3D reactor core simulations derive from standard energy collapsing and spatial homogenization performed during preliminary lattice transport calculations with reflective boundary conditions [1]. The infinite-medium neutron flux used for cross-section weighting does not account for environmental effects arising in case of heterogeneous core configurations, common examples of which are mixed MOX/UF₄ fuel-loading patterns, reflector boundaries, layouts with depletable strong local absorbers and elaborate insertion schemes of control mechanisms. With these increasingly widespread complex designs reducing the neutron leakage and optimizing the core-power distribution, nodal cross-sections built by the standard homogenization paradigm could fail to reproduce accurate estimates of reaction rates and the multiplication factor. Therefore, core-environment conditions need to be modeled to provide more accurate inputs for nodal solvers.

Environmental effects triggered by core and assembly heterogeneity affect the neutron flux shape in both space and energy. Though spatial and spectral effects are tightly coupled, for sake of simplicity they are usually addressed separately by reactor analysis methods. For example, at AREVA NP a spatial rehomogenization method has been developed [2]. In the present work we focus on spectral aspects. A number of techniques have been proposed in the past to correct single-assembly cross-sections for spectrum effects. One of them applies empirical correlations accounting for local spectral interactions [3]. Recently a spectral rehomogenization method has been developed at AREVA NP [4], as part of a more general cross-section correction model aiming to reproduce environmental effects of various nature [5]. The proposed approach consists of estimating the difference between the environmental and infinite-medium node-average spectra by means of a limited set of known modal components in the domain of energy. The energy-condensation defects are thus evaluated on-the-fly and added to the nodal cross-sections provided by the standard lattice calculation. A similar approach, called recondensation, has been also studied at MIT [6].

A critical point in the definition of a modal expansion method for the spectrum change in the real environment is the choice of a suitable set of basis and test functions. These considerably affect the accuracy of the core-flux energy distribution reconstruction and, hence, of the cross-section update calculation. Modal synthesis methods have been extensively used for reactor physics applications, and several “recipes” can be found in literature for the selection of modes and weighting operators, based on either physical insight as to the nature of the sought solution or purely mathematical considerations [7]. In the original version of the spectral rehomogenization model [4], the basis functions were chosen to be a combination of mathematical functions (Chebyshev polynomials and exponential functions), together with a physically justified mode (fission spectrum). Step functions were instead taken as weighting modes. Their range was defined by a heuristic procedure, attempting to minimize the deviation of the computed real-environment spectrum from the reference one for some benchmark problems. However, the results of this implementation showed that, despite of the use of the reference-leakage energy distribution as input, for certain assembly configurations the prediction of the spectral deformation caused by the