Dual Reference Perturbation Method for Fast Loading Pattern Evaluation

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1. Introduction

As an effort of fast evaluation of fuel assembly (FA) loading patterns (LP) during an LP optimization process, the hybrid harmonics and linearization perturbation (HHLP) method of combining a low order harmonics expansion and local perturbation terms was proposed by Zhang *et al.*[1]. Despite the excellent results obtained from HHLP, there are some drawbacks needing improvements. The major drawback is that the accuracy of HHLP is dependent on the reference LP. If the selected reference LP is unreasonable, the results of HHLP can be trustable even for benign LPs. The other important problem is that the accuracy deteriorates for cores having strongly absorbing fuel assemblies such as MOX fuels. As a way to overcome these drawbacks, we propose a dual reference perturbation (DRP) method that does not require any elaborate reference LP nor low order higher harmonics expansion. The fast LP evaluation model can be eventually used as a screening tool in the case that the full 3-D nodal calculations are to be performed in the LP optimization [2].

2. Methodology

The HHLP method is a method that obtains the reactivity and the core power distribution without performing the core flux calculation. It was tested so far for two-dimensional problems employing the fine mesh finite difference method as the reference case solver. The basic idea of this method is to convert a large eigenvalue problem involving pin flux unknowns into a tiny eigenvalue problem involving the expansion coefficients for the harmonic functions and local perturbation terms. This method is briefly presented below and the proposed DRP is then introduced.

2-1. The HHLP method

In HHLP, the flux vector of an arbitrary LP is represented as a combination of the harmonics modes obtained for a reference state and local perturbation terms which can be predetermined

$$\phi = \sum_{n=1}^{N}\sum_{g=1}^{G} a_{ng}\phi_{ng} + \sum_{k=1}^{K}\sum_{g=1}^{G} a_{k+N,g}\delta\phi_{kg} \qquad (1)$$

where

ϕ_{ng} = the n^{th} harmonic mode of Group g,

$\delta\phi_{kg}$ = flux change in Group g due to a perturbation introduced at location *k*.

The expansion coefficients and the eigenvalue of the perturbed state can be obtained by solving the following eigenvalue problem for the coefficient vector:

$$\mathbf{Aa} = \lambda\mathbf{a} \qquad (2)$$

Since only a few higher harmonics (in fact three) are used and the second term depends the number of perturbations from the reference state, the number of coefficients is in the order of tens and thus the reduced eigenvalue problem of Eq. (2) can be easily solved so that very quick solution is possible. The accuracy of the HHLP method was already proved by Zhang *et al.*[1]. However this method has a big drawback. Such that the errors in reactivity and in power increase largely as the LP becomes worse. However, the performance of this method depends on the choice of the reference LP from which all the harmonic modes and local perturbation terms are generated.

2-2. The DRP method

In order to be independent of the reference LP, the DRP method is now proposed that uses two references to obtain the flux vector at a changed state. Here we introduce doubled local perturbation terms because a state can be considered as two perturbed states which are differently changed from the two reference LPs. Instead, only the fundamental harmonic mode is used. This provides addition merit of avoiding the higher harmonics calculation.

Let ϕ_g^j denote the fundamental harmonic mode flux of Group g of the j^{th} reference LP. $\delta\phi_{kg}^j$ represents the flux change of Group *g* due to a perturbation at location *k* from the j^{th} reference LP. K_j is the number of perturbed sites from the j^{th} reference LP. Then the flux vector of a new LP is expressed as

$$\phi = \sum_{j=1}^{2}\left(\sum_{g=1}^{G} a_g^j\phi_g^j + \sum_{k=1}^{K_j}\sum_{g=1}^{G} a_{k+1,g}^j\delta\phi_{k,g}^j \right). \qquad (3)$$

And the same eigenvalue problem of Eq. (2) is derived with approximately double size. The two reference LP can be easily constructed by merely placing a single fuel type uniformly.

3. Performance Examination

In order to examine the effectiveness of the DRP method, two benchmark reload problems consisting of 3 and 6 fuel types are solved by both HHLP and DLP. The reference LP of the 6-type problem to be used in HHLP is shown in Figure 1.

The dual reference LPs for Problem 1 (3 FA Type core) consist of an LP loaded entirely with FA type 1 and the other loaded with FA type 2. For Problem 2, Types 1 and 6 are used as the dual references.

The problem specification requires that the five peripheral FAs which are in direct contact with the reflector, and one FA at the center should remain fixed at their current positions. For this requirement, the remaining 16 FAs were subject to shuffling under the condition that the number of each type fuel assemblies in the full core is fixed. With the six FAs fixed, there were a total of 195,776 and 31,328,640 possible LPs for Problems 1 and 2, respectively. Among the total possible LPs, 1,958 LPs for Problem 1 and 3,133 LPs for Problem 2 were generated randomly. The generated LPs were analyzed also by a fine mesh finite difference (FMFD) method to get the true solutions so that the accuracy of the HHLP and DRP methods can be assessed. The results are summarized in Table 1 and Figure 2.

In Table 1, it is observed that the accuracy of DRP to predict not only the k_{eff} but also the pin power is considerably better than HHLP for the two problems. For the 1,958 LPs of the 3-batch problem, the absolute k_{eff} and maximum pin power errors predicted by DRP are only 6.4 pcm and 4.5%, respectively. Even the maximum pin power error occurs at a pin whose relative power is only 0.152. Figure 2 also clearly indicates the superiority of DRP over HHLP.

4. Conclusions

The dual reference perturbation (DRP) method was proposed as an improved alternative of the HHLP method. Since it does not involve any elaborately chosen reference LP nor any higher harmonics, it is much more easily applicable as a fast LP evaluation model. Despite of the simplicity of this method, the accuracy in terms of reactivity and power peaking is superior to the HHLP method with the penalty of a slight increase in the computing time due to the use of more terms in the expansion.

Nevertheless, the computing time is still far much smaller than that of the FMFD method. Therefore extremely fast but very accurate LP evaluation is possible with DRP. This method will be expanded to 3D problems with the CMFD spatial solution method as the screening tool of the 3D nodal model based LP optimization.

6	**1**	**5**	**6**	**4**	**5**	**1**
	6	**6**	**5**	**3**	**1**	**4**
		6	**2**	**3**	**1**	
			5	**1**	**4**	
				3		

FA Type	k-inf
1	1.26249
2	1.16563
3	1.17983
4	1.14556
5	1.09277
6	1.06302

Figure 1. Reference LP and k-inf for 6-FA type problem

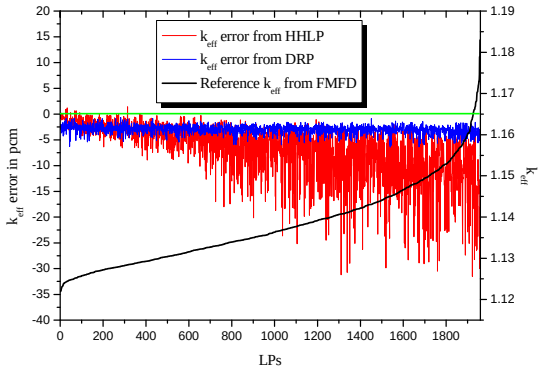

Figure 2. k_{eff} error for the 1,958 LPs of the 3-batch problem

REFERENCES

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[2] T. K. Park, H. C. Lee, H. G. Joo and C. H. Kim, "Multiobjective Loading Pattern Optimization by Simulated Annealing Employing Discontinuous Penalty Function and Screening Technique," *Nuclear Science and Engineering*, **162**, 134-147, 2009.

Table 1. Absolute errors in k_{eff} and pin power obtained from HHLP and DRP for the two core shuffle problem

FA Types/ Method		Per.[a]	Coe.[b]	Absolute Error in k_{eff} [pcm]			Absolute Error in Pin Power (%)								
							Peaking			Max.			RMS		
				Avg.	Std	Max.	Avg.	Std.	Max.	Avg.	Std.	Max.	Avg.	Std	Max
3	HHLP	9.8	25.5	7.0	5.5	31.5	0.6	0.3	1.8	3.6	0.9	7.8	0.9	0.3	2.1
	DRP	28.6	61.2	3.0	0.8	6.4	0.3	0.2	1.1	3.1	0.3	4.5	0.6	0.1	1.0
6	HHLP	11.3	28.6	12.4	5.5	31.7	0.2	0.1	0.6	5.0	1.0	13.1	1.2	0.4	4.0
	DRP	31.8	67.5	2.2	0.9	4.5	0.2	0.1	0.4	3.3	0.4	4.9	0.7	0.1	0.9

a) Average number of total perturbed sites b) Average number of expansion coefficients