노내외 핵계측기를 이용한 실시간 노심출력분포 합성법

On-line Core Axial Power Distribution Synthesis Method
from In-core and Ex-core Neutron Detectors

한국원자력연구소
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제출문

한국원자력연구소장 귀하

본 보고서를 1999 년도 "일체형원자로 노심설계기술개발에 관한 연구" 과제의 노심보호감시계통설계 기술보고서로 제출합니다.

1999. 10.

과제책임자 : 지성균
주저자 : 안응기
공저자 : 조병오
요 약 문

I. 제 목

노새의 핵계측기를 이용한 실시간 노심출력분포 합성법

II. 연구의 목적 및 중요성

이 연구는 원자로 감시 및 보호를 위해 노새 및 노의 핵계측기 신호를 이용하여 실시간으로 노심 출력분포를 합성하는 방법을 기술한 것으로 일체형원자로
노심보호감시계통 출력분포 합성법 결정에 필요한 자료를 제공한다.

III. 연구의 내용 및 범위

Fourier Series 와 Cubic Spline 함수를 이용한 노심 출력분포 합성 방법과 관련 계수 등을 기술하였다. 관련 계수의 생성과 노심 출력분포의 합성을 위하여 전산 프로그램도 작성하였다. 가압경수로인 영광 3호기와 일체형원자로에 대해 모의된 노새의 핵계측기 신호를 이용하여 합성된 노심 출력분포를 기존 출력분포와 비교하였다.

IV. 연구결과 및 활용계획

Fourier Series 합성법과 Cubic Spline 합성법에 대한 수학적 모델을 제시하고 출력분포 합성에 필요한 전산 프로그램을 개발하였다. 일체형원자로 노심보호 감시계통의 실시간 노심 출력분포 합성법의 결정과 정확도 평가에 활용될 것이 다.
SUMMARY

I. Project Title

On-line Core Axial Power Distribution Synthesis Method from In-core and Ex-core Neutron Detectors

II. Objective and Importance of the Project

The objective of this study is to describe a synthesis methodology of the on-line core axial power distribution using in-core/ex-core detector signals for the reactor monitoring and protection. This study also provides an information which is necessary for the decision of the power distribution method in SMART core protection and monitoring systems.

III. Scope and Contents of Project

This report describes the methodology of the core power distribution synthesis using Fourier series and cubic spline function. A computer program was developed to generate the synthesis coefficients and the core power distribution. The core power shapes for PWR plant (YGN 3) and SMART were synthesized using the simulated in-core/ex-core signals and compared with the reference (best estimate) shapes.

IV. Result and Proposal for Applications

This study documents a mathematical model of the Fourier Series method and the cubic spline method, and developed a computer program to construct core power distribution. The results of this study will be useful to select the best synthesis method for the SMART core monitoring and protection systems and to evaluate the accuracy of the synthesized power shape.
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1. Introduction

The designs of the monitoring and protective systems are integrated with the plant technical specifications (in which operating limits and limiting conditions for operation are specified) to assure that all safety requirements are satisfied. The plant monitoring systems, protection systems and technical specifications thus complement each other. Protection systems provide automatic action to place the plant in a safe condition should an abnormal event occur. The technical specifications set forth the allowable regions and modes of operation on plant systems, components and parameters. The monitoring systems (meters, displays, and systems) assist the operation personnel in enforcing the technical specification requirements. Making use of the monitoring systems, protection system and technical specifications in the manner described above will assure that if, (1) the operating personnel maintain all protective systems settings at or within allowable values, (2) the operating personnel maintain actual plant conditions within the appropriate limiting conditions for operation, and (3) equipment other than that causing an abnormal event or degraded by such an event operates as designed, then all anticipated operational occurrences or postulated accidents will result in acceptable consequences.

SCOPS\(^1\) is an on-line digital core protection system for SMART to provide the low DNBR and local power density trips, (1) assure that the specified acceptable fuel design limits on departure from nucleate boiling and centerline fuel melting are not exceeded during Anticipated Operational Occurrences (AOO), and (2) assist the Engineered Safety Features System in limiting the consequences of certain postulated accidents. SCOPS shall meet additional design bases via auxiliary trip functions. SCOPS computes the core average axial power distribution, pseudo hot pin power distribution, and the three dimensional power peak from the ex-core detector signals and target CEA positions.

SCOMS\(^2\) is an on-line digital core protection system for SMART implemented into the Plant Monitoring System (PMS) that aids the operator in maintaining plant operation within selected Limiting Conditions for Operation (LCOs) such as
DNBR margin, linear heat rate margin and axial offset, etc. SCOMS also computes the core average axial power distribution, pseudo hot pin power distribution, and the three dimensional power peak from the in-core detector signals and target CEA positions.

Fourier series expansion or cubic spline synthesis technique is currently used in the on-line calculations of the core axial power distributions from the in-core/ex-core detector signals in COLSS\(^3\) and CPC\(^4\) for the ABB-CE digital PWR plants. A forty node core average axial power distribution is calculated based on in-core detector power signals using a five mode Fourier series expansion. This calculation is performed once every ten seconds in COLSS. The cubic spline synthesis technique is also used in CPC to construct a twenty node core average axial power distribution from the ex-core detector signals once every one second. This document describes the methodology in detail and the synthesis coefficients of the Fourier series expansion and the cubic spline synthesis techniques. For the illustration, various axial power shapes for YGN 3 Cycle 1 and SMART are synthesized using the simulated in-core and/or ex-core detector signals.
2. Synthesis Methodology

2.1 Fourier Series Method

The Fourier series method uses the multiple modes of sine curves with the Fourier-mode amplitude coefficients. The number of Fourier modes is usually equal to the number of axial detectors. The core average axial power distribution is constructed based on the following trigonometric form by utilizing the N-level in-core detector signals.

\[ \phi(z) = \sum_{n=1}^{N} a_n \sin\left( m \frac{z + \delta}{H + 2\delta} \right) \]  \hspace{1cm} (1)

The axial boundary condition ("buckling") is defined as

\[ B = \frac{H}{H + 2\delta} \]  \hspace{1cm} (2)

Then the equation (1) can be written as

\[ \phi(z) = \sum_{n=1}^{N} a_n \sin\left( mB \frac{z + \delta}{H} \right) \]  \hspace{1cm} (3)

The in-core detector signal for j-th level can be expressed as

\[ D_j = \int_{z_j} \phi(z)dz. \]  \hspace{1cm} (4)

Where

- \( \phi(z) \) : Neutron flux at axial location \( z \)
- \( a_n \) : Fourier amplitude coefficients
- \( H \) : Active core height
- \( \delta \) : Extrapolated length where the neutron flux is assumed to be zero
- \( D_j \) : Normalized detector signals at level \( j \).

If the equation (3) is substituted into equation (4), it becomes
\[ D_j = \sum_{i=1}^{N} a_i \int_j \sin \left( \frac{\pi B z}{H} + \delta \right) dz. \]  

(5)

If we let

\[ HC_{ij} = \int_j \sin \left( \frac{\pi B z}{H} + \delta \right) dz \]

then, the equation (5) becomes

\[ D_j = \sum_{i=1}^{N} HC_{ij} a_i. \]  

(7)

Rewrite equation (7) in matrix form,

\[ D = HC A \]  

(8)

The Fourier series coefficients vector \( A \) is then determined as

\[ A = HC^{-1} D. \]  

(9)

Therefore, the axial power distribution can be obtained from the equation (1) by forming the product of the Fourier series matrix \( SPLIN \) and the Fourier series coefficients vector \( A \), i.e.,

\[ APD = SPLIN A. \]  

(10)

Where

\( APD \) : Vector of node axial powers

\( SPLIN \) : Fourier series matrix

The above two matrices \( HC^{-1} \) and \( SPLIN \) are determined based on the active core height \( H \), the axial locations of the detectors and the constant axial buckling \( B \). The optimal value of \( B \) is determined to result in the best fit of the core axial power.
distribution a priori.

2.2 Cubic Spline Method

The cubic spline synthesis assumes the core axial power distribution to be sum of splines as shown in Fig. 2.1, i.e.,

\[ \phi(z) = \sum a_i \mu_i(z). \quad (11) \]

Where

- \( \phi(z) \): Neutron flux at axial location \( z \)
- \( a_i \): Amplitude coefficients
- \( \mu_i(z) \): Cubic spline basis function

The various axial power distributions are classified depending on the characteristics, i.e., center peak, top and bottom peak, flat or saddle type. Appropriate number of nodes for each interval in Fig. 2.1 is then assigned based on the categorized axial power shapes. The break points between splines are chosen based on relative detector signals. The effect of moving the break points (node assignment) is shown in Fig. 2.2. Each spline is a piecewise cubic polynomials in Fig. 2.3. The cubic spline basis functions are defined as follows.

\[
\begin{align*}
\mu_i(z) &= f_1(z_i^1) & \text{for} & & z_{i-2} \leq z \leq z_{i-1} \\
\mu_i(z) &= f_2(z_i^2) & \text{for} & & z_{i-1} \leq z \leq z_i \\
\mu_i(z) &= f_2(z_i^3) & \text{for} & & z_i \leq z \leq z_{i+1} \\
\mu_i(z) &= f_1(z_i^4) & \text{for} & & z_{i+1} \leq z \leq z_{i+2} \\
\mu_i(z) &= 0 & \text{for} & & z < z_{i-2} \text{ or } z > z_{i+2}
\end{align*}
\]
Where

\[ \eta_1 = \frac{Z - Z_{i-2}}{Z_{i-1} - Z_{i-2}}, \quad \eta_2 = \frac{Z - Z_{i-1}}{Z_{i-1} - Z_{i}}, \quad \eta_3 = \frac{Z_{i+1} - Z}{Z_{i+1} - Z_i}, \quad \eta_4 = \frac{Z_{i+2} - Z}{Z_{i+2} - Z_{i+1}} \]

and

\[ f_1(\eta) = \eta^3/4 \]
\[ f_2(\eta) = \frac{1}{4} + \frac{3}{3} (\eta + \eta^2 - \eta^3). \]

The amplitude coefficients are found to satisfy the following conditions.

1) Detector responses

\[ D_i = \int \phi(z) dz \quad i = 1, 2, \ldots, N \] (12)

where \( N \) : Number of detector level

2) Empirical boundary point powers

\[ \phi(0) = a_1 D_N + a_2 \] (13)
\[ \phi(H) = a_3 D_1 + a_4 \] (14)

3) Extrapolated boundary conditions

\[ \phi(-\delta) = 0.0 \] (15)
\[ \phi(H + \delta) = 0.0 \] (16)

Where

\( a_{1-4} \) : Empirically correlated coefficients for boundary point powers
\( \delta \) : Extrapolated length
For a three level detector system, the equation (12) through the equation (16) can be expanded as follows by using the equation (11).

\[ D_1 = a_1 h_{11} + a_2 h_{12} + a_3 h_{13} + a_4 h_{14} + a_5 h_{15} + a_6 \cdot 0 + a_7 \cdot 0 \]

\[ D_2 = a_1 \cdot 0 + a_2 h_{22} + a_3 h_{23} + a_4 h_{24} + a_5 h_{25} + a_6 h_{26} + a_7 \cdot 0 \]

\[ D_3 = a_1 \cdot 0 + a_2 \cdot 0 + a_3 h_{33} + a_4 h_{34} + a_5 h_{35} + a_6 h_{36} + a_7 h_{37} \]

\[ \phi(0) = a_1 h_{41} + a_2 h_{42} + a_3 h_{43} \]

\[ \phi(H) = 0 \quad 0 \quad 0 \quad 0 \quad a_5 h_{55} + a_6 h_{56} + a_7 h_{57} \]

\[ 0 = a_1 h_{61} + a_2 h_{62} \]

\[ 0 = 0 \quad 0 \quad 0 \quad 0 \quad a_6 h_{76} + a_7 h_{77} \]

The above expanded equation can be rewritten in matrix form as

\[ H A = B. \] (17)

The amplitude coefficients vector \( A \) is then obtained as

\[ A = H^{-1} B. \] (18)

Where

\[ H^{-1} : \text{Spline matrix depending on the spline nodal assignment} \]

\[ B : \text{Vector of detector responses and boundary point powers} \]

Finally, the core axial power distribution can be computed by the equation (11) using the amplitude coefficients vector and the cubic spline basis function.
Fig. 2.1 Schematic of cubic spline synthesis (for 3-level detector system)

For interval A: $\phi(z) = \sum a_{ij}(z)$, $i=1,4$

Fig. 2.2 Effect of moving break points on axial power shape synthesis
Fig. 2.3 Cubic spline basis function
3. Synthesis Coefficients

3.1 Fourier Series

The core axial power distribution synthesis by the Fourier series expansion method requires an information of the Fourier series matrix $\text{SPLIN}$ and the matrix $\text{HC}$ as described in section 2. The axial power distribution can be rewritten as follows.

$$APD(k) = A(i) \cdot \text{SPLIN}(i,k)$$  \hspace{1cm} (19)

Here, the index $i$ is the Fourier series mode number ($i=1, 2, \ldots, N$) and the index $k$ is the number of axial nodes. The Fourier series matrix $\text{SPLIN}$, it can be written as

$$\text{SPLIN}(i,k) = \sin\left(i\pi\cdot\frac{z_k + \delta}{H + 2\delta}\right)$$  \hspace{1cm} (20)

and the $\text{HC}$ matrix are expressed as the equation (6).

Therefore the two matrices can be determined based on the active core height $H$, the axial locations of the detectors and the constant axial buckling $B$. The optimal value of $B$ is determined to result in the best fit of the core axial power distribution $a\ priori$. Appendix A shows a subroutine to determine $\text{SPLIN}$ and $\text{HC}^{-1}$.

The resultant values of $\text{SPLIN}$ and $\text{HC}^{-1}$ for the five uniformly located detectors ($N=5$), the active core height of 2 m and the axial buckling of 0.9 are shown in Tables 3.1 and 3.2, respectively.
3.2 Cubic Spline

The cubic spline method needs to determine the boundary point power correlation coefficients \( a_1 \) and the spline matrix \( \mathbf{H}^{-1} \) \textit{a priori}. The boundary point power correlation coefficients are empirically determined from the axial power distribution and the detector signals. The spline matrix is then determined depending on the spline nodal assignments in each spline zone. An appropriate number of axial nodes should be assigned in each spline zone of the active core depending on the characteristics of the axial power distribution. In other words, the various axial power distributions are classified depending on the characteristics, i.e., center peak, top and bottom peak, flat or saddle type. Appropriate number of nodes for each interval in Fig. 2.1 is then assigned based on the categorized axial power shapes. The break points between splines are chosen based on relative detector signals such as the middle detector power integral or the magnitude of the top to bottom difference in power integrals. Hence, there is a procedure that is judged to lead to a set of spline functions that will provide the optimum power synthesis.

Spline Function Set Selection for 3-Level Detector System

As was described in section 2, there are three break points for spline functions that are selected based on the relative values of the third core integrals. The number of axial nodes in each of the four regions (Intervals A, B, C, D in Fig. 2.1) is a convenient way to describe a function set. Thus 2 8 7 3 describes a function set where there are two nodes in interval A, eight nodes in interval B, seven nodes in interval C, and three nodes in interval D. It is also noted that the sum of the number of the axial nodes in a function set must be equal to the total number of axial nodes. Selection of the break points and the function sets is largely based on engineering judgement. The following describes a procedure to select optimum function sets for the twenty-node power shape synthesis in CPC\(^4\).

1) Limiting the Function Sets
There are a total of about 200 possible function set that meet the constraints of at least two nodes per axial region, at most eight nodes per axial region, and no more than one break point in either the top or bottom third core. This was too many to consider fully so a set of representative 24 axial shapes was chosen to reduce the number of function sets. The axial shape index (ASI) ranged from -0.37 to +0.57. For each of these 24 axial shapes, a full set of 200 function sets were used to synthesize an axial shape, compare the synthesized shape to the actual best estimate shape, and order the function sets based on a RMS error. Interactive examination of these results indicated a set of thirteen function set suitable for further consideration. These were 2 8 8 2, 3 7 7 3, 4 6 6 5, 2 8 6 4, 4 6 8 2, 2 8 7 3, 3 7 8 2, 2 8 3 7, 7 3 8 2, 2 7 8 3, 3 8 7 2, 2 6 8 4, and 4 6 8 2. Of these, 2 8 8 2 was most often the best and further note that all thirteen function sets have one break point near the mid plane with the remaining two break points well out towards the edges.

2) Function Set Evaluation

A full set of 1200 case of best estimate axial power shapes at three times of cycle (TOC) (typical uncertainty analysis case structure) was used to evaluate the thirteen function sets for the final selection. For each of the 3600 cases, all thirteen function sets were used to synthesize power shape and the function sets were ordered for each case by the RMS error. The cases were reordered at each TOC first by middle index (M.I.=Integer(Mid Detector Signal/2)+1) and then increasing asymmetry index (A.S.={(Top Det. Signal – Bottom Det. Signal)/2}). The results were reviewed to determine patterns in which of the function sets were providing the best RMS error for varying condition of the two sorting parameters.

The center peaked selection parameter should cause a break at M.I.=21. The function sets that give the best response for center peaked shapes are 2 8 8 2 for symmetric shapes and 2 8 7 3/3 7 8 2 for asymmetric shapes. In the range 13 ≤ M.I. ≤ 17, 2 8 8 2 is best and for the very small M.I., 2 7 8 3/3 8 7 2 and 2 8 7 3/3 7 8 2 pairs tend to be slightly better. For very large A.S. (> 50%), there are occasional cases where 2 8 6 4/4 6 8 2 is slightly better than 2 8 8 2. Hence, all
saddle shape (M.I. < 18) should use $2 8 8 2$ function set. The function sets $2 8 8 2$, $2 8 3 7/7 3 8 2$ are appropriate for the range $18 \leq M.I. \leq 21$ (Flat-type shape). The final function sets selected are summarized in Table 3.3 and illustrated in Fig. 3.1.

**Spline Function Set Selection for 5-Level Detector System**

The synthesis uses two more spline functions than the 3-level detector system. There are six(6) spline zones (five break points) in the active core and nine(9) spline functions. The ideal selection process would take all possible function sets and all the axial shapes used in the uncertainty analysis and evaluate the goodness of the resultant syntheses to select the best sets of functions. However, since there are too many combinations of the possible function sets (number of order dependent arrangements of six numbers that sum to total number of axial nodes) and axial shapes, a process to reduce the volume of data is required. The following describes the procedure to select optimum function sets for the forty-node power shape synthesis in COLSS$^{[3]}$.

1) Preliminary Function Sets

About 1250 function sets were selected based on the following ground rules: (a) The sum of the nodes in the six axial regions must equal to the total number of axial nodes, 40 in this case. (b) The first and last regions axially use a single node. This is based on preliminary calculations which showed that the presence of single node region gave significant improvement to the overall shape. (c) The four interior regions each contain an odd number of nodes less than 17 because the use of mixed odd and even numbers of node appeared to give no appreciable benefits. Using these preliminary function sets, a set of 20 representative B.E. axial power shapes were synthesized and the RMS power shape errors were examined. 28 function sets were selected that gave the smallest RMS errors for at least some of TOC.

2) Reduction of Function Sets
The full set of axial power shapes used in the uncertainty analysis (typically 1200 cases at each of three TOC) were used for comparison of the B.E. shapes and the synthesized shapes based on the preliminary 28 function sets. The results are sorted into counts of the number of power shapes that are well represented with a particular function set for each of approximately 40 gross power distribution classes. This stage produced a small number of function sets that held the most promise for use in the final evaluation.

3) Evaluation of Thermal Margin Impact

The reduced number of function sets was used to determine the impact of the synthesis method on the actual uncertainty calculations and on the base case thermal margin. Trial and error adjustments were needed to optimize the function sets to minimize the DNB uncertainty factor and to maximize the base case DNB margin.

The final spline function sets for five-level detector system and forty-node axial shape synthesis in PWR are 1 11 11 11 5 1 and 1 9 11 9 9 1. A similar procedure should be used to determine the optimum spline function sets for either three-level detector system or five-level detector system for SMART.

Appendix B shows a subroutine to determine the spline matrix $H^{-1}$ with the number of detector level, the active core height, the detector length and the spline function set. Table 3.4 shows the three different spline matrices with the function sets 2 8 8 2, 2 8 7 3, and 2 8 3 7 for the three-level detector system. Table 3.5 shows the two different spline matrices with the function sets 1 11 11 11 5 1 and 1 9 11 9 9 1 for the five-level detector system.
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<td>0.994384</td>
<td>0.210472</td>
</tr>
<tr>
<td>0.48750</td>
<td>0.999367</td>
<td>0.070627</td>
</tr>
<tr>
<td>0.51250</td>
<td>0.999367</td>
<td>-0.070627</td>
</tr>
<tr>
<td>0.53750</td>
<td>0.994384</td>
<td>-0.210472</td>
</tr>
<tr>
<td>0.56250</td>
<td>0.984427</td>
<td>-0.346117</td>
</tr>
<tr>
<td>0.58750</td>
<td>0.965652</td>
<td>-0.474856</td>
</tr>
<tr>
<td>0.61250</td>
<td>0.949636</td>
<td>-0.594121</td>
</tr>
<tr>
<td>0.63750</td>
<td>0.925375</td>
<td>-0.701531</td>
</tr>
<tr>
<td>0.66250</td>
<td>0.896293</td>
<td>-0.794944</td>
</tr>
<tr>
<td>0.68750</td>
<td>0.862734</td>
<td>-0.872496</td>
</tr>
<tr>
<td>0.71250</td>
<td>0.824867</td>
<td>-0.932639</td>
</tr>
<tr>
<td>0.73750</td>
<td>0.782880</td>
<td>-0.974173</td>
</tr>
<tr>
<td>0.76250</td>
<td>0.736983</td>
<td>-0.996270</td>
</tr>
<tr>
<td>0.78750</td>
<td>0.687404</td>
<td>-0.998489</td>
</tr>
<tr>
<td>0.81250</td>
<td>0.634393</td>
<td>-0.980785</td>
</tr>
<tr>
<td>0.83750</td>
<td>0.578214</td>
<td>-0.943512</td>
</tr>
<tr>
<td>0.86250</td>
<td>0.519146</td>
<td>-0.887414</td>
</tr>
<tr>
<td>0.88750</td>
<td>0.457486</td>
<td>-0.813608</td>
</tr>
<tr>
<td>0.91250</td>
<td>0.393541</td>
<td>-0.723570</td>
</tr>
<tr>
<td>0.93750</td>
<td>0.327630</td>
<td>-0.619094</td>
</tr>
<tr>
<td>0.96250</td>
<td>0.260083</td>
<td>-0.502266</td>
</tr>
<tr>
<td>0.98750</td>
<td>0.191237</td>
<td>-0.375416</td>
</tr>
</tbody>
</table>

Table 3.1 SPLIN Values for the Forty-Node Fourier Synthesis
(N = 5, H = 2 m, B = 0.9)
Table 3.2 \( H^{-1} \) Values for the Fourier Series Synthesis  
\((N=5, H=2 \text{ m}, B=0.9)\)

<table>
<thead>
<tr>
<th>(H^{-1})</th>
<th>(2^1)</th>
<th>(3^1)</th>
<th>(4^1)</th>
<th>(5^1)</th>
<th>(1^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.440821</td>
<td>2.633662</td>
<td>3.217986</td>
<td>3.220636</td>
<td>1.835422</td>
<td></td>
</tr>
<tr>
<td>3.101771</td>
<td>3.357519</td>
<td>0.686902</td>
<td>-2.742560</td>
<td>-2.639318</td>
<td></td>
</tr>
<tr>
<td>3.568619</td>
<td>0.000000</td>
<td>-3.900244</td>
<td>0.000000</td>
<td>2.893329</td>
<td></td>
</tr>
<tr>
<td>3.101770</td>
<td>-3.357519</td>
<td>0.686902</td>
<td>2.742559</td>
<td>-2.639317</td>
<td></td>
</tr>
<tr>
<td>1.440822</td>
<td>-2.633664</td>
<td>3.217987</td>
<td>-3.220636</td>
<td>1.835423</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.3 Summary of Spline Function Sets for 3-Level Detector System

<table>
<thead>
<tr>
<th>Middle Index (M.I.)</th>
<th>Asymmetry Index (A.S.)</th>
<th>Axial Shape Pattern</th>
<th>Best Function Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>M.I. (\geq) 21</td>
<td>A.S. &lt; 12 %</td>
<td>Symm. Center Peak</td>
<td>2 8 8 2</td>
</tr>
<tr>
<td></td>
<td>A.S. (\geq) 12 %</td>
<td>Asymm. Center Peak</td>
<td>2 8 7 3/3 7 8 2</td>
</tr>
<tr>
<td>M.I. &lt; 18</td>
<td>Arbitrary</td>
<td>All Saddle Types</td>
<td>2 8 8 2</td>
</tr>
<tr>
<td>18 (\leq) M.I. &lt; 21</td>
<td>A.S. = 20-30 %</td>
<td>Mildly Asymm. Flat</td>
<td>2 8 8 2</td>
</tr>
<tr>
<td></td>
<td>A.S. = 35-40 %</td>
<td>Significantly Asymm. Flat</td>
<td>2 8 3 7/7 3 8 2</td>
</tr>
</tbody>
</table>
Table 3.4  $H^1$ Values for the Twenty-node Cubic Spline Synthesis  
(3-Level Detector System)

**Spline Function Set #1 : 2882**

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11951E+01</td>
<td>-0.13224E-01</td>
<td>0.63656E-02</td>
<td>-0.22855E-02</td>
<td>0.21779E-01</td>
</tr>
<tr>
<td>-0.48173E+00</td>
<td>0.49589E-01</td>
<td>-0.23871E-01</td>
<td>0.85708E-02</td>
<td>-0.81672E-01</td>
</tr>
<tr>
<td>0.16990E+00</td>
<td>-0.17808E-01</td>
<td>0.46989E-01</td>
<td>-0.17808E-01</td>
<td>0.16990E+00</td>
</tr>
<tr>
<td>-0.81672E-01</td>
<td>0.85708E-02</td>
<td>-0.23871E-01</td>
<td>0.49589E-01</td>
<td>-0.48173E+00</td>
</tr>
<tr>
<td>0.21779E-01</td>
<td>-0.22855E-02</td>
<td>0.63656E-02</td>
<td>-0.13224E-01</td>
<td>0.11951E+01</td>
</tr>
</tbody>
</table>

**Spline Function Set #2 : 2873**

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11944E+01</td>
<td>-0.13147E-01</td>
<td>0.62619E-02</td>
<td>-0.24966E-02</td>
<td>0.31613E-01</td>
</tr>
<tr>
<td>-0.47863E+00</td>
<td>0.49300E-01</td>
<td>-0.23482E-01</td>
<td>0.93622E-02</td>
<td>-0.11855E+00</td>
</tr>
<tr>
<td>0.16411E+00</td>
<td>-0.17207E-01</td>
<td>0.46129E-01</td>
<td>-0.19377E-01</td>
<td>0.24566E-00</td>
</tr>
<tr>
<td>-0.66004E-01</td>
<td>0.69269E-02</td>
<td>-0.19336E-01</td>
<td>0.50890E-01</td>
<td>-0.65739E-00</td>
</tr>
<tr>
<td>0.17601E-01</td>
<td>-0.18472E-02</td>
<td>0.51562E-02</td>
<td>-0.13571E-01</td>
<td>0.12420E+01</td>
</tr>
</tbody>
</table>

**Spline Function Set #3 : 2837**

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11932E+01</td>
<td>-0.13032E-01</td>
<td>0.66954E-02</td>
<td>-0.54627E-02</td>
<td>0.12453E+00</td>
</tr>
<tr>
<td>-0.47460E+00</td>
<td>0.48869E-01</td>
<td>-0.25108E-01</td>
<td>0.20485E-01</td>
<td>-0.46698E+00</td>
</tr>
<tr>
<td>0.15455E+00</td>
<td>-0.16251E-01</td>
<td>0.48974E-01</td>
<td>-0.41366E-01</td>
<td>0.94553E+00</td>
</tr>
<tr>
<td>-0.17121E-01</td>
<td>0.18002E-02</td>
<td>-0.54251E-02</td>
<td>0.66135E-01</td>
<td>-0.16193E+01</td>
</tr>
<tr>
<td>0.45655E-02</td>
<td>-0.48004E-03</td>
<td>0.14467E-02</td>
<td>-0.17636E-01</td>
<td>0.14985E+01</td>
</tr>
</tbody>
</table>
Table 3.5 $H^1$ Values for the Forty-node Cubic Spline Synthesis
(5-Level Detector System)

<table>
<thead>
<tr>
<th>Spline Function Set #1 : 1 11 11 11 1 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11073E+01</td>
</tr>
<tr>
<td>-0.15251E+00</td>
</tr>
<tr>
<td>0.47084E-01</td>
</tr>
<tr>
<td>-0.28350E-01</td>
</tr>
<tr>
<td>0.30100E-01</td>
</tr>
<tr>
<td>-0.34926E-01</td>
</tr>
<tr>
<td>0.93136E-02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spline Function Set #2 : 1 9 1 1 9 9 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10689E+01</td>
</tr>
<tr>
<td>-0.12079E+00</td>
</tr>
<tr>
<td>0.23933E-01</td>
</tr>
<tr>
<td>-0.81324E-02</td>
</tr>
<tr>
<td>0.42873E-02</td>
</tr>
<tr>
<td>-0.27030E-02</td>
</tr>
<tr>
<td>0.72261E-03</td>
</tr>
</tbody>
</table>
Fig. 3.1 Selection of Spline Function Sets for 3-Level Detector System (CPC)
4. Synthesis Results

4.1 PWR(YGN 3)

The nominal core axial power shapes at three burnup points (BOC, MOC, EOC) of YGN 3 cycle 1 were chosen to demonstrate the power shape synthesis techniques. The best estimate shapes and the corresponding in-core/ex-core signals were simulated by a neutronics design code. The Fourier series technique constructs axial power shape using the 5-level in-core signals and the synthesis coefficients matrices in Tables 3.1 and 3.2. The cubic spline technique generates axial power shape using the 3-level ex-core signals and the coefficient matrix for the spline function sets in Table 3.4. The cubic spline technique also generates axial power shape using the 5-level in-core signals and the coefficient matrix for the spline function sets in Table 3.5.

Fig. 4.1 shows the comparison of the BOC axial power shape (center-peak). The synthesized power shapes agrees well with the best estimate shape. The comparison of the MOC axial power shape in Fig. 4.2 shows an excellent agreement between the Fourier/cubic spline(ex-core) shapes and the best estimate shape. However, the cubic spline shape(in-core) using the in-core signals shows a large difference near the top peak. This means that current spline function sets (and the criteria for the axial power shape classification based on the in-core signals) are not good for the deep saddle-type shape and therefore an additional function set should be considered to reduce the difference. The flat-type EOC axial shapes are compared in Fig. 4.3. Similar to the saddle-type shape in Fig. 4.2, the agreement between the Fourier/cubic spline(ex-core) shapes and the best estimate shape is satisfactory but the cubic spline shape(in-core) shows somewhat large difference with the best estimate shape.

The spline function sets with the 5-level in-core system were modified to improve the accuracy of the synthesized axial power shape for the deep saddle-type shape and the flat-type shape. Various function sets were examined and finally found new function sets 3 5 13 11 5 3 for the saddle-type shape and 3 7 11 9 7 3 for
the flat-type shape. Fig. 4.4 shows the comparison of the deep saddle-type axial power shapes using the new function set. Unlike the poor agreement in Fig. 4.2, it clearly shows an excellent agreement of the power shape by the cubic spline method and the best shape. The comparison of the flat-type shape in Fig. 4.5 also shows the improvement in the accuracy of the axial shape synthesis by the cubic spline method based on the new spline function set. It should be therefore noted that the selection of spline coefficients specific to a particular set of axial power shapes is the key point to improve the accuracy of synthesizing the axial power shapes by the cubic spline technique.

4.2 SMART

The core average axial power shapes at four burnup points (0, 300, 600 and 990 EFPD) of SMART were synthesized by the cubic spline method and the Fourier series method. The simulated neutron flux powers at 5-level in-core locations were used in this synthesis. Fig. 4.6 through Fig. 4.9 respectively show the comparisons of the best estimate power shape and the fitted power shapes at four different burnups. Both the cubic spline method and the Fourier series method constructed the core axial power shapes well agreeing with the best estimate power shape. This analysis used the synthesis coefficients in Table 3.1 and Table 3.2 for the Fourier series method and in Table 3.5 for the cubic spline method.
Fig. 4.1  Comparison of center-peak axial power shape (YGN 3 BOC1)

Fig. 4.2  Comparison of saddle-type axial power shape (YGN 3 MOC1)
Fig. 4.3 Comparison of flat-type axial power shape (YGN 3 EOC1)

Fig. 4.4 Comparison of saddle-type axial power shape using new spline function set (3 5 13 11 5 3)
Fig. 4.5 Comparison of flat-type axial power shape using new spline function set (3 7 1 1 9 7 3)

Fig. 4.6 Comparison of SMART core axial power shape at 0 EFPD
Fig. 4.7 Comparison of SMART core axial power shape at 300 EFPD

Fig. 4.8 Comparison of SMART core axial power shape at 600 EFPD
Fig. 4.9 Comparison of SMART core axial power shape at 990 EFPD
5. References


Appendix A: Source Listing of a Subroutine to Determine the Fourier Synthesis Coefficients Matrices SPLIN and HC⁻¹

SUBROUTINE MATGEN(BUCKL,SPLIN,H)

C---------------------------------------------------------------C
C THIS IS A SUBROUTINE TO COMPUTE SPLIN AND H MATRICES FOR USE IN FOURIER SYNTHESIS BASED ON INPUT BUCKLING
C---------------------------------------------------------------C

REAL*8 DETM
REAL*8 TT(5,5)
REAL*8 X

DIMENSION SPLIN(5,40),H(5,5),T(5,5),LW(5),MW(5)
1 ,DTOP(5),DBOT(5)

INCORE DETECTOR SPAN (IN FRACTION OF CORE HEIGHT.)
ASSUMES THE 1/5 CORE HEIGHT SECTIONS

DATA (DTOP(I),I=1,5) / .15,.35,.55,.75,.95 /
DATA (DBOT(I),I=1,5) / .05,.25,.45,.65,.85 /

HEIGHT=200,
EPSLN = 1.0E-8
NODES = 40
LSTOP = 0
PI = 3.141592654

EXTRP = HEIGHT * (1 - BUCKL)/(2.*BUCKL)
OFFST = EXTRP/HEIGHT
WAVE = PI * BUCKL

WRITE(6,100)BUCKL,EXTRP,OFFST
100 FORMAT(5X,'------ SPLINE & HC GENERATION BY SPLNGEN ------'
1 /5X,'BUCKLING = ',F10.6@i,'EXT. DISTANCE = ',F10.6
2 /5X,'OFFSET' = ',F10.6'/5X,'J',8X,'z ',10X
3 ',SPLIN(1-5,Z))'

GENERATE THE SPLIN ARRAY

DO 120 J=1,NODES

Z = (FLOAT(J) - 0.5)/FLOAT(NODES)

DO 110 I= 1,5

110 CONTINUE

120 CONTINUE

33
SPLIN(I,J) = SIN(FLOAT(I)*WAVE*(Z+OFFST))

110 CONTINUE

WRITE(6,115) J,Z,(SPLIN(I,J),I=1,5)
115 FORMAT(4X,I2,2X,F10.5,2X,5(3X,F10.6))

120 CONTINUE

DO 140 J=1,5
  DO 130 I=1,5
    CALCULATE THE PRE-H MATRIX
    SIGN CHANGE FROM DEFINITIONS TESTED OK
    A = FLOAT(I)*WAVE
    T(I,J) = (-COS(A*(DTOP(J)+OFFST))+COS(A*(DBOT(J)+OFFST)))/A
    TT(I,J) = DBLE(T(I,J))
  130 CONTINUE
  140 CONTINUE

CALL MINV(TT,5,DETM,LW,MW)

IF(DABS(DETM).GE.DBLE(EPSLN)) GO TO 160

WRITE(6,150) DETM
150 FORMAT(/5X,'SPLNGEN ERROR - DETERMINANT TOO SMALL ('J312.4,')')

LSTOP = 1

INVFLG = 0

NORMALIZATION

HNORM=0.

DO 190 I = 1,5
  HNORM=HNORM + 2.*(DTOP(I) - DBOT(I))
  DO 180 J = 1,5
    X = 0.0
    DO 170 K = 1,5
      X = X + DBLE(T(I,K))*TT(K,J)
    170 CONTINUE
  180 CONTINUE
  190 CONTINUE
IF(LEQ(J) X = X - 1.0
IF(DABS(X).GT.DBLE(EPSLN)) INVFLG = INVFLG + 1
C
180 CONTINUE
190 CONTINUE
C
IF(INVFLG.EQ.0) GO TO 220
C
LSTOP = 1
WRITE(6,200) INVFLG
200 FORMAT(//'SPLGEN ERROR - ',I3,' FAILURE OF INVERSE MATRIX CHECK')
GO TO 250
C
220 WRITE(6,230)
230 FORMAT(//7X,'INVERSE MATRIX VERIFIED')
C
250 IF(LSTOP.EQ.1) STOP '- SPLNGEN ABORTED: SPLNGEN ERROR'
C
DO 270 J = 1,5
DO 260 I = 1,5
C
H(I,J) = REAL(TT(J,I))*HNORM
C
260 CONTINUE
270 CONTINUE
C
WRITE(6,300) HNORM,((H(I,J),I=1,5)
1 ,J=1,5)
300 FORMAT(/~,'HNORM = ',F10.4
1 J/5X,'wErS E H(I,J) MATRIx',5v5X,5F15.6)
C
RETURN
END
SUBROUTINE MINV(A,N,D,L,M)
C
PURPOSE
INVERT A MATRIX
C
USAGE
CALL MINV(A,N,D,L,M)
C
DESCRIPTION OF PARAMETERS
A - INPUT MATRIX, DESTROYED IN COMPUTATION AND REPLACED
BY
RESULTANT INVERSE.
N - ORDER OF MATRIX A
D - RESULTANT DETERMINANT
L - WORK VECTOR OF LENGTH N
M - WORK VECTOR OF LENGTH N

REMARKS
MATRIX A MUST BE A GENERAL MATRIX

SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
NONE

METHOD
THE STANDARD GAUSS-JORDAN METHOD IS USED. THE
DETERMINANT IS ALSO CALCULATED. A DETERMINANT OF ZERO
INDICATES THAT THE MATRIX IS SINGULAR.

DIMENSION A(10000),L(10000),M(10000)
DIMENSION A(*),L(*),M(*)

IF A DOUBLE PRECISION VERSION OF THIS ROUTINE IS DESIRED, THE
C IN COLUMN 1 SHOULD BE REMOVED FROM THE DOUBLE PRECISION
STATEMENT WHICH Follows.

DOUBLE PRECISION AD,BIGA,HOLD

THE C MUST ALSO BE REMOVED FROM DOUBLE PRECISION
STATEMENTS APPEARING IN OTHER ROUTINES USED IN CONJUNCTION
WITH THIS ROUTINE.

THE DOUBLE PRECISION VERSION OF THIS SUBROUTINE MUST ALSO
CONTAIN DOUBLE PRECISION FORTRAN FUNCTIONS. ABS IN
STATEMENT 10 MUST BE CHANGED TO DABS.

SEARCH FOR LARGEST ELEMENT

D=1.0
NK=-N
DO 80 K=1,N
NK=NK+N
L(K)=K
M(K)=K
KK=NK+K
BIGA=A(KK)
DO 20 J=K,N
IZ=N*(J-1)
DO 20 I=IZ,I
IJ=IZ+I
10 IF(DABS(BIGA)-DABS(A(IJ))) 15,20,20
15 BIGA=A(IJ)
L(K)=I
M(K)=J
20 CONTINUE
INTERCHANGE ROWS

J=L(K)
IF(J-K) 35,35,25

KI=K-N
DO 30 I=1,N
KI=KI+N
HOLD=-A(KI)
JI=KI-K+J
A(KI)=A(JI)
30 A(JI)=HOLD

INTERCHANGE COLUMNS

35 I=M(K)
IF(I-K) 45,45,38

JP=N*(I-1)
DO 40 J=1,N
JK=NK+J
JI=JP+J
HOLD=-A(JK)
A(JK)=A(JI)
40 A(JI)=HOLD

DIVIDE COLUMN BY MINUS PIVOT (VALUE OF PIVOT ELEMENT IS CONTAINED IN BIGA)

45 IF(BIGA) 48,46,48
46 D=0.0

STOP

48 DO 55 I=1,N
IF(I-K) 50,55,50
50 IK=NK+I
A(IK)=A(IK)/(-BIGA)
55 CONTINUE

REDUCE MATRIX

DO 65 I=1,N
IK=NK+I
HOLD=A(IK)
IJ=I-N
DO 65 J=1,N
IJ=IJ+N
IF(I-K) 60,65,60
60 IF(J-K) 62,65,62
62 KJ=IJ-I+K
A(IJ)=HOLD*A(KJ)+A(IJ)
65 CONTINUE
C
C DIVIDE ROW BY PIVOT
C
KJ=K-N
DO 75 J=1,N
KJ=KJ+N
IF(J<K) 70,75,70
70 A(KJ)=A(KJ)/BIGA
75 CONTINUE
C
C PRODUCT OF PIVOTS
C
D=D*BIGA
C
C REPLACE PIVOT BY RECIPROCAL
C
A(KK)=1.0/BIGA
C
80 CONTINUE
C
C FINAL ROW AND COLUMN INTERCHANGE
C
K=N
100 K=(K-1)
   IF(K) 150,150,105
105 I=L(K)
   IF(I<K) 120,120,108
108 JQ=N*(K-1)
   JR=N*(I-1)
   DO 110 J=1,N
      JK=JQ+J
      HOLD=A(JK)
      JI=JR+J
      A(JK)=A(JI)
110 A(JI)=HOLD
120 J=M(K)
   IF(J<K) 100,100,125
125 KI=K-N
   DO 130 I=1,N
      KI=KI+N
      HOLD=A(KI)
      JI=KI-K+J
      A(KI)=A(JI)
130 A(JI)=HOLD
   GO TO 100
C
150 RETURN
END
Appendix B: Source Listing of a Subroutine to Determine the Cubic Spline Synthesis Matrix $H^{-1}$

SUBROUTINE SPLNGEN(NT,NODE,HINV)

C

C THIS SUBROUTINE COMPUTES THE INVERSE SPLINE MATRIX ($H^{-1}$) FOR
C USE IN CUBIC SPLINE AXIAL POWER SHAPE SYNTHESIS
C

C VARIABLE DESCRIPTION:
C
C N = NUMBER OF CORE SPLINE ZONES
C NT = TOTAL NUMBER OF AXIAL NODES IN ACTIVE CORE
C (ASSUMPTION: NODE LENGTH IS CONSTANT.)
C NODE(I) = NUMBER OF NODES IN I'TH ZONE OF ACTIVE CORE
C COREH = ACTIVE CORE LENGTH
C DTCTH = DETECTOR LENGTH
C ZNOD(I) = START POSITION OF ZONE I
C ZDS(I) = START POSITION OF I'TH DETECTOR
C ZDE(I) = END POSITION OF I'TH DETECTOR
C NM = SIZE OF ORIGINAL SPLINE COEFFICIENT MATRIX : $H$
C NA = SIZE OF REDUCED $H$ MATRIX
C

COMMON /GEOVAR/COREH,DTCTH,NS,ND
REAL NODE,NT,N1,N2,COREH,DTCTH
DIMENSION NODE(10),ZNOD(10),ZDS(10),ZDE(10),Y(10,10)
1 ,INDX(10),H(10,10),HINV(10,10),HTEMP(10,10)

C

N1(A)=A**4./16.
N2(A)=A/4.+3.*A**2./8.+A**3./4.-3.*A**4./16.

C

N=ND+1
DSPAN = DTCTH/COREH
DINT = 1.0/FLOAT(N-1) - DSPAN

C

DO 1 I=1,ND
ZD(I)=FLOAT(I-1)/FLOAT(N-1)
ZDS(I)=ZD(I)+DINT/2.0
1 ZDE(I)=ZDS(I)+DSPAN

WRITE(6,500) DSPAN, DINT
WRITE(6,601) ZDS(I),I=1,ND)
WRITE(6,605) (ZDE(I),I=1,ND)
ZNOD(1)=0.
ZNOD(2)=0.
DO 10 I=1,N
10 ZNOD(I+2)=ZNOD(I+1)+NODE(I)/NT
NM=N+3
ASSIGN PREDETERMINED VALUE OF H MATRIX ELEMENTS
(ROW 1, 2, N+2 AND N+3)

DO 20 I=1,NM
DO 20 J=1,NM
20 H(I,J)=0.0
H(1,1)=1.0
H(1,2)=0.25
H(2,1)=0.25
H(2,2)=1.0
H(2,3)=0.25
H(N+2,N+1)=0.25
H(N+2,N+2)=1.0
H(N+2,N+3)=0.25
H(N+3,N+2)=0.25
H(N+3,N+3)=1.0

DETERMINE THE VALUE OF H MATRIX ELEMENTS FROM ROW 3 TO ROW N+1

NA=N+1
NL=2
DO 90 I=3,NA

DETERMINE THE ZONE NUMBER COVERED BY (I-2)TH DETECTOR
NL = ZONE NUMBER FOR START POSITION
NH = ZONE NUMBER FOR END POSITION

ID=I-2
II=NL
22 IF(ZDS(ID).LT.ZNOD(II+1)) THEN
NL=II
ELSE
II = II + 1
GO TO 22
ENDIF
24 IF(ZDE(ID).LE.ZNOD(II+1)) THEN
NH = II
ELSE
II = II + 1
GO TO 24
ENDIF
MD=NH-NL

CALCULATE H(I,J) USING INTEGRATION METHOD FOR CASE 1,2,3
CASE 1: NL=NH, CASE 2: NH=NL+1, CASE 3: NH.GT.(NL+1)

IF(MD.GE.1) GO TO 30
CASE 1

K=NL
J=K+2
DZ=ZNOD(K+1)-ZNOD(K)
ETA10=(ZDS(ID)-ZNOD(K))/DZ
ETA11=1.-ETA10
ETA20=(ZDE(ID)-ZNOD(K))/DZ
ETA21=1.-ETA20
DZ=DZ*100.
H(I,J)=DZ*(N1(ETA20)-N1(ETA10))
H(I,J-1)=DZ*(N2(ETA20)-N2(ETA10))
H(I,J-2)=DZ*(N2(ETA21)-N2(ETA21))
H(I,J-3)=DZ*(N1(ETA11)-N1(ETA21))
GO TO 80

CASE 2 AND PART OF CASE 3

30 K=NL
J=K+2
DZ=ZNOD(K+1)-ZNOD(K)
ETA10=(ZDS(ID)-ZNOD(K))/DZ
ETA11=1.-ETA10
DZ=DZ*100.
H(I,J)=DZ*(1./16.-N1(ETA10))
H(I,J-1)=DZ*(1./16.-N2(ETA10))
H(I,J-2)=DZ*N2(ETA11)
H(I,J-3)=DZ*N1(ETA11)
IF(MD.GT.1) GO TO 50

40 K=NH
J=K+2
DZ=ZNOD(K+1)-ZNOD(K)
ETA20=(ZDE(ID)-ZNOD(K))/DZ
ETA21=1.-ETA20
DZ=DZ*100.
H(I,J)=DZ*N1(ETA20)+H(I,J)
H(I,J-1)=DZ*N2(ETA20)+H(I,J-1)
H(I,J-2)=DZ*(1./16.-N2(ETA21))+H(I,J-2)
H(I,J-3)=DZ*(1./16.-N1(ETA21))+H(I,J-3)
GO TO 80

MIDDLE PART OF CASE 3

50 KI=NL+1
KF=NH-1
DO 60 K=KI,KF
J=K+2
DZ=(ZNOD(K+1)-ZNOD(K))*100.
H(I,J)=DZ/16.+H(I,J)
H(I,J-1)=DZ*11./16.+H(I,J-1)

END
H(I,J-2) = DZ*11./16. + H(I,J-2)
H(I,J-3) = DZ/16. + H(I,J-3)
60 CONTINUE
   GO TO 40
C
C ASSIGN THE START ZONE NUMBER OF NEXT DETECTOR
C
80 NL=NH
90 CONTINUE
C
C REDUCE H MATRIX TO (N+1)*(N+1) SIZE
C
   HF=H(1,2)/H(1,1)
   HL=H(N+3,N+2)/H(N+3,N+3)
   DO 100 I=1,NA
   H1=H(I+1,1)
   H2=H(I+1,NA+2)
   DO 100 J=1,NA
   H(I,J)=H(I+1,J+1)
   IF(J.EQ.1) H(I,J)=H(I,J)-HF*H1
   IF(J.EQ.NA) H(I,J)=H(I,J)-HL*H2
100 CONTINUE
C
C TEMPORARY STORAGE FOR H MATRIX
C
   DO 110 I=1,N+1
      DO 110 J=1,N+1
110 HT(I,J)=H(I,J)
C
C ---- CALCULATE INVERSE MATRIX OF H BY LU DECOMPOSITION ----
C
   NP=N+1
   NPP=10
C
C SET UP IDENTITY MATRIX
C
   DO 121 I=1,NP
      DO 120 J=1,NP
120 Y(I,J)=0.
121 Y(I,I)=1.
C
C -----------------------------------------------
CALL LUDCMP(H,NP,NPP,INDX,D)
C -----------------------------------------------
C
C COMPUTE DETERMINANT OF A MATRIX
C
   DO 122 J=1,NP
122 D=D*H(J,J)
   IF(ABS(D).LT.ABS(1.E-10)) THEN
      WRITE(6,700) D
      42
700 FORMAT(1X,2F15.6)
GOTO 9999
ENDIF

DO 130 J=1,NP
    CALL LUBKSB(H,NP,NPP,INDX,Y(I,J))
130 CONTINUE

C
DO 140 I=1,NP
    DO 140 J=1,NP
        HINV(I,J)=Y(I,J)
    140 H(I,J)=HTEMP(I,J)
C
C CHECK INVERSE MATRIX
C
INVFLG = 0
EPSLN = 1.0E-06

DO 160 I = 1, NP
    A = 0.0
    DO 150 J = 1, NP
        A = A + H(I,J) * HINV(J,I)
    150 B?(I.EQ.J)A=A-1.O
    IF(ABS(A) .GT. EPSLN) INVFLG = INVFLG+1
160 CONTINUE

IF(INVFLG.NE.0) THEN
    WRITE(6,650) INVFLG
ELSE
    WRITE(6,660)
ENDIF
C
C WRITE THE ELEMENTS OF REDUCED H MATRIX AND INVERSE MATRIX
C
WRITE(6,610)
DO 170 I=1,NA
    WRITE(6,611) (H(I,J),J=1,NA)
170 WRITE(6,612)
    DO 180 I=1,NA
    WRITE(6,611) (HINV(I,J),J=1,NA)
180 WRITE(6,611) (HINV(I,J),J=1,NA)

9999 RETURN
C
500 FORMAT(/2X,'DETECTOR SPAN (IN FRACTION) = ',F10.6,
      $ /2X,'DETECTOR INTERVAL (IN FRACTION) = ',F10.6)
601 FORMAT(2X,'DBOT(I) = ',10F10.4)
605 FORMAT(2X,'DTOP(I) = ',10F10.4)
610 FORMAT(2X,'*** COEFF OF SPLINE(H) MATRIX ***',/)
611 FORMAT(1H ,2X,1OE14.5)
612 FORMAT(2X,'*** COEFF OF INVERSE SPLINE (HC) MATRIX ***',/)
650 FORMAT(/2X,'*** ERROR ***',13,'FAILURES OF INVERSE CHECK')
660 FORMAT(/2X,'--- INVERSE MATRIX VERIFIED ---')
700 FORMAT(/2X,'!!! ERROR -- DETERMINANT TOO SMALL (',G12.4,')')
END
## 서지 정보 양식

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제목 / 부제

노내외 핵계측기를 이용한 실시간 노심 출력분포 함성법

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참고사항

비밀여부

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연구위탁기관

계약 번호

초록 (15-20줄내외)

Fourier Series 와 Cubic Spline 함수를 이용한 노심 출력분포 함성 방법과 관련 계수 등을 기술하였다. 관련 계수의 생성과 노심 출력분포의 함성을 위하여 전산 프로그램도 작성하였다. 예로써 영광 3호기 1주기와 일체형원자로(SMART)에 대해 모의된 노내외 핵계측기 신호를 이용하여 여러 형태의 노심 출력분포를 함성하였다. 이 연구 결과는 일체형원자로 노심보호감시계통의 실시간 노심 출력분포 최적 함성법의 결정과 정확도 평가에 활용될 것이다.

주제명기워드

(10단어내외) 합성, 노내, 노외, Fourier series, Cubic Spline, 출력분포, 실시간.
**BIBLIOGRAPHIC INFORMATION SHEET**

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**Title / Subtitle**

On-line Core Axial Power Distribution Synthesis Method from In-core and Ex-core Neutron Detectors

**Project Manager and Department**

In Wang Kee (Advanced Reactor Development)

**Researcher and Department**

Cho Byung-Oh (Advanced Reactor Development)

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**Abstract**

This document describes the methodology in detail and the synthesis coefficients of the Fourier series expansion and the cubic spline synthesis techniques. A computer program was developed to generate the synthesis coefficients and the core power distribution. For the illustration, various axial power shapes for YGN 3 Cycle 1 and SMART were synthesized using the simulated in-core and/or ex-core detector signals. The results of this study will be useful to select the best synthesis method for the SMART core monitoring and protection systems and to evaluate the accuracy of the synthesized power shape.

**Subject Keywords**

Synthesis, In-core, Ex-core, Fourier Series, Cubic Spline, Power Distribution (Shape), On-line