Hexagonal Nodal Diffusion in Ants

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Outline

Background
• Kraken and Ants

Solution method
• Outlines of the solution method

AER FCM-101 Benchmark
• Specification
• Results

X2 VVER-1000 Fresh Core Benchmark – HZP case
• Specification
• Results
Background

Serpent

ARES

Serpent

Ants

TH/Fuel solvers

Reactor core interface

NPP interface
Ants

Deterministic nodal neutronics solver module for relatively light-weight calculations

Scope for computational resources

- For example, 1 to 32 CPU cores on the same shared-memory platform

Future aim

- Handling the neutronics of routine burnup and transient analysis calculations
- Platform for developing group constant generation with Serpent
- Currently: Ants is functional for steady state calculations in rectangular and hexagonal assembly geometries
Solution method

Based on

- AFEN (Analytic Function Expansion Nodal)\(^1\)
- FENM (Function Expansion Nodal Method)\(^2\)

Features

- Large number of unknowns/degrees of freedom per node
- Slower than transverse integration
- Avoids transverse integration – significant benefit for hexagonal geometry

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Solution method

Intranodal flux is expanded using analytic basis functions.

\[-\nabla^2 \vec{\phi}(\vec{r}) + L \vec{\phi}(\vec{r}) = 0,\]

\[L = D^{-1} \left ( A - \frac{\chi}{k_{\text{eff}}} F^T \right ),\]

\[L = U \Lambda U^{-1},\]

\[\vec{\psi}(\vec{r}) = U^{-1} \vec{\phi}(\vec{r}).\]
Flux expansion

If all eigenvalues are real, the result is $G$ decoupled equations for eigenmode fluxes:

$$-\nabla^2 \psi_m(\vec{r}) + \lambda_m \psi_m(\vec{r}) = 0, \ m = 1, \ldots, G,$$

For these, sets of analytic solutions can be found. For hexagonal geometry, Ants uses three radial directions + their linear transverse gradients. Axially there is simple SN/CN.

$$C_{m,i} \text{SN} (k_m \vec{r} \cdot \hat{r}) + C_{m,i+1} \text{CN} (k_m \vec{r} \cdot \hat{r})$$

$$C_{m,j} (\bar{s} \cdot \hat{r}) \text{SN} (k_m \vec{r} \cdot \hat{r}) + C_{m,j+1} (\bar{s} \cdot \hat{r}) \text{CN} (k_m \vec{r} \cdot \hat{r})$$

$\bar{s} \perp \vec{r}$
Using the flux expansion

C = coefficients of the flux expansion

\[ Q_{\text{in}} C = J^+ \]
\[ Q_{\text{out}} C = J^- \]

\[ J^- = Q_{\text{out}} Q_{\text{in}}^{-1} J^+ = R J^+ \]

Here vectors J are 20*G vectors of partial neutron current moments.
AER FCM-101 Benchmark  1/3

VVER-1000 3D diffusion benchmark\(^3\)

- 30 deg. symmetry
- Group constants provided as input
  - Two group problem
- Partially inserted control rods
- Zero-incoming boundary conditions

Results

- \(k_{\text{eff}}\) and power distribution from Ants
- Comparison to SIMULATE5 and DYN3D
- Extrapolated CRONOS finite element solution as a reference

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AER FCM-101 Benchmark  2/3

Slight tilt from middle to the edges

\[ 100 \times |\Delta P|_{\text{max}} \]
### AER FCM-101 Benchmark 3/3

| Case            | $100 \times |\Delta P|_{\text{max}}$ | $\Delta P_{\text{rms}}$ (%) | $k_{\text{eff}}$ | $\Delta k_{\text{eff}}$ (pcm) |
|-----------------|---------------|-----------------|----------------|-----------------|------------------|
| CROCUS (ref.)   | --            | --              | 1.049526       | --              | --               |
| Ants            | 0.47          | 0.20            | 1.049678       | 15              |                  |
| DYN3D HEXNEM3   | 0.41          | 0.22            | 1.04945        | --7             |                  |
| SIMULATE5-HEX   | 0.31          | 0.18            | 1.04971        | 18              |                  |
Description of first 4 cycles of the unit 2 of Khmelnitsky NPP

- Here, HZP critical state of the fresh core is examined
- Partially inserted control rods
- Measurements available
- Here measurements are omitted: 3D full core Serpent calculation is used as a reference

Group constants

- Provided by Dr. Bilodid

Serpent 3D full core results

- Also provided by Dr. Bilodid
  - See [5]

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Slight tilt at the core edge in the difference
- From the Serpent solution
- Diffusion solution is symmetric
### X2 VVER-1000 Benchmark 3/3

| Case              | $100 \times |\Delta P|_{\text{max}}$ | $\Delta P_{\text{rms}}$ (%) | $k_{\text{eff}}$ | $\Delta k_{\text{eff}}$ (pcm) |
|-------------------|--------------|------------------|-----------------|------------------|------------------|
| Serpent 2 (ref.)  | –            | –                | 1.000692        | –                |
| Ants              | 1.34         | 0.89             | 1.001681        | 99               |
| DYN3D HEXNEM3     | 1.32         | 0.74             | 1.001442        | 75               |
Bonus Slide
A brighter future is created through science-based innovations.