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Corner neutronic code

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Abstract

The neutronic code CORNER is based on the S_N discrete ordinates method [1] and the P_M scattering cross-section approximation. It is intended for high-precision deterministic neutronic calculations of fast-neutron reactors and can be used to solve two types of steady-state neutron transport and gamma quanta problems in a 3D hexagonal geometry: K_{eff} problems (homogeneous) and source problems (inhomogeneous).

The code is developed in the Fortran language and has a modular structure. Its key modules are a module for the preparation of neutron constants in the ANISN format; a geometric module containing a description of the core's loading map and fuel assembly types, including their axial meshing and material composition; a module for preparing angular quadrature sets; an input data module containing the parameters of the approximation used and the control parameters; a neutronic calculation module and a calculation data processing module.

The Directional Theta-Weighted (*DTW*) difference scheme [2] has been built to approximate the spatial dependence. It has advantages over the *DD* (Diamond Difference) scheme broadly used in coarse-mesh problems.

The energy dependence is represented by multigroup approximation. The angular variable is discretized by introduction of the angular quadrature set. Quadrature sets can be also defined by the user.

An iterative solution process is used, including external iterations for the fission source and internal iterations for the scattering source. The paper presents the results of a cross-verification against the Monte Carlo MMK code [3] and on a model of the BN-800 reactor core.

Keywords: Fast-neutron reactor; Neutronic calculation; Discrete ordinates method; Hexagonal geometry; Difference scheme.

Problem definition

The steady-state distribution of neutrons is described by the linear Boltzmann equation [4], which, in a multigroup approximation, has the form

$$\boldsymbol{\Omega}\cdot\nabla\phi^g(\boldsymbol{r},\boldsymbol{\Omega})+\Sigma_t^g(\boldsymbol{r})\phi^g(\boldsymbol{r},\boldsymbol{\Omega})=Q^g(\boldsymbol{r},\boldsymbol{\Omega}), \quad (1)$$

$$Q^g(\boldsymbol{r},\boldsymbol{\Omega})=\sum_{g'=1}^{g}\int_{4\pi}\Sigma_s^{g'\to g}\big(\boldsymbol{r},\boldsymbol{\Omega}'\cdot\boldsymbol{\Omega}\big)\phi^g(\boldsymbol{r},\boldsymbol{\Omega})d\boldsymbol{\Omega} + \chi^g\sum_{g'=1}^{G}\nu\Sigma_f^{g'}\Phi^{g'}(\boldsymbol{r})+S^g(\boldsymbol{r}). \quad (2)$$

where φ^g ($\mathbf{r}$, $\mathbf{\Omega}$) is the neutron flux density at the point $\mathbf{r}$ in the direction $\mathbf{\Omega}$ in the group g; Φ^g ($\mathbf{r}$) is the scalar neutron flux at the point $\mathbf{r}$ in the group g; $\Sigma_t{}^g$ ($\mathbf{r}$) is the full macroscopic cross-section of interaction; $\Sigma_s{}^{g'\to g}$ ($\mathbf{r}$, $\mathbf{\Omega'}\cdot\mathbf{\Omega}$) is the macroscopic cross-section of the neutron scattering from group g' into group g; χ^g is the fission neutron spectrum; G is the total number of energy groups; $\nu\Sigma_f{}^{g'}$ is the number of fission neutrons generated in a single fission event; and S^g ($\mathbf{r}$) is the distribution function of internal sources.

The CORNER code supports the solution of an inhomogeneous problem and a conditional-critical problem (with zero boundary conditions, zero internal sources and the $1/K_{eff}$ multiplier preceding the fission integral).

S_NP_M approximation

To calculate the collision integral, it is necessary to define the angular quadrature (S_N approximation of the discrete or-

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dinates method) and expand the scattering indicatrix in series of Legendre polynomials (P_M approximation).

The variation range of angular variables is a single sphere of directions $\mathbf{\Omega}=(\theta, \phi)$ where θ is the polar angle, and ϕ is the azimuthal angle. In the S_N approximation, this range is substituted by a set of discrete directions $\mathbf{\Omega}_m$, each of which is matched by a point on the sphere surface and a surface element of the area w_m. The surface elements w_m play the role of angular quadrature weights in the computation of integrals in expression (2). The total number of discrete directions is equal to 2^d N $(N+2)/8$ where d is the geometrical dimension.

$$\Omega_m = \Omega^x_m \boldsymbol{i} + \Omega^y_m \boldsymbol{j} + \Omega^z_m \boldsymbol{k},$$
$$\Omega^x_m = \xi_m = \cos(\theta_m),$$
$$\Omega^y_m = \mu_m = \cos(\varphi_m)\sin(\theta_m),$$
$$\Omega^z_m = \eta_m = \sin(\varphi_m)\sin(\theta_m).$$

The CORNER code supports two types of quadrature sets: Level Symmetric (LQ_N) and Legendre-Chebyshev (P_N–T_N) [5]. The angular quadratures of the LQ_N set are symmetrical relative to the rotation about each axis but are limited: when $N > 20$, negative quadrature weights occur. The P_N–T_N set combines the Gauss quadratures for the polar variable and the Chebyshev quadratures with equal weights for the azimuthal variable.

With regard for the expansion of the scattering indicatrix in series of Legendre polynomials, the collision integral has the form

$$Q^g_s(\boldsymbol{r}, \mathbf{\Omega}) = \sum_{g'=1}^{g}\sum_{l=0}^{L}(2l+1)\Sigma^{g'\to g}_{s,l}(\boldsymbol{r})\big[P_l(\xi)\Phi^{g'(0,0)}_C(\boldsymbol{r})\big]$$
$$+2\sum_{k=1}^{l}\frac{(l-k)!}{(l+k)!}P^k_l(\xi)\big\{\Phi^{g'(k,l)}_C(\boldsymbol{r})\cos(k\varphi)$$
$$+\Phi^{g'(k,l)}_S(\boldsymbol{r})\sin(k\varphi)\big\}, \tag{3}$$

where $\Sigma_{s,l}{}^{g'\to g}$ ($\mathbf{r}$) is the lth moment of the scattering cross-section; $P_l(\xi)$ is the 1st order Legendre polynomial; and $P_l{}^k(\xi)$ is the associated Legendre polynomial. The flux angular moments have the form

$$\Phi^{g(k,l)}_C(\boldsymbol{r}) = \frac{1}{4\pi}\int_{-1}^{1}P^k_l(\xi)d\xi\int_0^{2\pi}\phi^g(\boldsymbol{r},\xi,\varphi)\cos(k\varphi)d\varphi, \tag{4}$$

$$\Phi^{g(k,l)}_S(\boldsymbol{r}) = \frac{1}{4\pi}\int_{-1}^{1}P^k_l(\xi)d\xi\int_0^{2\pi}\phi^g(\boldsymbol{r},\xi,\varphi)\sin(k\varphi)d\varphi. \tag{5}$$

Finite-difference schemes

The computational domain consists of regular hexagonal prisms which simulate the reactor core FAs with a pitch of Δx. Let us consider the computational cell $[x_{i-1/2}, x_{i+1/2}]\times[y_{b-}(x), y_{b+}(x)]\times[z_{i-1/2}, z_{i+1/2}]$ (see Fig. 1) with the center at (x_i, y_j, z_k), where

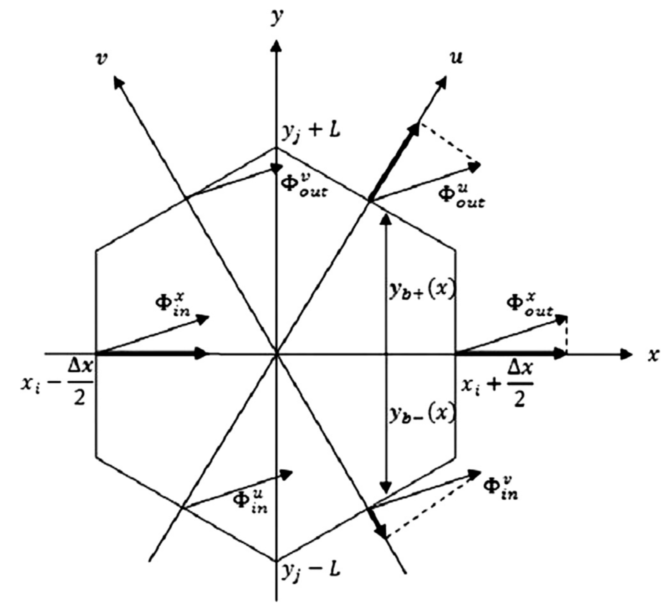

Fig. 1. A computational cell in the XY plane and the neutron transport direction for the case $\mu^x{}_m > 0$, $\mu^u{}_m > 0$, $\mu^n{}_m > 0$.

$$y_{b\pm}(x) = y_j \mp \frac{|x-x_i|-\Delta x}{\sqrt{3}}$$

We shall introduce auxiliary directions u and v such that

$$\mu^x_m = \mu_m;\ \ \mu^u_m = \frac{\sqrt{3}}{2}\eta_m + \frac{1}{2}\mu_m;\ \ \mu^v_m = \frac{\sqrt{3}}{2}\eta_m - \frac{1}{2}\mu_m.$$

The balance equation for the zero moments of the angular flux in the cell and on the faces is obtained by the integration of Eq. (1) in a difference cell for the fixed direction m (the index of group g is omitted for simplicity):

$$\frac{2}{3\Delta x}\sum_{\alpha\in\{x,u,v\}}\left|\mu^\alpha_m\right|\left(\Phi^\alpha_{m,out}-\Phi^\alpha_{m,in}\right)$$
$$+\frac{|\eta_m|}{\Delta z_k}\left(\Phi^z_{m,out}-\Phi^z_{m,in}\right)+\Sigma_t\Phi_m = Q_m, \tag{6}$$

where

$$\Delta S = \frac{3}{2}L\Delta x,\ \ L = \frac{\Delta x}{\sqrt{3}},$$

$$\Phi_m = \frac{1}{\Delta z_k\Delta s}\int_{z_{k-\frac12}}^{z_{k+\frac12}}\int_{x_{i-\frac12}}^{x_{i+\frac12}}\int_{y_{b-(x)}}^{y_{b+(x)}}\phi_m(x,y,z,\mathbf{\Omega}_m)dxdydz,$$

$$\mathrm{Q}_m = \frac{1}{\Delta z_k\Delta s}\int_{z_{k-\frac12}}^{z_{k+\frac12}}\int_{x_{i-\frac12}}^{x_{i+\frac12}}\int_{y_{b-(x)}}^{y_{b+(x)}}Q(x,y,z,\mathbf{\Omega}_m)dxdydz,$$

$$\frac{1}{\mathrm{L}\Delta z_k}\int_{z_{k-\frac12}}^{z_{k+\frac12}}\int_{y_{j-\frac{L}{2}}}^{y_{j+\frac{L}{2}}}\phi_m(x_{i+\frac12},y,z,\mathbf{\Omega}_m)dydz$$
$$=\begin{cases}\Phi^x_{m,out,}\mu^x_m > 0\\ \Phi^x_{m,in,}\mu^x_m < 0\end{cases},$$