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A modified predictor-corrector quasi-static method in NECP-X for reactor transient analysis based on the 2D/1D transport method

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ABSTRACT

The 2D/1D transport method is a widely applied method for the whole-core heterogeneous transport calculation. The transient simulation based on the pin-resolved 2D/1D method is implemented in the high-fidelity code NECP-X. The 3D transient fixed source problem (TFSP) is transformed into 2D TFSP and 1D TFSP coupled by leakage, and the pin-based coarse mesh finite difference method (CMFD) is used to accelerate convergence of the 2D/1D TFSP. In this paper, a modified predictor-corrector quasi-static (mPCQS) method is developed to provide better reactivity prediction for PK calculations. Furthermore, the simplified source scaling method (SSSM) is used to accelerate the convergence of the CMFD TFSP iterations. The results of three problems are presented including the 2D C5G7-TD benchmark, a MiniCore-3D rod-ejection problem and a 3D heterogeneous rod-ejection problem. Numerical results reveal that the SSSM method can significantly reduce the number of CMFD iterations without increasing the computational complexity, and the mPCQS method can provide better results than the standard PCQS for step perturbation transient event and rod ejection transient event no matter in the homogeneous case or in the heterogeneous case.

1. Introduction

At present, the two-step method is the mainstream approach in commercial nuclear reactor physics simulation for the limitation of the computational ability. However there are two obvious disadvantages in the two-step method: 1) there are errors in the homogenization process of the lattice calculation and the detailed pin-resolved power distribution cannot be obtained accurately; 2) the environmental effect of the assembly in reactor core cannot be considered directly even with the discontinuity factors and the neutron leakage model.

To avoid the above problems and considering the development of the computational hardware, the high-fidelity deterministic whole-core transport method has been developed in recent years. The three-dimensional (3D) whole-core modeling in pin-resolved detail is still a challenge for the current computational hardware (Lewis et al., 2001a; Hoogenboom et al., 2011), especially for the transient simulation. As a replacement of the direct 3D whole-core calculation, the 2D/1D fusion method is proposed (Cho, 2002; Cho et al., 2002; Joo et al., 2004). Now the 2D/1D method is widely used in high-fidelity codes, such as DeCART (Hursin, 2010), CRX (Lee, 2006), nTRACER (Weber et al., 2007), MPACT (Kochunas, 2013) and NECP-X (Chen et al., 2018; Liang et al., 2017; Zhao et al., 2017; Liu et al., 2018 ; Wang et al., 2017). The main strategy of the 2D/1D fusion method is decomposing the 3D whole-core problem into 2D problems considering the radial complex heterogeneous geometry and 1D problems. The 2D and 1D problems are coupled through the transverse leakage terms. In most 2D/1D codes the 2D problems are solved by the Method of Characteristic (MOC), which is widely used to deal with the heterogeneous problems. While the 1D problems can be solved by a variety of methods, such as the discrete ordinates (S_N) or the simplified P_3 method (SP_3), etc.

The transient simulation module has also been developed in recent years based on the pin-resolved 2D/1D fusion method, such as DeCART (Cho et al., 2005), MPACT (Zhu et al., 2015a), CRX (Cho and Cho, 2015) and nTRACER (Ryu and Joo, 2017). In the DeCART code, the theta method is used to discretize the time derivative term and a fixed time step is used, and the 3D TFSP is driven by the CMFD method. The Backward Euler method and Transient Multi-Level (TML) method are applied into MPACT, while the CMFD adjoint flux is used as weighting function to get point kinetics parameters, for the TML method, two level of couplings are used between 3D transport/3D CMFD and 3D CMFD/point kinetics (PK) equations. The CRX code introduced the fully implicit method to discretize the time derivative term and adopted a second order approximation of fission source, and the predictor-corrector quasi-static method (PCQS) was also implemented in CRX with the p-CMFD adjoint flux as the weighting function. Three temporal discretization schemes are available in nTRACER, which are the Crank-

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Nicolson (CN) method, the CN method with exponential transformation (CNET) and the Backward Differentiation Formula (BDF) method.

However, there are three obvious problems in the existing transient transport methods: 1)A low-order CMFD method is usually used to accelerate the convergence of 2D/1D method, but the CMFD calculation becomes a bottle neck for the transient running time (Zhu, 2016); 2)In the standard PCQS method, the linear interpolation of the PK parameters is used in one macro time step, which will introduces obviously errors when the reactivity is not linear over time and the error increases with the larger time step (Cho and Cho, 2016); 3) For step perturbation, the reactivity will be introduced instantaneously, the standard PCQS will obviously produce error with large time step, and the error decreases with smaller time step but needs much more computational time.

To address the above problems, a modified PCQS (mPCQS) method is developed in this paper based on the high-fidelity reactor physics code NECP-X. To reduce the CMFD computational time, the simplified source scaling method (SSSM) is used to accelerate the convergence of the CMFD TFSP by introducing a rebalance factor; the online high-order interpolation of reactivity is introduced to obtain better reactivity for the point kinetics calculation in the PCQS method; a FIM-PCQS (Full-implicit method-PCQS) coupling method is proposed to avoid the reactivity interpolation error for the step-turbulence problems.

In this paper, section 2 presents the details of transient methodology without feedback in the NECP-X code, the discretization strategy of the time derivative term is presented to formulate the 3D TFSP, and then the 3D TFSP is transformed into 2D/1D TFSP; section 3 presents standard PCQS with CMFD adjoint flux as weighting function first, and then the mPCQS method is presented. The mPCQS method consists of SSSM, FIM-PCQS and online high-order interpolation; section 4 presents the numerical results, 2D heterogeneous C5G7-TD benchmark are presented to check the performance of SSSM and mPCQS for step perturbation, the homogeneous MiniCore-3D problem and 3D heterogeneous assembly rod ejection problem are presented to demonstrate the accuracy and performance of mPCQS for the rod-ejection transient events.

2. Transient 2D/1D transport methodology

The derivation of the transient transport equation begins with the continuous 3D space-time dependent transport equations. The 3D transient fixed source problem (TFSP) is obtained by using implicit difference method to discretize the time-dependent variable in section 2.1. The 2D TFSP equation with the axial leakage supplied by the 1D solver is formulated in section 2.2 while the 1D TFSP equation with the radial leakage from the 2D solver is formulated in section 2.3. The 3D CMFD TFSP equation is formulated in section 2.4.

2.1. 3D transport transient fixed source equation

The formulation of 3D multi-group time-discretized transport equation begins with the continuous time-dependent neutron equation as shown by Eq. (1) and the precursor equations shown as Eq. (2).

$$\begin{aligned}\frac{1}{v_g}\frac{\partial\varphi_g(\mathbf{r},\mathbf{\Omega},t)}{\partial t} &= -\Omega\cdot\nabla\varphi_g(\mathbf{r},\mathbf{\Omega},t)-\Sigma_{t,g}(\mathbf{r},t)\varphi_g(\mathbf{r},\mathbf{\Omega},t)\\ &+\frac{1}{4\pi}\sum_{g'=1}^{G}\Sigma_{s,g'\to g}(\mathbf{r},t)\phi_g(\mathbf{r},t)+\frac{1}{4\pi}(\chi_{p,g}(\mathbf{r},t)(1-\beta(\mathbf{r},t))S_F(\mathbf{r},t)\\ &+S_{d,g}(\mathbf{r},t))\end{aligned} \tag{1}$$

$$\frac{dC_k(\mathbf{r},t)}{dt}=\beta_k(\mathbf{r},t)S_F(\mathbf{r},t)-\lambda_k(\mathbf{r},t)C_k(\mathbf{r},t),\ k=1,2,\ \cdots,6 \tag{2}$$

where

$$\begin{aligned}S_F(\mathbf{r},t)&=\frac{1}{k_{eff}^s}\sum_{g=1}^{G}\nu\Sigma_{f,g}\phi_g(\mathbf{r},t)\\ S_{d,g}(\mathbf{r},t)&=\sum_{k=1}^{6}\chi_{dk,g}\lambda_k(\mathbf{r},t)C_k(\mathbf{r},t)\\ \chi_g&=\chi_{p,g}(1-\beta)+\sum_k\chi_{dk,g}\beta_k\end{aligned} \tag{3}$$

where k_{eff}^s is the steady-state multiplication factor, χ_p and χ_d are the prompt fission spectrum and delayed fission spectrum, respectively, S_F and S_d are the total fission source and the delayed neutron source, respectively, and the other notations are the same with what were used in reference (Zhu, 2016).

The fully implicit method (FIM) is used for the discretization of the time derivative term in Eq. (1), thus Eq. (1) can be discretized as follow:

$$\frac{\varphi_g^n(\mathbf{r},\mathbf{\Omega})-\varphi_g^{n-1}(\mathbf{r},\mathbf{\Omega})}{v_g\Delta t_n}=R_g^n(\mathbf{r},\mathbf{\Omega}) \tag{4}$$

where Δt_n is the time step size at time step n, R^n is the right hand side (RHS) of Eq. (1).

The difference of the angular flux to time is replaced by the difference of the scalar flux to time, which is proved enough accurate for light water reactor (Hoffman, 2013). Then Eq. (4) is changed as follows:

$$\frac{\varphi_g^n(\mathbf{r},\mathbf{\Omega})-\varphi_g^{n-1}(\mathbf{r},\mathbf{\Omega})}{v_g\Delta t_n}\approx\frac{\phi_g^n(\mathbf{r})-\phi_g^{n-1}(\mathbf{r})}{4\pi v_g\Delta t_n}=R_g^n(\mathbf{r},\mathbf{\Omega}) \tag{5}$$

Actually the RHS of Eq. (5) contains precursor density at time step$n$, thus neutron transport equation is coupled with precursor equations. The second order precursor integration method is used to obtain the delayed neutron precursor concentration at the current time step, which is based on the second order variation of the fission rate during the time step n (Downar et al., 2009), Eq. (2) is solved as follows:

$$C_k^n(\mathbf{r})=\Omega_k^0(\tilde{\lambda}_k^n)C_k^{n-1}(\mathbf{r})+\frac{1}{\lambda_k^n}\begin{bmatrix}\beta_k^n(\mathbf{r})S_F^n(\mathbf{r})\Omega_k^n(\tilde{\lambda}_k^n)+\\ \beta_k^{n-1}(\mathbf{r})S_F^{n-1}(\mathbf{r})\Omega_k^{n-1}(\tilde{\lambda}_k^n)+\\ \beta_k^{n-2}(\mathbf{r})S_F^{n-2}(\mathbf{r})\Omega_k^{n-2}(\tilde{\lambda}_k^n)\end{bmatrix} \tag{6}$$

where

$$\begin{aligned}&\tilde{\lambda}_k^n=\lambda_k^n\Delta t_n,\ \gamma=\frac{\Delta t_{n-1}}{\Delta t_n},\ E(x)=e^{-x}\\ &k_0(x)=1-e^{-x},\ k_1(x)=1-\frac{k_0(x)}{x},\ k_2(x)=1-\frac{2k_1(x)}{x}\\ &\Omega_k^0(\tilde{\lambda}_k^n)=E(\tilde{\lambda}_k^n)\\ &\Omega_k^n(\tilde{\lambda}_k^n)=\frac{k_2(\tilde{\lambda}_k^n)+\gamma k_1(\tilde{\lambda}_k^n)}{1+\gamma}\\ &\Omega_k^{n-1}(\tilde{\lambda}_k^n)=\left(k_0(\tilde{\lambda}_k^n)-\frac{k_2(\tilde{\lambda}_k^n)+(\gamma-1)k_1(\tilde{\lambda}_k^n)}{\gamma}\right)\\ &\Omega_k^{n-2}(\tilde{\lambda}_k^n)=\frac{k_2(\tilde{\lambda}_k^n)-k_1(\tilde{\lambda}_k^n)}{(1+\gamma)\gamma}\end{aligned} \tag{7}$$

By inserting the precursor terms into Eq. (1), the delayed neutron source can be expressed as:

$$S_{d,g}^n(\mathbf{r})=\sum_{k=1}^{6}\chi_{dk,g}\lambda_k^n(\mathbf{r})C_k^n(\mathbf{r})=\omega_g^nS_F^n(\mathbf{r})++\tilde{S}_{d,g}^{n-1}(\mathbf{r}) \tag{8}$$

where

$$\begin{aligned}\omega_g^n&=\sum_{k=1}^{6}\chi_{dk,g}\beta_k\Omega_k^n(\tilde{\lambda}_k^n)\\ \tilde{S}_{d,g}^{n-1}(\mathbf{r})&=\sum_{k=1}^{6}\chi_{dk,g}\lambda_k\Omega_k^0(\tilde{\lambda}_k^n)C_k^{n-1}(\mathbf{r})\\ &+S_F^{n-1}(\mathbf{r})\sum_{k=1}^{6}\chi_{dk,g}\beta_k^{n-1}(\mathbf{r})\lambda_k\Omega_k^{n-1}(\tilde{\lambda}_k^n)\\ &+S_F^{n-2}(\mathbf{r})\sum_{k=1}^{6}\chi_{dk,g}\beta_k^{n-2}(\mathbf{r})\lambda_k\Omega_k^{n-2}(\tilde{\lambda}_k^n)\end{aligned} \tag{9}$$

By inserting the delayed neutron source terms Eq. (8) into RHS of Eq. (1), the final time-discretized TFSP is obtained as follows: