Coarse-Mesh Finite-Difference Acceleration in the NEWT Generalized-Geometry Lattice Physics Package

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INTRODUCTION

One of the fundamental approximations applied in modern reactor physics calculations is homogenization theory, which states that an equivalent homogenized problem can be constructed for a heterogeneous problem by introducing additional degrees of freedom. Smith[1] proposed the most popular form of homogenization theory used today, based on discontinuity factors calculated from heterogeneous transport solutions. The concept of discontinuity factors was later extended to the coarse-mesh finite-difference (CMFD) formulation, in which an equivalent coarse-mesh problem is constructed to reproduce a fine-mesh or higher-order problem. However, in this case the discontinuity factor is determined dynamically for each coarse-mesh surface by employing a nonlinear iteration technique. In most CMFD applications, the discontinuity factor is replaced with a coupling correction factor or a corrective nodal coupling coefficient.

The use of the CMFD method to accelerate a higher-order heterogeneous problem in reactor physics is a variation of multigrid methods, which have been used successfully for many years to accelerate generalized boundary value problems in computational physics. The essential idea is to use a coarse-grid solution to remove the low-frequency (long-range) components of the error, which initially slow convergence of iterative methods on a fixed grid.

In this work, the CMFD technique has been applied to accelerate the higher-order transport solution of NEWT. NEWT is a two-dimensional (2-D) arbitrary-geometry discrete-ordinates method based on Extended Step Characteristic (ESC) discretization.[2] By alternating between heterogeneous and coarse-mesh homogenized cells, the CMFD solution provides the solution kernel in NEWT with much faster convergence of the fission and scattering source distributions. This approach was developed and tested during a student internship under the Nuclear Engineering Student Laboratory Synthesis program at the Oak Ridge National Laboratory.

APPROACH

In multi group NEWT transport calculations for heterogeneous fuel lattice configurations, the computational mesh must be fine enough to capture material structures and the spatial variation of the angular flux within the cell. Thus, a single fuel cell containing a fuel rod, clad, and moderator will involve several (tens) of fine-mesh cells. The entire fuel cell can be regarded as coarse relative to the constituent fine-mesh ESC cells and may be taken as the base coarse mesh in the CMFD. In order to formulate such a CMFD problem, one needs homogenized cell group constants and cell coupling coefficients that relate the cell interface current with the two adjacent cell-averaged fluxes. These parameters may be determined from a partially converged ESC solution that yields regional scalar fluxes as well as net interface average currents. The multi group CMFD parameters can be further condensed to a two-group system that can be solved with even lower computational cost to further accelerate the fission source distribution and the eigenvalue of the problem.

Cell-averaged fluxes resulting from the CMFD solution can then be used to update the fission and scattering source distributions for the subsequent transport calculation. In the reconstruction of the regional source, the spatial shape of the scalar flux within a cell is determined from the previous transport calculation, and the currents obtained at the problem boundary in the CMFD solution may be used to update the boundary incoming angular fluxes for the transport calculation. The alternating execution of the homogeneous CMFD calculation and the heterogeneous ESC calculation continues until convergence is reached.

RESULTS

The performance of the two-level CMFD formulation was analyzed for various assembly-size test problems with different geometries, compositions, and energy group structures. One configuration analyzed was the VENUS-2 2-D multi assembly model, consisting of three fuel assemblies (each with pitch 15 × 15, 1.26 cm.), surrounded by baffle and reflector. The large reflecting region outside the core baffle provided significant scattering, requiring many outer iterations to converge in the unaccelerated mode. With CMFD enabled, the problem solution is significantly accelerated. A comparison of the computational times is also shown in Table I (using a 1.8 gHz HP Alpha workstation). The values of *k-eff* of the NEWT calculation with and without CMFD acceleration are the same within convergence tolerance (1×10^{-5}). It is also noted in that the run time is reduced by a factor of 7.5 and the number of transport

sweeps is reduced by a factor of about 8.1. In this case the CMFD takes less than 4% of the total run time.

TABLE I. Summary of the Results

Model	Unaccelerated Case			Accelerated Case				Speedup
	No. of Transport Sweeps	Total Run Time (min)	*k-eff*	#No. of Transport Sweeps	Total Run Time (min)	CMFD Run Time (min)	*k-eff*	
VENUS whole core	129	1285.9	1.07180	16	171.2	6.3	1.07180	7.51

CONCLUSION

The CMFD formulation enables dynamic homogenization of the cells in a heterogeneous whole-core transport calculation and provides an efficient means to accelerate convergence of heterogeneous calculations. Through the application of CMFD acceleration to various test problems, (i.e., the heterogeneous transport solution) experience has shown that the eigenvalue is reproduced exactly while the number of ESC transport sweeps is reduced significantly.

REFERENCES

1. K. S. SMITH, "Spatial Homogenization Methods for Light Water Reactors," Ph.D. thesis, Massachusetts Institute of Technology (1980).
2. M. D. DeHART, "NEWT: A New Transport Algorithm for Two-Dimensional Discrete Ordinates Analysis in Non-Orthogonal Geometries," Vol. II, Sect. F21 of *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations*, NUREG/CR-0200, Rev. 7, (ORNL/NUREG/CSD-2/R7), Vols. I, II, and III (May 2004, DRAFT). Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-725.