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To cite this version:
Pierre Blanchard, Arnaud Etcheverry, Olivier Coulaud, Laurent Dupuy, Marc Bletry, et al.. OptiDis: A parallel Fast Multipole Dislocation Dynamics code. 7th International Conference on Multiscale Materials Modeling, Oct 2014, Berkeley, United States. <hal-01095274>
OptiDis: A parallel Fast Multipole Dislocation Dynamics code

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ABSTRACT

Among all the steps involved in DD simulations, the computation of the internal elastic forces and energy are by far the most resources consuming. However, since these are long-ranged and fast decreasing interactions, hierarchical algorithms like the Fast Multipole Method (FMM) are well suited for their fast evaluation. The relatively low accuracy required for the interaction forces between dislocations brought us to develop a more efficient approximation method for the farfield. On the other hand, the nearfield interactions are still evaluated analytically, which required a rather performant implementation (AVX, GPU...).

Regarding parallelism, our code benefits from a hybrid OpenMP/MPI paradigm and a cache-conscious datastructure. Finally, an accurate handling of topological elements intersecting the structure of the octree was considered. The latter feature implied careful modifications of the P2M/L2P operators in order to deal with shared memory model of parallelism.

The motion of dislocations is ruled by a prescribed mobility law (e.g. viscous glide) depending on the internal (i.e. created by dislocations themselves) and external (i.e. applied by user) contributions on the nodal forces.

The isoporic elastic stress field created by a dislocation loop (bT U) at point x in space is given by Mur's formula [4]

\[ \sigma_{ij}(x) = \frac{\mu}{2\pi} \int (A_{ij}(y) + A_{ij}(x) + \frac{1}{2}B_{ij}(y) - A_{ij}(y)) \delta_{ij} dy \]

where \((\mu, \nu)\) are the Lamé coefficients and

\[ (A_{ij}(y)) = \int f_{C} R_{ij}(x, y) \gamma_{ijkl} b_{kj} dy \]

\[ (B_{ij}(y)) = \int f_{C} R_{ij}(x, y) \gamma_{ijkl} b_{kl} dy \]

where \(f_{C}\) is a linear shape functions. While the isotropic elastic interaction energy is given by

\[ E(C, C') = \frac{\mu}{4\pi} \int f_{C}^T f_{C'} R_{kl}(x, y) \gamma_{ijkl} b_{klj} dy \]

The cost of updating the nodal forces (and the energy) at each time step is quadratic and involves the evaluation of 2 line integrals, therefore it is usually the bottleneck of DD simulations.

A NEW FFT-ACCELERATED FMM

Fast Multipole DD

The idea of the FMM is to balance the computational cost of near and farfield interactions by approximating the farfield and rely on a tree structure (see figure 1) to perform all computations. In our case we consider the interaction potential \(R(x,y) = (R_{ij}(x,y))_{i,j=1}^{n}\) and apply the interpolation formula

\[ R(x,y) = \sum_{i,j=1}^{n} R_{ij}(x,y) x_{ij} y_{ij} \]

where \(R_{ij}\) and \(y_{ij}\) denote 2 sets of interpolation nodes in 2 well separated clusters containing \(x\) and \(y\). \(S\) denotes a polynomial interpolator (either Lagrange or Chebyshev).

The farfield approximation consists in 3 steps:

- **P2P** Analytical evaluation of the nearfield.
- **P2M/L2P** Integration of polynomial interpolators on all leaf cell returns expansion:

\[ M_{ij} = \int_{f_{C}} S_{ij}(y) dy \]

- **M2L/L2M** Transfer expansions between levels.

Both stress and energy expansions share the same M2L operators \(R_{ij}\), but the extra derivation involved in the stress field is applied to the interpolator. This results in a slightly lower accuracy but less M2L operations to be performed (see figure 2).

Acceleration by Fast Fourier Transform (FFT)

Even though the Chebyshev-based FMM [3] provides a very accurate algorithm it is very expensive in terms of memory and CPU time, namely \(O(\mu n^{3})\) for the M2L step. Thus a new interpolation scheme based on an equispaced grid (Lagrange) was considered. In this approach \(R_{ij}\) is Toeplitz since \(R = R(x-y)\).

As illustrated below, \(R_{ij}\) can be seen as a convolution and applied in Fourier space with a linear cost.

\[ \text{If } R(x,y) = R_{ij}(x,y) \quad \text{then } \text{FFT}(C1, C2) = \text{FFT}(X, Y) \]

The scheme remains stable and sufficiently accurate in the scope of DD simulations (min. accuracy on force computation \(\approx 10^{-3}\)) while dramatically decreasing the computational cost of the M2L, namely to \(O(\mu n \log n)\). Let \(y \geq 5\) then in double precision the memory required for the M2L equals:

\[ 316 \times (2 \times 5 - 1)^2 \times 7 \times (2 \times 8) \approx 25 \text{ MBytes} \]

IMPLEMENTATION AND PERFORMANCES

Our experiments were performed on the core program OptiDis whose data structure relies heavily on the open source ScaLFF library [1]. The latter also provides the generic Fast Multipole algorithms. OptiDis-implemented is used to evaluate specific P2M/L2P matrices involving exact integration over segments as well as analytic expressions for nearfield taken from Arsenlis et al [2].

REFERENCES

[1] ScaLffm - software library to simulate large scale n-body interactions using the fast multipole method. Developed @ baec-team, inria bordeaux.

FUNDINGS

This work was supported by the French ANR grants ANR-10-COSI-0011 and the associate team FastLA.

In collaboration with CEA Saclay