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Improving the Accuracy and Efficiency of Hybrid Finite Element / Particle-In-Cell Methods for Modeling Geologic Processes

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Mack Gregory, University of California Davis, Computational Infrastructure for Geodynamics, Davis, CA, United States and Elbridge Gerry Puckett, University of California Davis, Mathematics and Computational Institute for Geodynamics (CIG), Davis, CA, United States

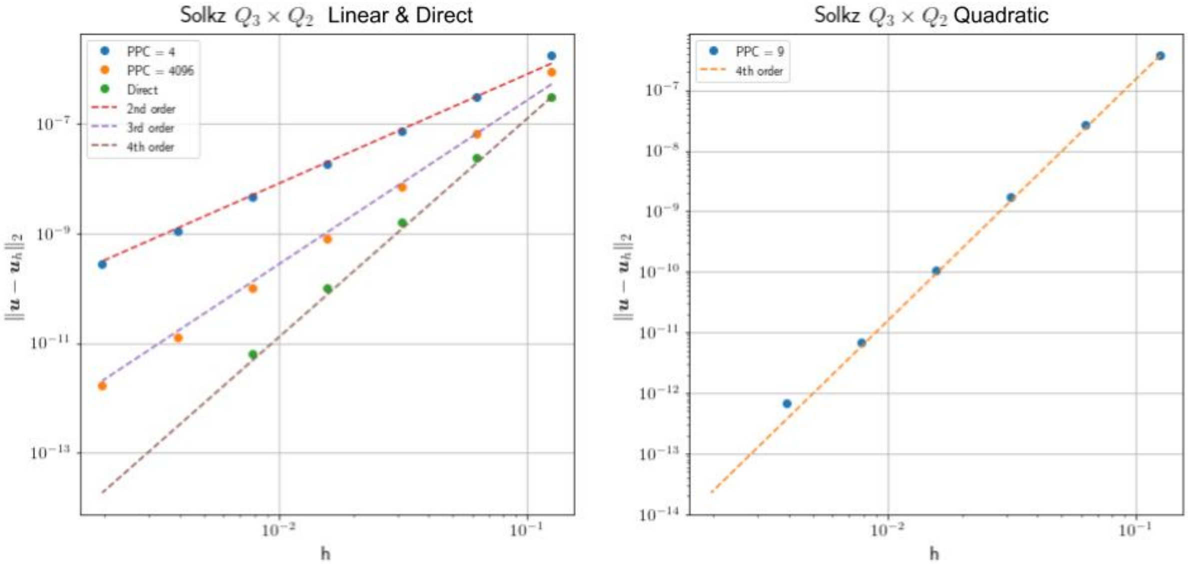
Abstract Text:

In many computational geodynamics models, properties such as density or viscosity are modeled with particles that carry the values of these properties and move with the underlying flow field. At each time step, the properties carried on the particles are interpolated onto the grid on which other quantities, such as the velocity, are computed. The most common interpolation method is to average the property values from the particles to the grid. More recently it has been shown that a Linear Least Squares (LLS) approximation to the particle values in each cell provides much greater accuracy. However, to achieve optimal accuracy, the LLS method requires the number of particles per cell (PPC) to continually increase as the grid size h goes to zero.

Here we demonstrate that a Quadratic Least Squares (QLS) interpolation requires only a small, fixed number of PPC, to achieve optimal accuracy as the cell size h goes to zero. In order to test the QLS method and compare it with the LLS method, we implemented both in the open source geodynamics code ASPECT and tested them on several 'classical' benchmarks, SolCx and SolKz, and on a new time-dependent benchmark in an annulus.

Our results demonstrate that with a small, fixed number of PPC QLS is as accurate as solving all three benchmarks directly (i.e., without particles). We also verify that LLS requires an increasing number of PPC to have the same convergence rate as the direct method or the QLS method. Thus, since QLS only requires 3 or 4 PPC, it significantly decreases the cost of using particles in a high-order accurate computation. Furthermore, since one can carry multiple properties on one particle, this enables researchers to make more complex computations of important geodynamic processes such as plate tectonics, rifting, etc. with greater accuracy but without the high cost of using an increasingly large number particles to ensure an accurate computation as is required

with the LLS method.



Our new Quadratic Least Squares interpolation method maintains high-order accuracy with a small number of particles per cell (PPC) when interpolating both density and viscosity from the particles to the grid. As shown in the plot on the right we achieve fourth-order accuracy with a constant PPC of 9 as the grid size h→0. The plot on the left shows that for the same computation Linear Least Squares (LLS) interpolation only achieves third-order accuracy with 4096 PPC, or fourth-order accuracy without using particles (the direct method). In a recent paper [1] the authors found that no number of PPC will achieve fourth-order accuracy with the LLS interpolation algorithm for this problem. (See Fig. 1 of [1].)

[1] - Gassmöller, R. Et al. Evaluating the accuracy of hybrid finite element/particle-in-cell methods for modelling incompressible Stokes flow. Geophysical Journal International, 219(3):1915–1938.

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Submitter's E-mail Address:
mgr@ucdavis.edu

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