EDGE: BENCHMARKING THE SEISMIC WAVE PROPAGATION SOLVER

A. Breuer¹, A. Heinecke² and Y. Cui³

ABSTRACT

We present the status of ongoing work, benchmarking the Extreme-scale Discontinuous Galerkin Environment (EDGE) for seismic wave propagation. EDGE uses the Discontinuous Galerkin (DG-) Finite Element Method (FEM) to solve hyperbolic partial differential equations. EDGE targets seismic model setups with high geometric complexity and extreme-scale ensemble simulations, using beyond 500,000 computer cores. The entire software stack is uniquely tailored to "fused" simulations. Fused simulations allow for different model setups within one execution of the forward solver. For example, the software allows to share the mesh and velocity model in the fused runs, but alter the kinematic source from run to run. This approach allows the code to exploit inter-simulation parallelism and reach significantly higher simulation throughput.

EDGE supports a broad range of configurations, influencing the quality of the numerical solutions, and the required time and computational power for obtaining these. We present results of the solver in the elastic wave propagation benchmarks HSP1a, HSP1b, HHS1, LOH.1 and Can4 of the SISMOWINE models. Our study’s modeling knobs cover 1) the solver’s order of convergence, 2) the used floating point precision, and 3) h-adaptivity, i.e., the number of elements per wavelength. Thus, additionally to benchmarking the accuracy of the solver, our study will ease the choice of important parameters, heavily influencing time-to-solution of EDGE. Our benchmarks’ setups and solutions, including the raw data, are available through EDGE’s data and software repositories from http://dial3343.org.

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Introduction

Benchmarking of numerical models is key to assess the accuracy of seismic wave propagation solvers. In terms of the elastic wave equations, the simplest set of benchmarks studies the propagation of plane waves in a periodic domain. In previous work [1, 2], we used a plane wave setup to study the performance of the Arbitrary DERivative Discontinuous Galerkin (ADER-DG) method, implemented in modal formulation on unstructured tetrahedral meshes. The work in [2] covered the impact of the convergence rate, floating point precision and mesh refinement on the accuracy of the solution in terms of well-defined error norms. This work also included a comprehensive study of time- and energy-to-solution on three generations of CPUs, as well as

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the Xeon Phi coprocessor. While we observed a reduction in energy-consumption by over 30% through the use of single precision arithmetic, the stagnation of the convergence plots at machine precision demands further investigation. In this ongoing work, we continue our systematic assessment of the ADER-DG solver’s accuracy and performance, initiated in [2], through step-wise increases of the benchmark complexity. We follow the structure of the SISMOWINE benchmarks, available from http://sismowine.org. Our first benchmarks, HSP1a and HSP1b study the accuracy of seismic wave propagation in a homogeneous fullspace. Next, we introduce free-surface boundaries via the homogeneous halfspace benchmark HHS1. The introduction of a material contrast through the Layer Over Halfspace 1 (LOH.1) benchmark is the last step in our extensive study. We conclude by showing sample results of the E2VP-Can4 benchmark [3].

Homogeneous Examples: HSP1a and HHS1

The HSP1a benchmark targets the assessment of numerical local and dispersion errors. The benchmark’s waves are generated through a double-couple point source at (0,0,0) with $M_{xy} = M_{yx} = 10^{18}$ Nm being the only non-zero components of the moment tensor. The moment-rate time history of the source is given through $s(t) = M_{xy} \cdot t/T^2 \cdot e^{-t/T}$, where $t$ is time and $T = 0.1$. The benchmark’s solution, given as the particle velocities in all three Cartesian directions, can be obtained analytically by following [4], as done for SISMOWINE’s reference solution. The HSP1a benchmark compares the solution at a set of 12 receivers in the first 5s. The receivers sample the wave field at line segments, originating from the point source. With a targeted, maximum resolved frequency of 5Hz, the minimum wave length is given by $\lambda_{\text{min}} \approx 693$ m. The seismic receivers of the HSP1a benchmark have a source distance of $1\lambda_{\text{min}}$, $8\lambda_{\text{min}}$ and $15\lambda_{\text{min}}$. We used the software gmsh [5] (version 3.0.5) to generate a series of problem-adapted meshes for the HSP1a benchmark problems. As illustrated in Fig. 1, we specified a spherical-shaped domain with a spherical, strongly refined region of interest. Domain boundaries are set to outflow boundary conditions. The targeted length of the tetrahedral elements’ edges is called characteristic length within gmsh. We set up different benchmark runs with characteristic lengths of the inner sphere, $c_{l_{\text{in}}}$, sampled in [100m,650m]. The remainder of the domain was aggressively coarsened by using a ten times larger characteristic length. Additionally, we used gmsh’s built-in optimizer and gmsh’s Netgen interface to improve the quality of the tetrahedrons. Comparing the specified characteristic length, $c_{l_{\text{in}}}$, with the obtained mean edge length of the tetrahedrons in the inner sphere, we observe a consistent $\sim38\%$ increase in the final mesh.
The HHS1 benchmark adds a planar free surface at \( z = 0 \) to the complexity of the HSP1a benchmark. The HHS1 double-couple point source is located at \((0, 0, 693\text{m})\). Moment rate time history and homogeneous material parameters are identical to HSP1a. The HHS1 benchmark compares seismograms of nine receivers to a reference solution in the time interval \([0, 5\text{s}]\). SISMOWINE’s reference solution is given through synthetics, obtained with the DWN method. The targeted, maximum frequency is 5 Hz, which results in an identical minimum wave length of \( \lambda_{\text{min}} \approx 693\text{m} \) and seismic receivers at the surface using identical source distances. Analogue to HSP1a, we used gmsh to set up problem-adapted meshes. In addition to a refined region of interest, we set an attractor to gradually coarsen the mesh. We refined the region of interest with characteristic lengths of \( c_{\text{roi}} \) sampling \([100\text{m}, 500\text{m}]\). Fig. 2 illustrates the HHS1 mesh for \( c_{\text{roi}} = 500\text{m} \). We used gmsh’s built-in optimizer and Netgen to improve the mesh quality. Similar to HSP1a, we observed a \( \sim 35\% \) increase of the mean edge length over the specified characteristic length w.r.t. the region of interest.

**Benchmark Results**

We varied the polynomial degree of our numerical simulations between \( P0 – P6 \) for the benchmarks, resulting in convergence rates \( O1 – O7 \). Additionally, we ran all simulations in single precision (32bit) and double precision (64bit) floating point arithmetic. The simulations used the Cori-II supercomputer at the National Energy Research Scientific Computing Center (NERSC). The benchmarks compare synthetics to a reference solution. Consequently, determining the accuracy of the numerical solution is more demanding than the simple error norm computations of the convergence benchmark in [1, 2]. We use the software TF_MISFIT_GOFCRITERIA [6] to compute envelope and phase misfits, as well as goodness-of-fit criteria. Fig. 2 exemplary compares EDGE’s synthetics to the reference solution. We see a good fit of EDGE’s solution, which is confirmed by the low misfits.

![Figure 2. Exemplary illustration of EDGE’s solutions. Shown are the seismograms, time-frequency envelope misfits and time-frequency phases misfit in [0.13Hz, 5Hz]. Left (HSP1a, O5, 32bit): Particle velocity in x-direction for receiver six at (7348m, 7348m, 0), using \( c_{\text{lin}} = 500\text{m} \). Center (HHS1, O4, 64 bit): Particle velocity in z-direction for receiver eight at (4612m, 3075m, 0), using \( c_{\text{roi}} = 150\text{m} \). Right (HHS1, O4): Particle velocity in z-direction for receiver eight at (4612m, 3075m, 0), using \( c_{\text{roi}} = 150\text{m} \). The 64bit (reference) solution is compared to the 32bit solution.](image-url)
E2VP-Can4: Basin Model with Homogeneous Layers

We conclude our presentation by showing results for the geometrically demanding E2VP-Can4 verification benchmark. E2VP-Can4 simulates seismic wave propagation in a three-layer basin, simplifying the 3D structure of a Mygdonian basin model. The layers are only 17.3m, 72m, and 115.6m thick, challenging meshers and solvers. We ran a 4th order simulation using a mesh with 198,289,412 tetrahedral elements on 1,500 nodes of Stampede 2. A shown in Fig 3., our obtained solution is very close to the reference solution of [3].

Conclusions and Acknowledgments

As an early result, we observe almost identical solutions, when comparing single to double precision arithmetic. Single precision offers a theoretical two-times speedup over double precision on current computer architectures. Emerging architectures, e.g. Knights Mill, will have even higher ratios. Thus, if confirmed in the final, fully evaluated study, this result will shift our focus on lowered precision when developing EDGE. EDGE is available from http://dial3343.org. Respective raw data is CC0’d and publicly available through EDGE’s data repository: http://opt.dial3343.org. This research used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. This work used the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant number ACI-1548562.

References