Large-scale Ultrasound Simulations with Local Fourier Basis Decomposition

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ABSTRACT

This paper presents a novel approach to spectral methods domain decomposition. By reducing the communication overhead and accepting a small numerical inaccuracy, we managed to improve scaling from 512 up to 8192 cores while reducing the simulation time by a factor of 8.55.

Keywords

Ultrasound simulations, Local decomposition, Pseudospectral methods, k-Wave toolbox.

1. INTRODUCTION

The simulation of ultrasound wave propagation through biological tissue has a wide range of practical applications including planning therapeutic ultrasound treatments of various brain disorders such as brain tumours, essential tremor, and Parkinson's disease [5], [6]. The major challenge is to ensure the ultrasound focus is accurately placed at the desired target within the brain because the skull can significantly distort it. Performing accurate ultrasound simulations, however, requires the simulation code to be able to exploit thousands of processor cores and work with TBs of data while delivering the output within 24 hours.

We have recently developed an efficient full-wave ultrasound model (the parallel k-Wave toolbox) enabling to solve realistic problems within a week using the pseudospectral model and a global slab domain decomposition (GDD) [4]. Unfortunately, GDD limits scaling by the number of 2D slabs, which is usually below 2048. Moreover, since the method is reliant on the fast 3D Fourier transform, all-to-all communications concealed in matrix transpositions significantly deteriorate the performance [3].

This poster presents a novel decomposition method called Local Fourier basis decomposition (LDD) [2], [1]. This approach eliminates the necessity of all-to-all communications by replacing them with local nearest-neighbour communication patters. The reduced communication overhead leads to better scaling despite the fact that more work (calculation of the halo region) must be done.

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2. IMPLEMENTATION

The parallel k-Wave toolbox solves a system of three coupled PDEs describing the relation among acoustic pressure, acoustic particle velocity and acoustic destiny accounting for combined effects of medium heterogeneity, absorption and non-linear wave propagation. These equations are discretised using the k-space pseudo spectral method and solved iteratively [7].

The LDD partitions the 3D domain into a grid of subdomains coated with a halo region of a defined thickness. The gradients (FFTs) are only calculated on local data. In order to ensure the ultrasound wave can propagate over subdomain interfaces, the halo regions are periodically exchanged with the direct neighbours. To make the propagation over the interfaces smooth, a custom bell function was developed.

When developing the LDD, we addressed the communication overhead by (1) reducing the number of communication phases per time-step from 14 down to 7, (2) replacing global all-to-all communications by local nearest-neighbour patterns, and (3) overlapping the halo exchange with computation impossible under the global domain decomposition.

The main drawback of LDD is the reduced accuracy arising from the fact that the gradients are not calculated over the whole domain. The level of numerical error can be controlled by the thickness of the halo region. By experimental validation and numerical optimization, the thickness of 16 grid points was determined as sufficient.

3. EXPERIMENTAL RESULTS

The performance and scaling were investigated on realistic ultrasound simulations with various spatial resolutions between 512^3 and 2048^3 grid points. We used SuperMUC's thin nodes (two 8-core Sandy Bridges) and scaled the calculation from 8 cores (one socket) to 8192 cores (512 nodes).

Figure 1 presents strong scaling for GDD and LDD on several simulation domains. While GDD's scaling is quite limited and shows performance fluctuations, the LDD scales nicely up to 8192 cores for all domain sizes. Moreover, the scaling curves for LDD are smoother and steeper yielding much higher efficacy. The convenient shape of the scaling curves suggests that large domains will be easy to scale to even higher number of cores.

Fig. 2 directly compares the GDD and three types of LDDs (pure-MPI version, and hybrid OpenMP/MPI versions with a single process per socket and per node). The hybrid versions further reduce communication overhead and the relative size of the halo region. This leads to superior performance of both hybrid versions which can outperform the pure-MPI and GDD versions on the same number of cores by a factor of 1.5 and 4, respectively.

4. CONCLUSIONS

This poster has presented a novel domain decomposition for spectral methods based on local Fourier basis allowing to employ up to 16 times more computer cores. The time per simulation timestep was reduced by a factor of 8.55 in the best case. Since typical ultrasound simulations need a week to finish on 1024 cores, this decomposition can finally get us below 24 hours, which is necessary for clinical trials.

5. ACKNOWLEDGMENTS

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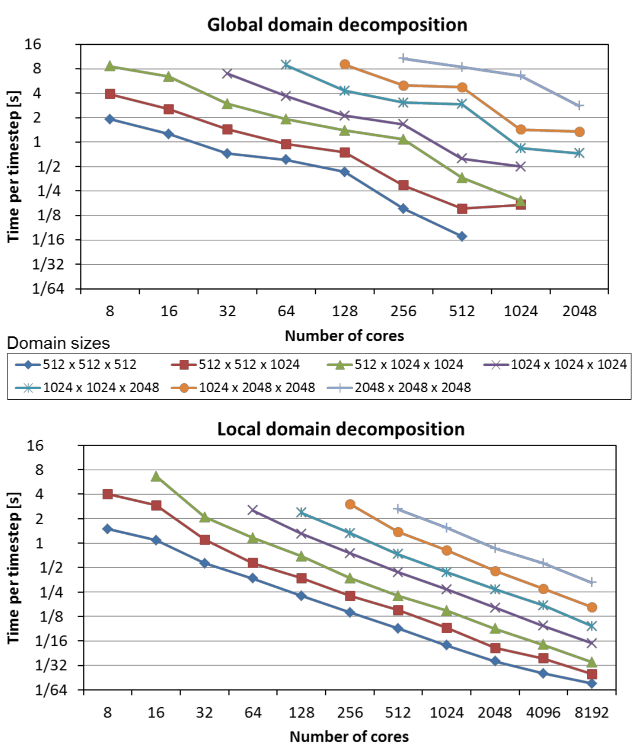

Figure 1: GDD and LDD strong scaling on SuperMUC.

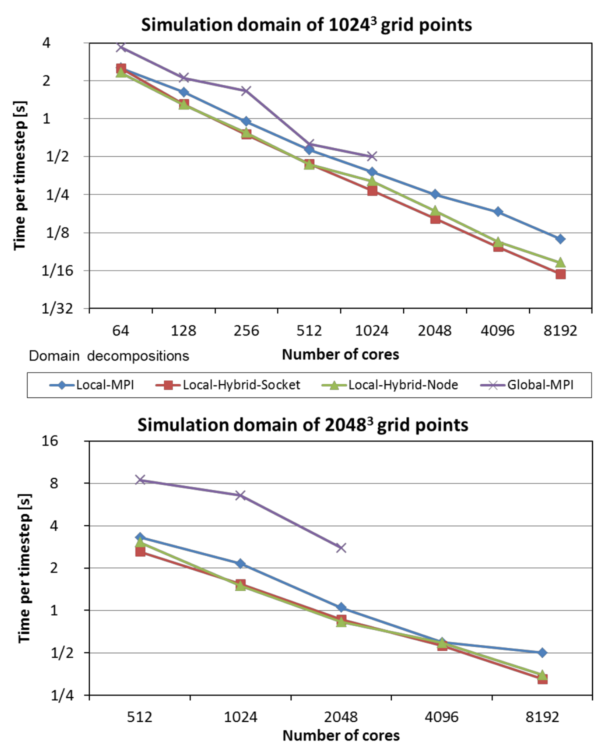

Figure 2: Comparison of investigated decompositions on domains of 1024^3 and 2048^3 grid points.