GPU-accelerated Immersed Boundary Method for the efficient simulation of biomedical fluid-structure interactions

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Background: the AV-FLOW Project

High-Performance Numerical Simulation of Fluid-Structure Interaction in the aortic heart valve system.

Crucial role in medical device implantation in case of aortic valve disease.

Challenging due to pulsatile turbulent blood flow and elastodynamical behaviour of soft tissue.

Immersed Boundary Method is widely used to avoid expensive mesh-fitting operation of the fluid domain.

Scalable highly accurate incompressible flow solver (IMPACT) simulates the complex blood flow. The elastodynamic deformation of soft tissue is simulated in a dedicated parallel FEM solver (PASSO).

Continuous Immersed Boundary Method

Transfer operations between the fluid grid and the FE mesh are targeted to be accelerated on GPGPUs.

General Purpose Graphical Processing Units (GPGPU)

Accelerating floating point operations in shared memory paradigm.

Thousands of parallel threads can be executed on GPU.

Maximum GPU capacity should be utilized to hide the memory-latency.

Tesla K20x GPUs on Cray XC30 machine (CSCS-Piz Daint):
14 multiprocessors
5.6GB GDDR5 memory
max 2048 threads per multiprocessor
max 1024 threads per block

Sharp Interface Immersed Boundary Method

Flow simulation in moving 3D complex geometries on a Eulerian fluid mesh

Sharp-Interface Method is extensively used for biomedical FSI simulations

Ghost Cell Methodology for Immersed Boundary treatment

No need for conforming mesh, but the IB treatment is still expensive!

Remedy: Computational Geometry operations can be accelerated on GPUs.

Considerations:
1. CPU-GPU data bandwidth is limited
2. More operation on staggered grid
3. Dynamic allocation is crucial for moving boundaries
4. Parallel reduction is restricted by the "shared memory"
5. Double precision accuracy not achievable on all threads

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Results

Turbulent incompressible flow through an array of 30 rigid cylinders (Re=10000).

Multi-beat simulation of turbulent incompressible flow through a mechanical valve (Re=3000).

Extensive IB computations due to:
High-resolution grid for resolving the turbulent flow
Large and discrete solid-fluid interface
Staggered grid in the flow solver

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References