Case 3.4: 2D Laminar Flapping Wing

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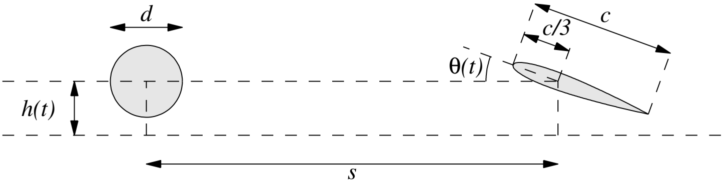
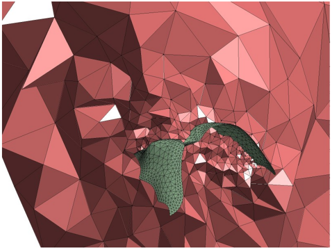
Problem Description

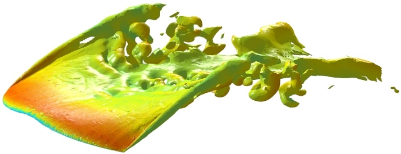
- Inspired by experimental study [Gopalkrishnan/Triantafyllou/et al, '94], computational study in [Persson/Peraire/Bonet '09]
- An oscillating cylinder produces vortices that interact with a heaving and pitching airfoil, in a typical flapping motion
- Freestream Mach = 0.2, Re = 500, St = 0.1 (for cylinder)
- Thrust on airfoil highly dependent on distance s and the vortices convected from cylinder – potentially good case for high-order methods



Implementation: The 3DG Software Package

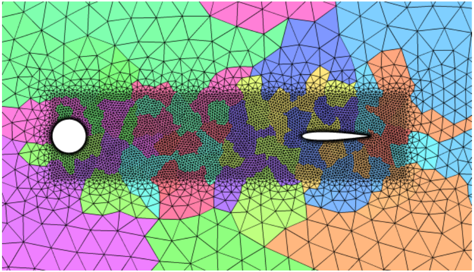
- High-order fully consistent DG on unstructured meshes
- CDG fluxes for viscous terms – sparsest known scheme
- Newton-Krylov solvers, ILU/p-multigrid preconditioning
- Minimum Discarded Fill element ordering
- MPI-parallelization by connectivity-weighted domain partitioning
- Deforming domains by mapping-based ALE-approach
- Curved and deformed meshes by nonlinear elasticity
- Nonlinear stability by hierarchical sensors and artifical viscosity

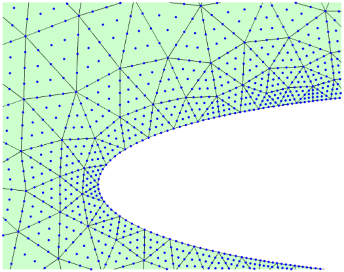




Simulation details

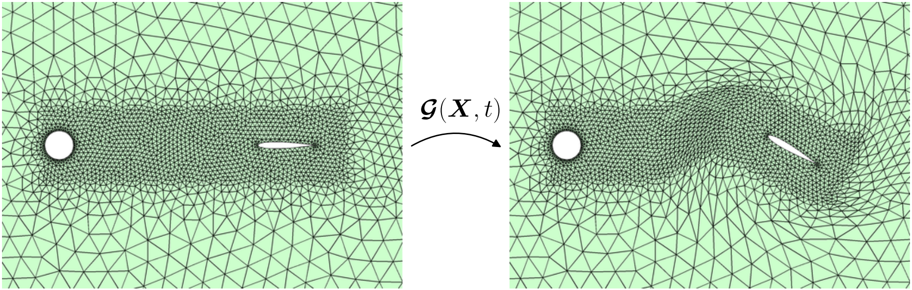
- Two meshes: 4,362 and 12,885 triangular elements
- Polynomial degrees $p = 1, 2, 3, 4$
- Explicit RK4 scheme in time, $\Delta t = 2.5 \cdot 10^{-5}$ for all cases
- Parallel execution on 96 cores, 4 million timesteps per case





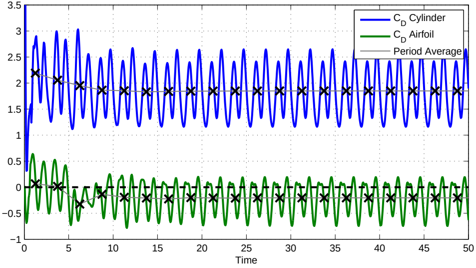
Mapping between reference and deforming domain

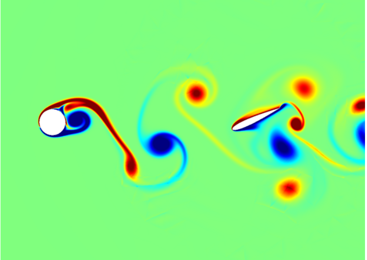
- Analytically prescribed mapping $\mathcal{G}(\boldsymbol{X}, t)$
- Combination of rigid motions and smooth blending functions
- Symbolic computation of grid velocity $\boldsymbol{v}_X = \frac{\partial \mathcal{G}}{\partial t}\Big|_X$ and deformation gradient $\boldsymbol{G} = \nabla_X \mathcal{G}$
- No moving meshes $\longrightarrow$ high-order accuracy in space and time



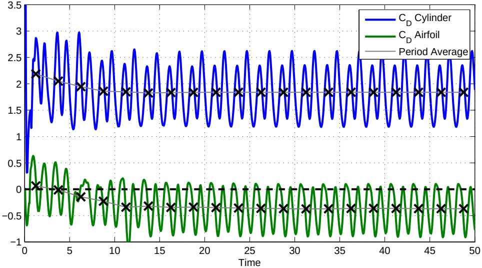
Results, St = 0.2 (drag coefficients)

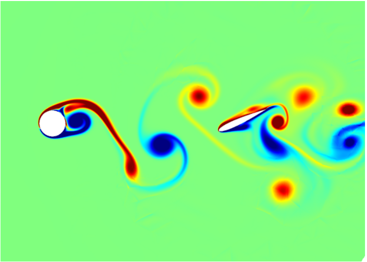
Airfoil position $s = 3.76$:





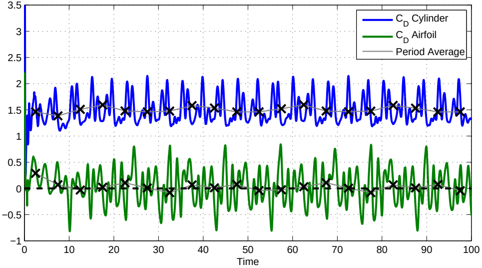
Airfoil position $s = 3.50$:

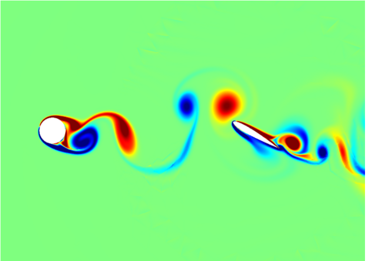




Results, St = 0.1 (drag coefficients)

Airfoil position $s = 3.76$:





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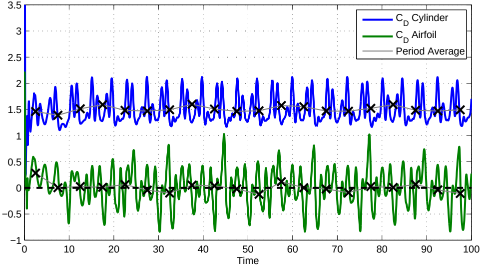
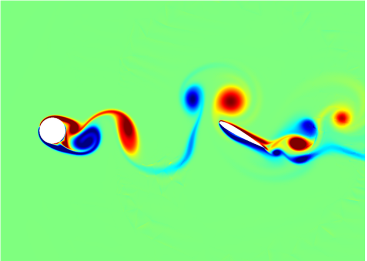
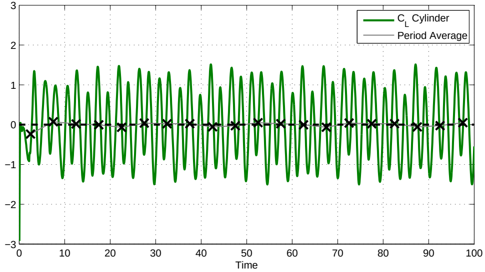
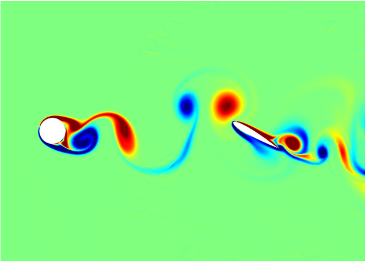




Results, St = 0.1 (lift coefficient, cylinder)

Airfoil position $s = 3.76$:





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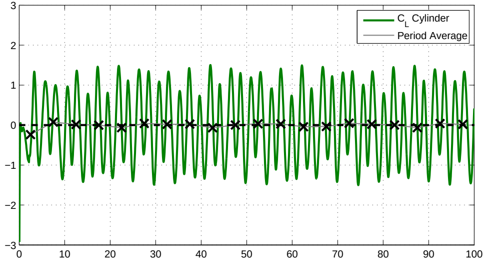
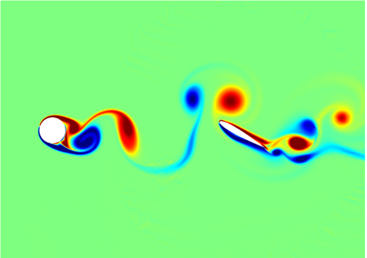
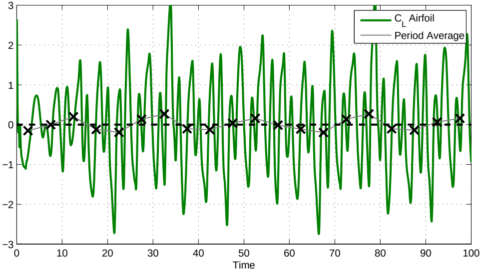
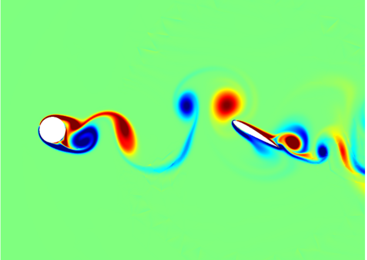




Results, St = 0.1 (lift coefficient, airfoil)

Airfoil position $s = 3.76$:





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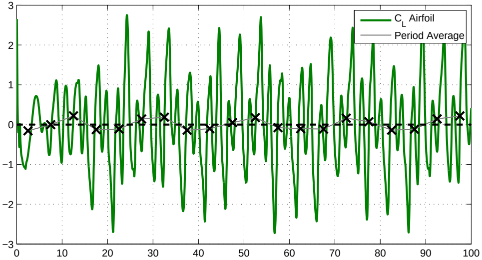
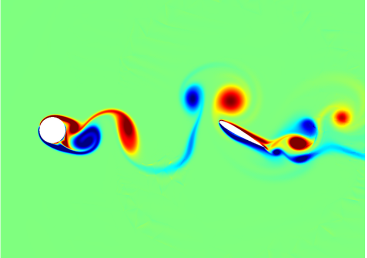
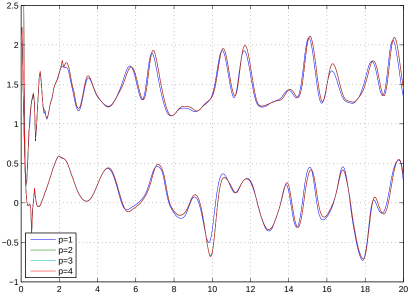
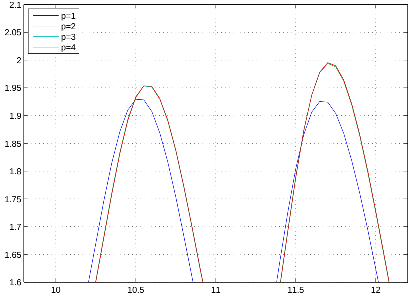
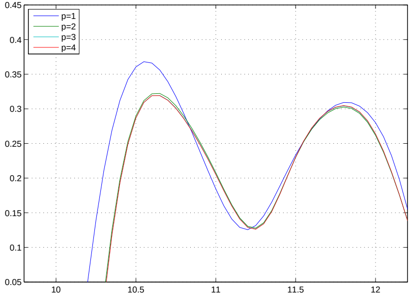




Convergence, time plot: $s = 3.5$, fine mesh



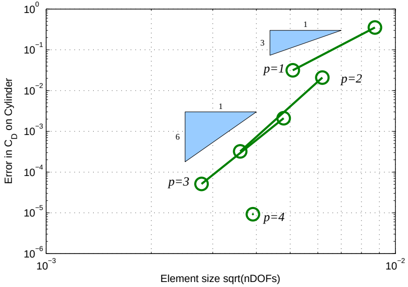


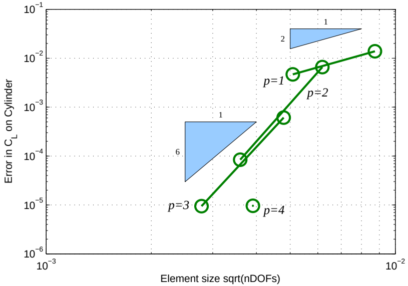


- C_D on cylinder (top) and on airfoil (bottom)

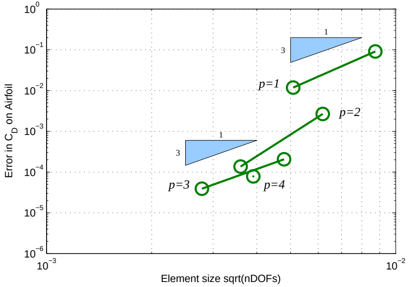
Convergence vs DOF: $s = 3.5$, last period averages

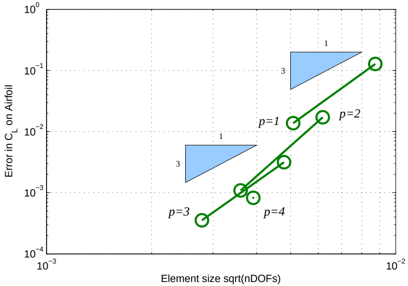
Cylinder





Airfoil





Convergence vs work: $s = 3.5$, last period averages

Cylinder

Airfoil