High-order spatial and temporal approaches for overset applications and AMR grids

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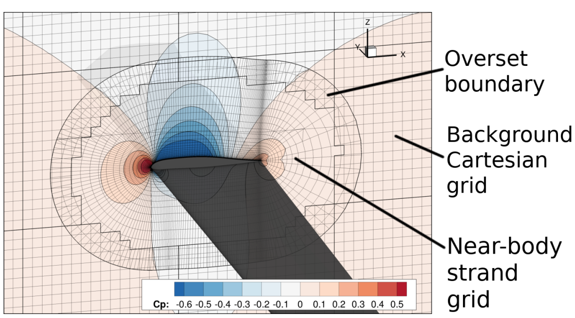
1 Introduction and Problem Statement

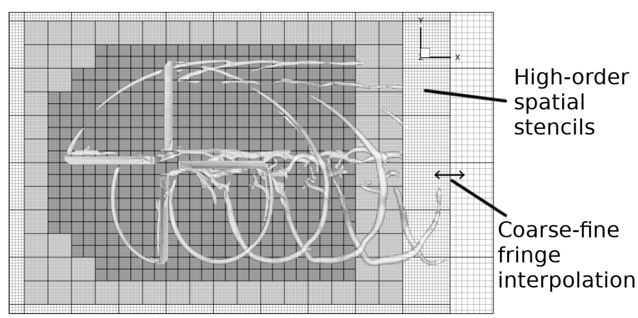
Overset approaches in Computational Fluid Dynamics (CFD) have become widely adopted for simulating applications with complex geometries and moving bodies. The HPCMP CREATE^{TM}-AV Helios framework[1], developed for rotorcraft simulations, is a successful example of the overset, multi-solver paradigm; simulation components are meshed individually and overset within a background Cartesian Adaptive Mesh Refinement (AMR) grid.

A typical rotor simulation solution from Helios is shown in Fig. 1. The near-blade region is solved using the strand-based solver mStrand and the background region is solved using the octree-based AMR solver Orchard [2]. Figure 1(a) shows the respective domains near the blade as well as the overset interface. Each solver uses its own spatial and temporal discretizations; a domain connectivity module in Helios performs hole-cutting and interpolation at domain boundaries.

Helios de-couples the timestepping between each solver resulting in first-order temporal accuracy near the overset region. Higher-order temporal accuracy cannot be achieved using this methodology, regardless of the time-marching scheme used in each solver. For the entire overset simulation to be high-order accurate in time the time-stepping scheme would have to include communication between solvers at the non-linear solver iteration level of the governing equation. Furthermore, if a multi-stage RK-type scheme is used, any grid motion and corresponding domain re-connectivity has to be recomputed for each stage.



(a) Blade cross-section pressure



(b) Rotor Q-Criterion solution

Figure 1: Overset solution of PSP rotor using Helios with mStrand and Orchard.

Figure 1(b) shows the top view of the Q-criterion solution in the background Cartesian grid for a rotor simulation. Orchard uses high-order finite-difference stencils up to 5th-order accurate for inviscid terms and 4th-order accurate for viscous terms. Refinement is prescribed around the rotor to capture the rotor wake. In neighboring blocks of the same refinement level, fringe communication involves no interpolation. At coarse-fine interfaces, however, cell-centered quantities must be interpolated and sent to neighboring blocks. Fringe interpolation in Orchard (as well as most other AMR codes) is only 2nd order accurate. The low interpolation accuracy affects the overall accuracy of the full simulation. Increasing the interpolation order is not a trivial task, since widening any interpolation stencil will extend to include ghost cells as donors. When a ghost cell becomes a donor in an interpolation stencil to another ghost cell this can be thought of as "implicit" interpolation. Implicit interpolation can have negative impacts on convergence or linear solver performance.

2 Recent and Projected Work

Internally the Cartesian AMR solver, Orchard, can use either standard backwards-Euler (BDF-type) or Singly Diagonal Implicit Runge Kutta (SDIRK) schemes for time integration. For a vortex convection case, as shown in Fig. 3, Orchard attains up to 4^{th}-order accuracy in time. The same SDIRK schemes are being implemented at the framework level in Helios with communication between overset solvers within each stage. An important consideration for cases with moving grids will be to ensure the grids are updated (and reconnected) at each stage of the SDIRK scheme.

Orchard uses balanced octrees for prescribing refinement and guarantees a maximum ratio of 2:1 difference between the levels of neighboring octants. Currently with 2^{nd}-order interpolation, a 2-step procedure is used to avoid implicit interpolation at fringes. For high-order interpolation with larger stencils, avoiding implicit interpolation can be done by including points from the domain of the receiver fringe cell. An example stencil for higher-order interpolation is shown in Fig. 2, where a coarse (blue) fringe is interpolated from red cells in the neighboring mesh as well as blue cells in the current mesh. Interpolation weights can be computed using different methods, for example high-order least-squares or tensor-product interpolation.

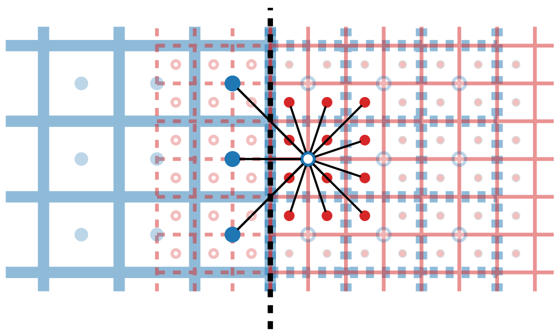


Figure 2: 4^{th}-order interpolation stencils at coarse-fine block boundaries. The fine and coarse grids are shown in red and blue respectively.

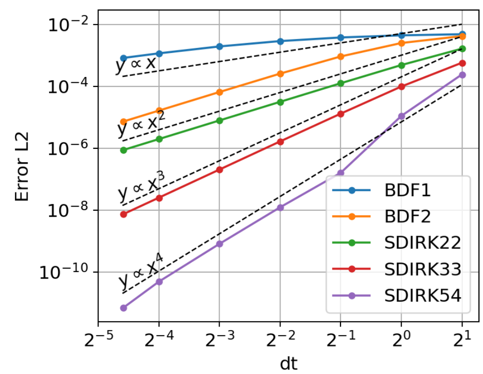


Figure 3: Vortex convection: temporal accuracy convergence.

The final paper will include:

- Methodology for achieving high-order temporal accuracy using SDIRK schemes with moving, overset meshes.
- Methodology for interpolating and exchanging fringe information for AMR meshes using 4^{th} order interpolation stencils.
- Time-accuracy validation up to 4^{th} order for a shedding sphere or triangular wedge.
- Spatial-accuracy validation of the AMR fringe interpolation up to 4^{th} order.
- Application of the high-order space and time methodologies to a hovering rotor solution.

References

[1] Andrew M. Wissink, Dylan Jude, Buvaneswari Jayaraman, Beatrice Roget, Vinod K. Lakshminarayan, Jayanarayanan Sitaraman, Andrew C. Bauer, James R. Forsythe, and Robert D. Trigg. New capabilities in CREATE-AV helios version 11. In *AIAA Scitech 2021 Forum*, Nashville, Tennessee, jan 2021. American Institute of Aeronautics and Astronautics.

[2] Dylan Jude, Jay Sitaraman, and Andrew M. Wissink. An octree-based, cartesian navier–stokes solver for modern cluster architectures. *The Journal of Supercomputing*, 2022. (yet to appear).