Coupling meso- and micro-scale fluid dynamics codes for wind-energy computing

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Motivating problem

NREL LDRD Project (PI: Pat Moriarty): Wind Turbine Array Fluid Dynamic and Aero-elastic simulations

- Create a computational simulation tool that predicts the response and interaction of
  - turbine structural dynamics
  - turbine-proximity fluid dynamics
  - meso-scale atmospheric fluid dynamics

- Couple Weather Research and Forecasting (WRF) code to OpenFOAM

- Couple OpenFOAM to NREL’s aeroelastic design code, FAST
OpenFOAM-WRF coupling: Challenges

- Codes are addressing different physics
  - OpenFOAM: incompressible Navier-Stokes equations
  - WRF: compressible Euler equations

- Codes use different discretization methods
  - OpenFOAM: finite volume plus semi-implicit time integration
  - WRF: finite differences plus explicit time integration

- Computational grids are non-matching (space and time)
Approach

- Create an open-source test platform comprised of 2-D codes that mimic WRF and OpenFOAM
- Develop and implement algorithmic-coupling strategies and examine performance
Notation:

\( \mathbf{u}_E(x, y, t), \rho_E(x, y, t) \): Solution to Euler equations in \( \Omega_E \)

\( \mathbf{u}_{NS}(x, y, t) \): Sol’n to Navier-Stokes eqs. in \( \Omega_{NS} \); \( \rho_{NS} = \text{const} \)

\( \Omega_{NS} \subset \Omega_E \)
2-D Test-problem domain

Challenge:

\[ \nabla \cdot (\rho_{NS} \mathbf{u}_{NS}) = 0 \quad \nabla \cdot (\rho_{E} \mathbf{u}_{E}) \neq 0 \]
Consider case where mean flow is North-East in the Euler domain and we wish to drive the flow in the Navier-Stokes (NS) domain.
One-way coupling: Partial boundary

\[ \Gamma_{NS} \]

\[ \frac{\partial \mathbf{u}_{NS}}{\partial n} = 0 \]

- Apply velocity boundary conditions where there is inflow; outflow BCs where there is outflow

- What is \( \mathbf{F} \)?

\[ \mathbf{u}_{NS} = \mathbf{F}(\mathbf{u}_E, \rho_E, \rho_{NS}) \]
Partial boundary coupling: Inflow

- What is an appropriate \( F \) in \( \mathbf{u}_{NS} = F(\mathbf{u}_E, \rho_E, \rho_{NS}) \)?

- If we take \( F = \sqrt{\frac{\rho_E}{\rho_{NS}}} \mathbf{u}_E \), then the kinetic-energy density along the "inflow" interface is matched, i.e.
  \[
  \frac{1}{2} \rho_{NS} \mathbf{u}_{NS} \cdot \mathbf{u}_{NS} = \frac{1}{2} \rho_E \mathbf{u}_E \cdot \mathbf{u}_E \quad \text{on inflow}
  \]

- We expect that \( \frac{\rho_E}{\rho_{NS}} \approx 1 \)
One-way coupling: Projection

- Interested in defining flow boundary condition on all sides

\[ \mathbf{u}_{NS} = G(\mathbf{u}_E, \rho_E, \rho_{NS}) \text{ on } \Gamma_{NS} \]

- Challenge: Need to choose “appropriate” \( G \)
Projection coupling

- Use Lagrange multiplier to project $\rho_E u_E$ onto incompressible solution

- Introduce “projection” domain $\Omega_P$ with boundary $\Gamma_P$, where $\Omega_{NS} \subseteq \Omega_P \subset \Omega_E$

- Problem: Find $\lambda(x, y)$ in $\Omega_P$, with $\lambda = 0$ on $\Gamma_P$

  \[ \nabla \cdot (\rho_E u_E - \nabla \lambda) = 0 \quad \Rightarrow \quad \nabla^2 \lambda = \nabla \cdot (\rho_E u_E) \]

- Let $u_{NS} = (\rho_E u_E - \nabla \lambda)/\rho_{NS}$ on $\Gamma_{NS}$
2-D Test problem

\[ u_0(x, y) = u_\infty - \frac{\lambda y}{2\pi} \exp \left[ \eta(1 - r^2) \right] \]

\[ v_0(x, y) = v_\infty + \frac{\lambda x}{2\pi} \exp \left[ \eta(1 - r^2) \right] \]

\[ \rho_0(x, y) = \left\{ T_\infty - \frac{(\gamma - 1)\lambda^2}{16\eta\gamma\pi^2} \exp \left[ 2\eta(1 - r^2) \right] \right\} \frac{1}{(\gamma-1)} \]

\[ r = \sqrt{(x - x_0)^2 + (y - y_0)^2} \]

\[ u_\infty = v_\infty = T_\infty = 1 \]

\[ x_0 = y_0 = -5, \quad \lambda = 5, \quad \eta = 1, \quad \gamma = 1.4 \]

- \( \Omega_E = [-10, 10]^2; \Omega_{NS} = [-2.5, 2.5]^2 \)

- Isentropic vortex (Garnier et al., 2001); exact solution to compressible Euler equations

- Propagate vortex from Euler domain into NS domain
One-way coupling results: Velocity magnitude

Perturbation velocity magnitude in $\Omega_{NS}$ at $t = 5$:

Euler  Partial Boundary  Projection

[0, 1] color scale; $Re = 100$
One-way coupling results: Kinetic-energy density

Kinetic-energy density in $\Omega_{NS}$ at $t = 5$:

Euler  Partial Boundary  Projection

[0, 2.5] color scale; $Re = 100$
Next steps

- Continue evaluating one-way coupling
- Extend coupling schemes for two-way interaction
- For now, ignore the elephant in the room
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