Modeling Rotor Wakes with a Hybrid OVERFLOW-Vortex Method on a GPU Cluster

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APPLIED SCIENTIFIC RESEARCH
Engineering and Software Development Consultants

Outline

- Motivation
  - physical and numerical
- Method
  - Lagrangian vortex particle methods
  - Hybrid coupling scheme
- Test simulations

Motivation

- Rotor wakes are long-lived
- Blade interaction causes noise, loss of lift
- Obstructions make motion unpredictable
- Understanding vortex ring state

http://flickr.com/photos/93995449@N00/1223845347

http://www.web.mek.dtu.dk/staff/jhw/projekter.htm

Eulerian CFD

- Advantages
  - High-order methods
  - Body-fitted grids with high aspect ratio
  - Generality
- Disadvantages
  - Numerical diffusion
  - Gridding effort
  - Start-up
  - Far-field BCs

Lagrangian CFD

- Advantages
  - Numerical diffusion can be explicit (not limited by CFL)
  - Lower dimension grids
  - Efficient use of computational elements/far-field BCs automatic
  - Continuity preserved by construction
  - No start-up problems

- Disadvantages
  - Computationally expensive
  - Largely incompressible
  - Spatial adaptation difficult

Hybrid solution

- Euler solver near boundaries
  - Capture boundary layer
  - Proper vorticity creation at boundary

- Lagrangian solver in wake
  - Maintain vorticity in wake
  - No need for overset grids to far-field

OVERFLOW 2.1ae

- Developed over 20 years by P.G. Buning *et al.*
- Fully-compressible Navier-Stokes Eulerian solver
- Chimera overset structured grids
- Supports multi-threading via OpenMP
- Distributed parallelism via MPI

Ω-Flow v2

- Developed over 10 years by A. Gharakhani *et al.* at ASR
- Multipole-accelerated treecode N-body solver
- Multipole-accelerated BEM solver
- Supports multi-threading via OpenMP
- Distributed parallelism via MPI
- Accelerates computations on capable GPUs
- See our other paper: “A GPU-Accelerated Boundary Element Method and Vortex Particle Method”, AIAA-2010-5099

Lagrangian vortex methods

- **Navier-Stokes equations in vorticity**

$$\frac{D\omega}{Dt} = \omega \cdot \nabla u + \nu \nabla^2 \omega$$

- **Discretized onto Lagrangian particles**

$$\begin{aligned} \bar{\omega}(\bar{x},t) &= \sum_{i=1}^{N_v} \bar{\Gamma}_i(t)\, \phi_\sigma(\bar{x} - \bar{x}_i) \\ \bar{\Gamma}_i &= \bar{\omega}_i\, \Delta V_i \end{aligned}$$

Lagrangian vortex methods

- **Helmholtz integral formula**

$$
\begin{aligned}
\vec{u}(\vec{x}) = \vec{U}_\infty \quad & + \quad \nabla \times \int_V \vec{\omega}(\vec{x}')\, G(\vec{x},\vec{x}')\, dV(\vec{x}') \\
& - \quad \nabla \int_V \theta(\vec{x}')\, G(\vec{x},\vec{x}')\, dV(\vec{x}') \\
& + \quad \nabla \times \int_S \big(\vec{\gamma}(\vec{x}') + \hat{n}(\vec{x}') \times \vec{u}(\vec{x}')\big) G(\vec{x},\vec{x}')\, dS(\vec{x}') \\
& - \quad \nabla \int_S \big(\hat{n}(\vec{x}') \cdot \vec{u}(\vec{x}')\big) G(\vec{x},\vec{x}')\, dS(\vec{x}')
\end{aligned}
$$

Lagrangian vortex methods

- **Inviscid flow**

$$\begin{aligned} \frac{\partial \bar{x}_i}{\partial t} &= \bar{u}_i \\ \frac{\partial \bar{\Gamma}_i}{\partial t} &= \bar{\Gamma}_i \cdot \nabla \bar{u}_i \end{aligned}$$

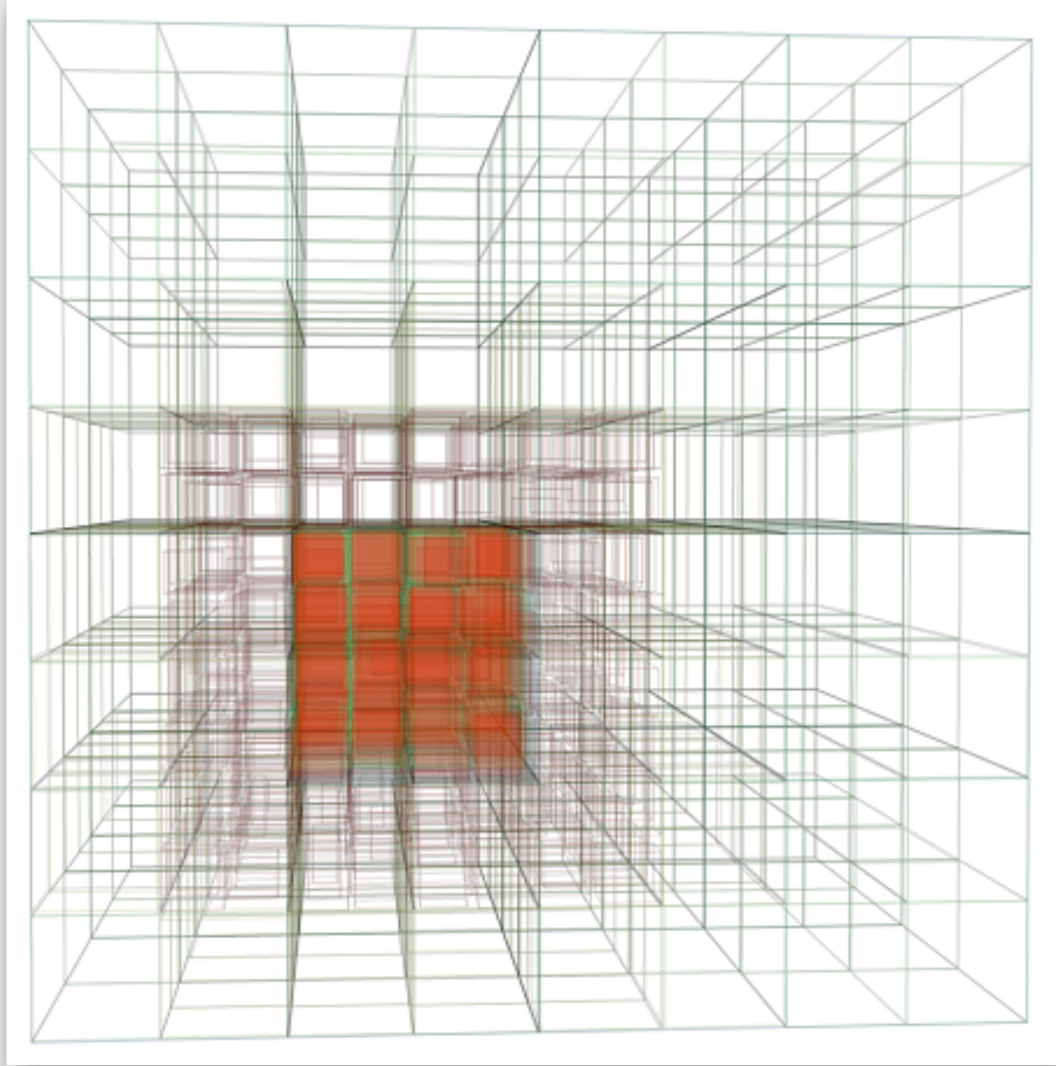
- **Viscous diffusion via VRM (Shankar and van Dommelen, 1996)**

$$\frac{\partial \bar{\Gamma}_i}{\partial t} = \nu \nabla^2 \bar{\Gamma}_i$$

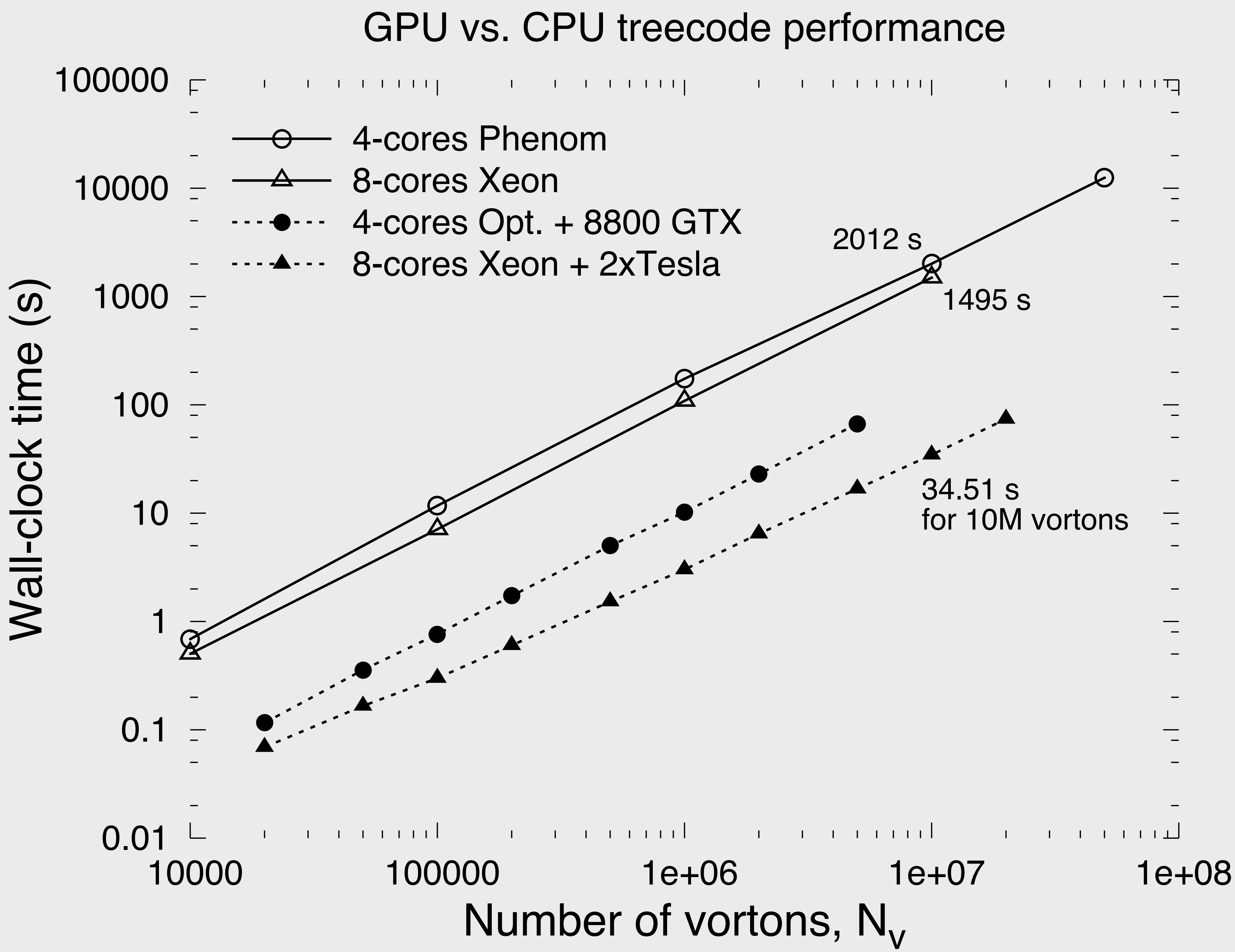
- **Anisotropic SGS dissipation (Cottet *et al*. 1996, 2003)**

Faster summations

- Barnes and Hut *Treecode* (1986), Greengard-Rokhlin *FMM* (1987)
- Distributed-memory parallelization (Salmon 1991)
- Data structures organized to prevent cache misses
- Real spherical multipoles cast to Cartesian for far-field



Faster summations



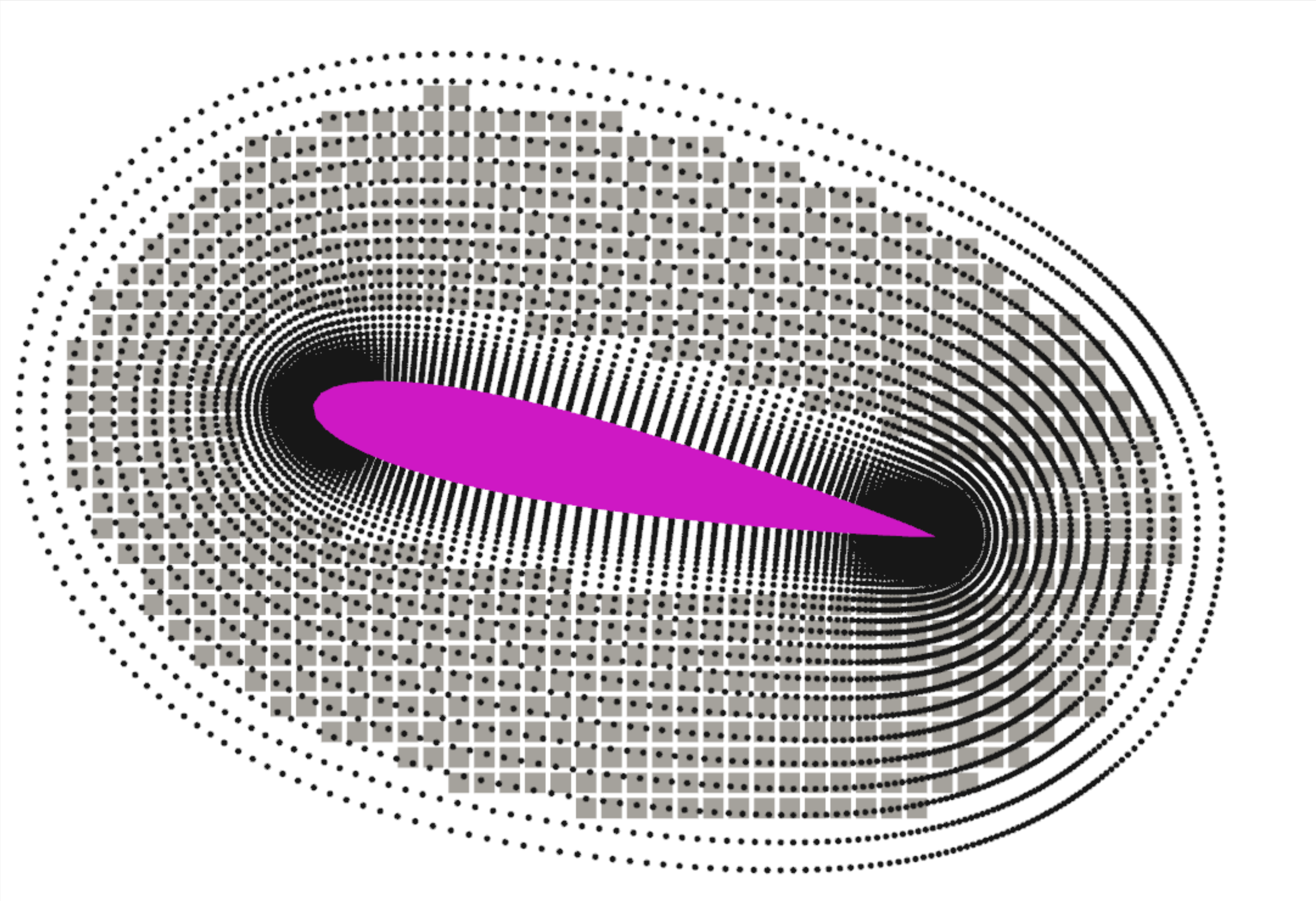
Hybrid scheme

- Eulerian domain
  - Requires only near-body grids, 10-20 particle separations wide
  - Outer BC will be set by Lagrangian solution
- Lagrangian domain
  - Particles exist throughout Eulerian domain
  - Particle strengths are only modified when they are the middle of the Eulerian domain---away from either boundary
  - BEM solution accounts for near-body vorticity

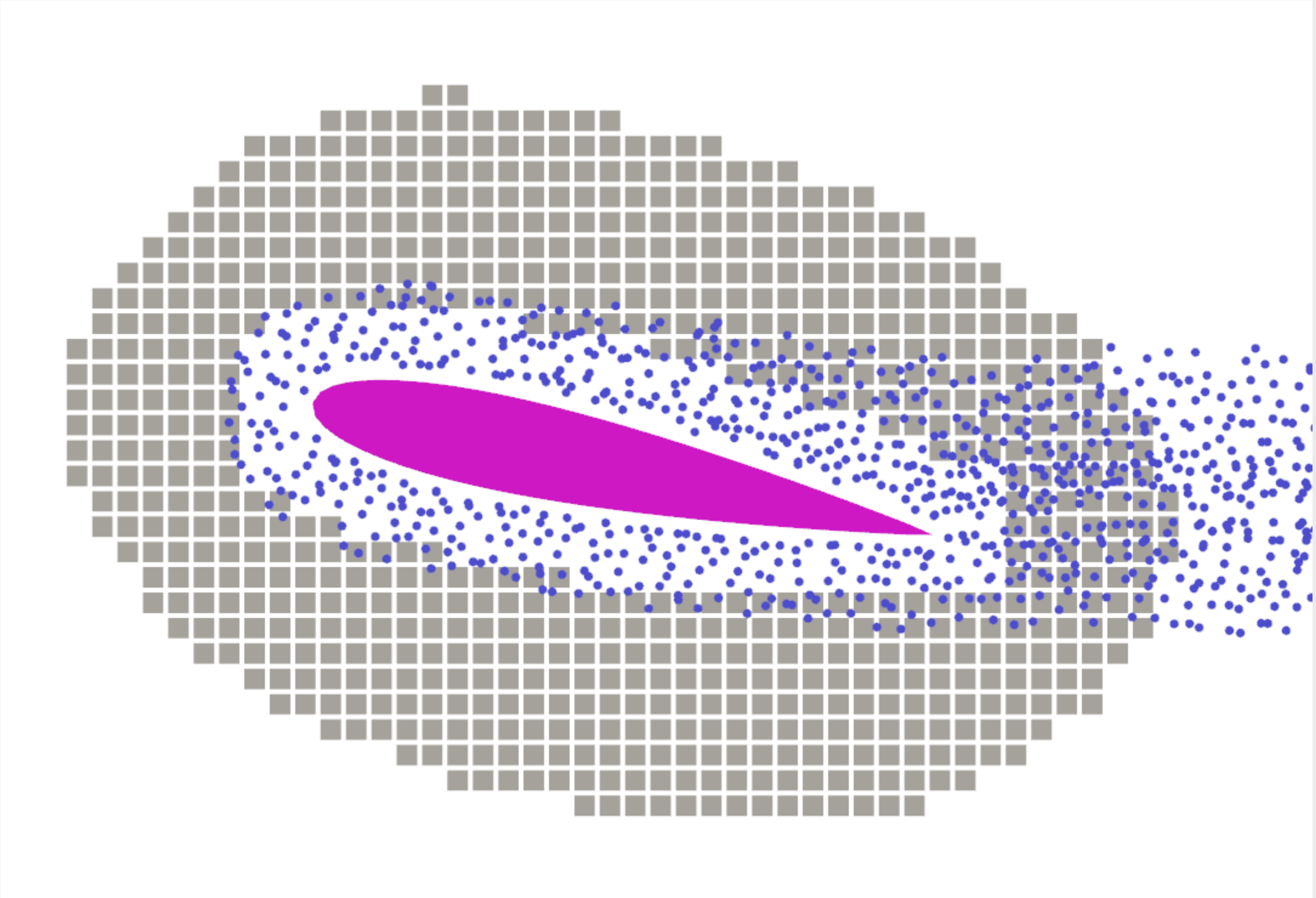
Hybrid method - procedure

1) **Interpolate vorticity from Eulerian grid to particles**
   a) **Prepare a Cartesian grid covering the Euler domain**
   b) **Interpolate ω from all Euler grid cells not within Δx of body**
   c) **Mask out particles outside Euler region, too close to body, and too close to outer Euler boundary (2-3 Δx)**
   d) **Reset those particles' strengths from this field**
2) **Advance Lagrangian solution, fill gaps**
3) **Compute velocities at outer Euler boundary nodes**
4) **Complete Euler BCs assuming constant ρ**
5) **Advance Euler solution**

Hybrid method - interpolation



Hybrid method - interpolation



Hybrid method - compressibility

- Currently Lagrangian regime is incompressible
- Euler BCs are set using:

$$\rho = \mathrm{const}$$

$$e = \frac{1}{\gamma(\gamma - 1)} + \frac{\mathrm{M}^2}{2}$$

Test cases

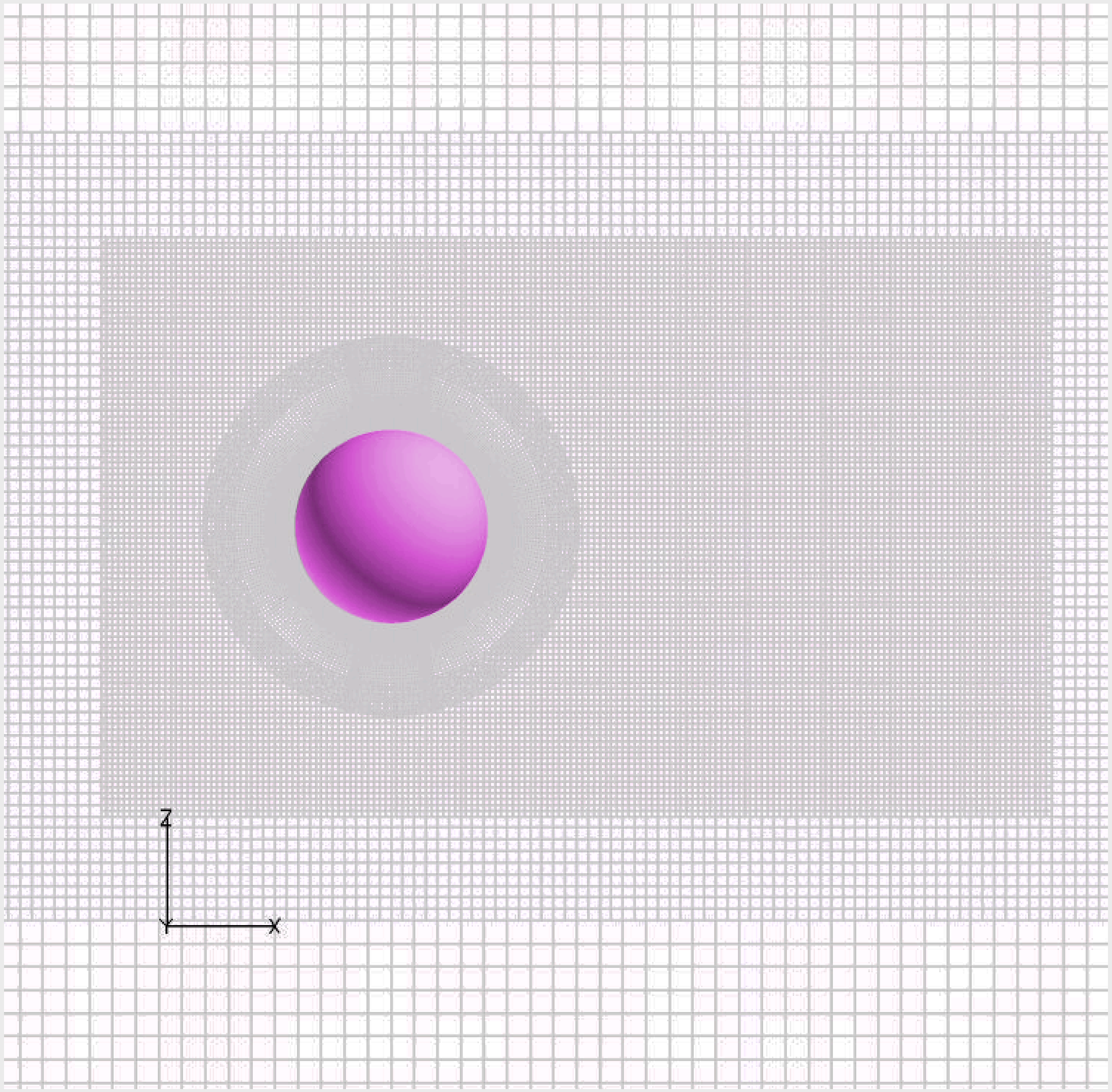
- Sphere, Re=100
- Finite wing, 6.6:1 AR
- 4-bladed rotor (no hub), 0.23 advance ratio

Test systems

	Nodes	cores per node	GPUs	GPU PEs/ node
Local	1	4 @ 2.5GHz	2x GTX 275	480 @ 1.5 GHz
Lincoln	8	8 @ 2.33 GHz	1/2x Tesla S1070	480 @ 1.44 GHz

- gfortran 4.3.2, OpenMP, CUDA 2.2, and OpenMPI

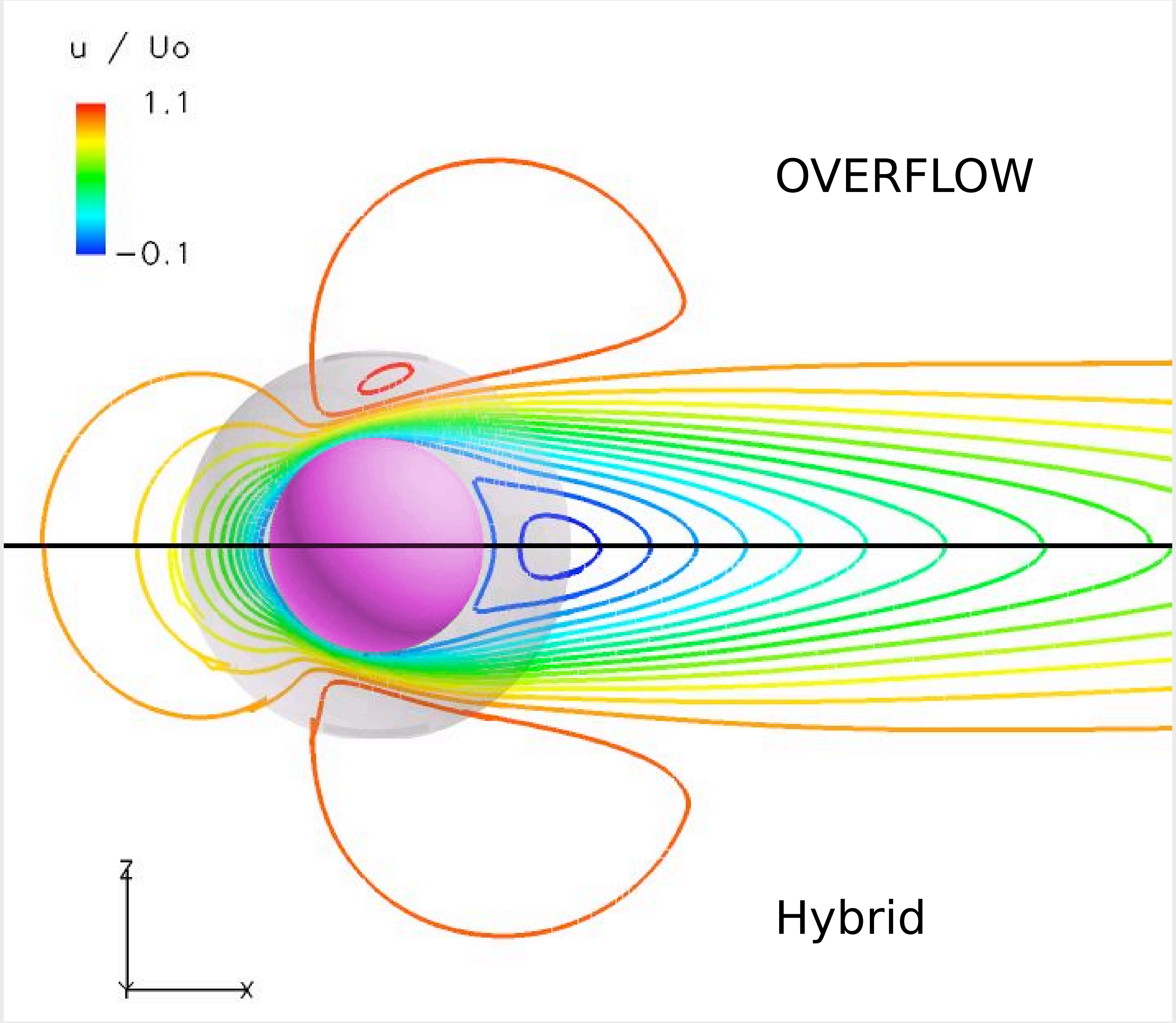
Sphere at Re_D=100



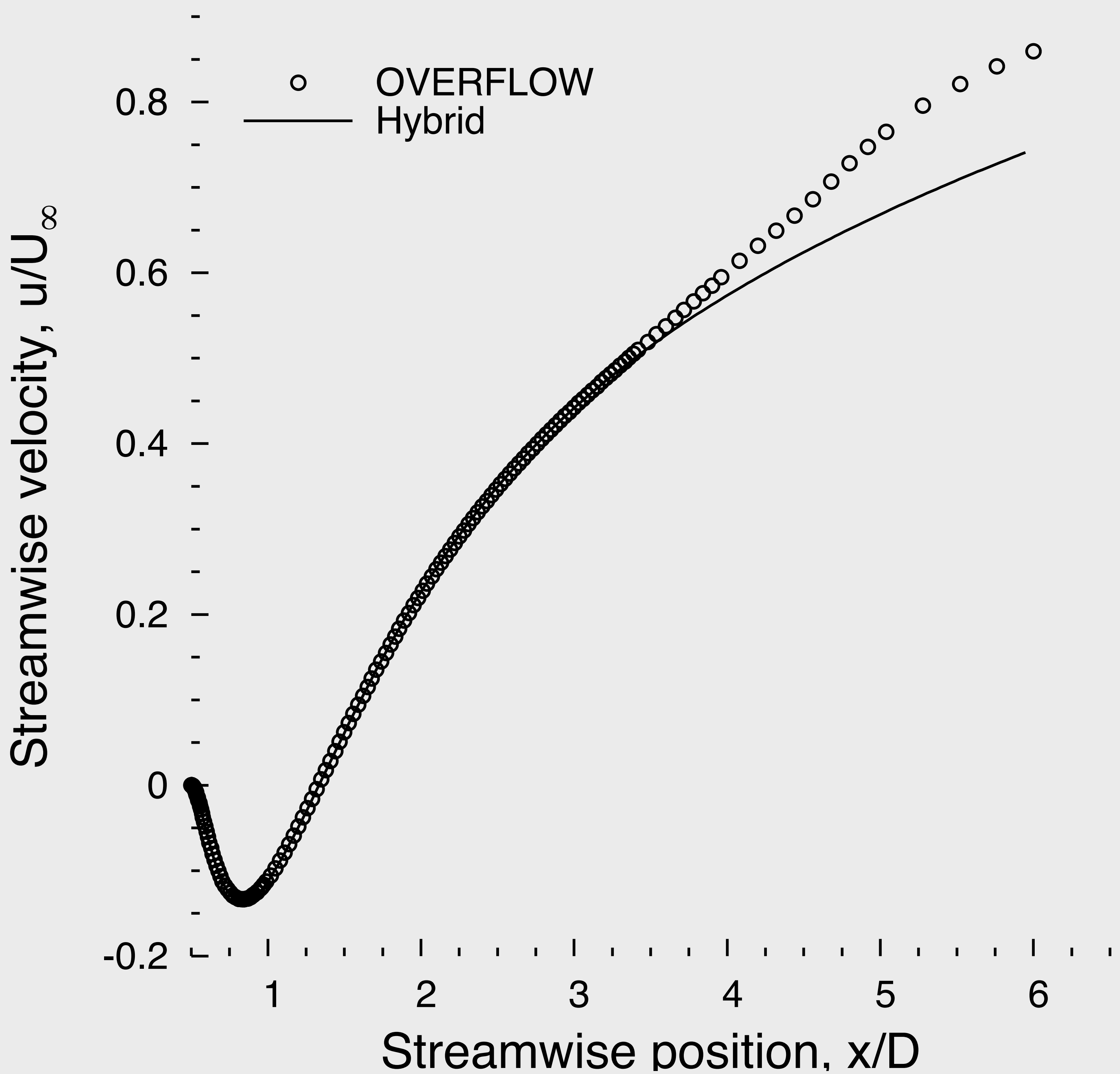
Sphere at Re_D=100

	Primary Δx	Δt	Newton subiterations	Euler grid nodes
Full OVERFLOW	0.03D to x/D=3.5	0.025	5	4.12M
Hybrid	0.0447D	0.05 / 0.025	5	1.41M plus 1M particles

Sphere at Re_D=100



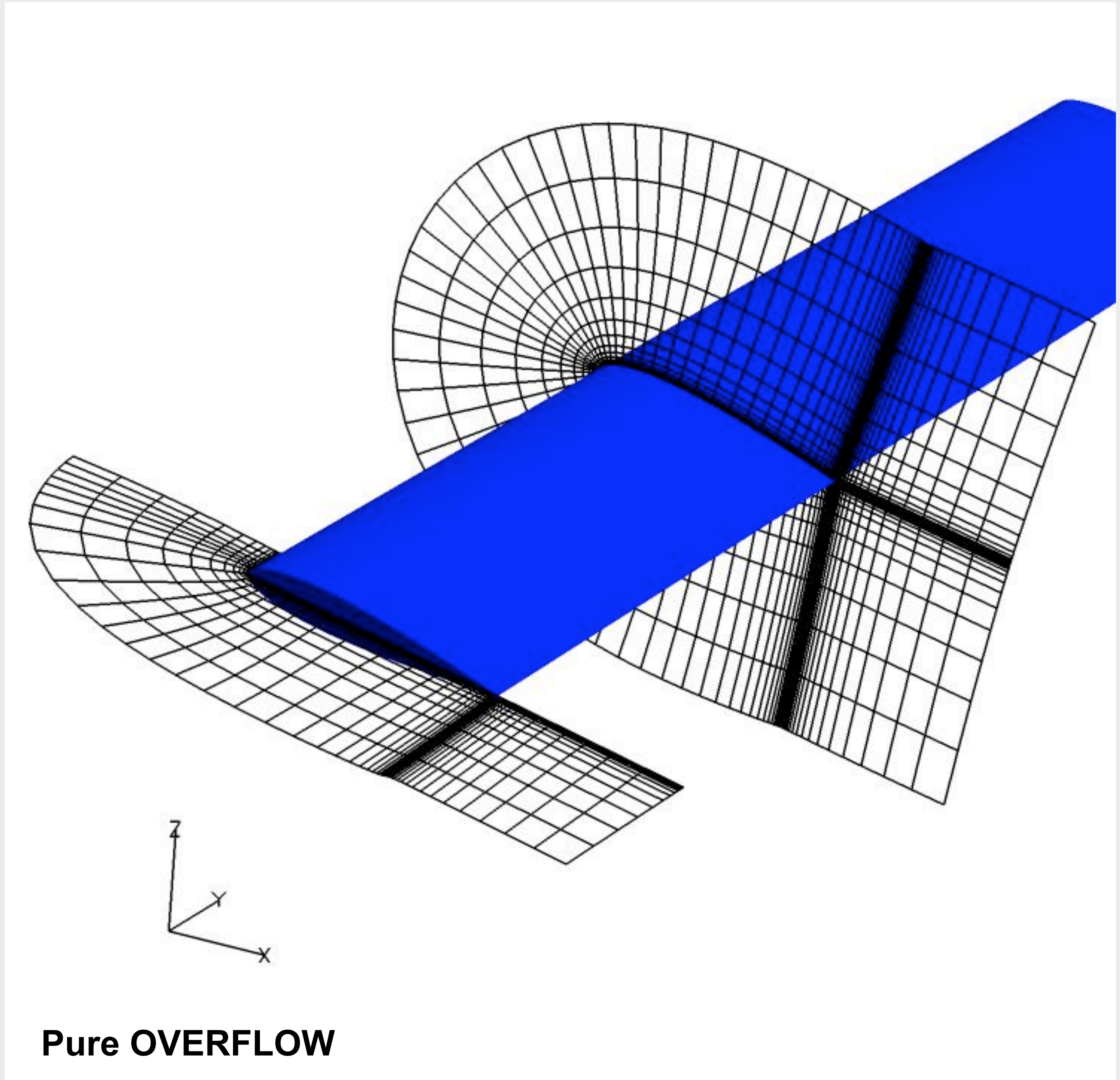
Sphere at Re_D=100



6.6:1 AR wing at 12°

- NACA 0015 section
- 6.6 AR regular planform at α =12°
- Flat tips
- M_∞ = 0.17, Re = 1,500,000
- Similar to McAlister & Takahashi, NASA TP-3151, 1991.

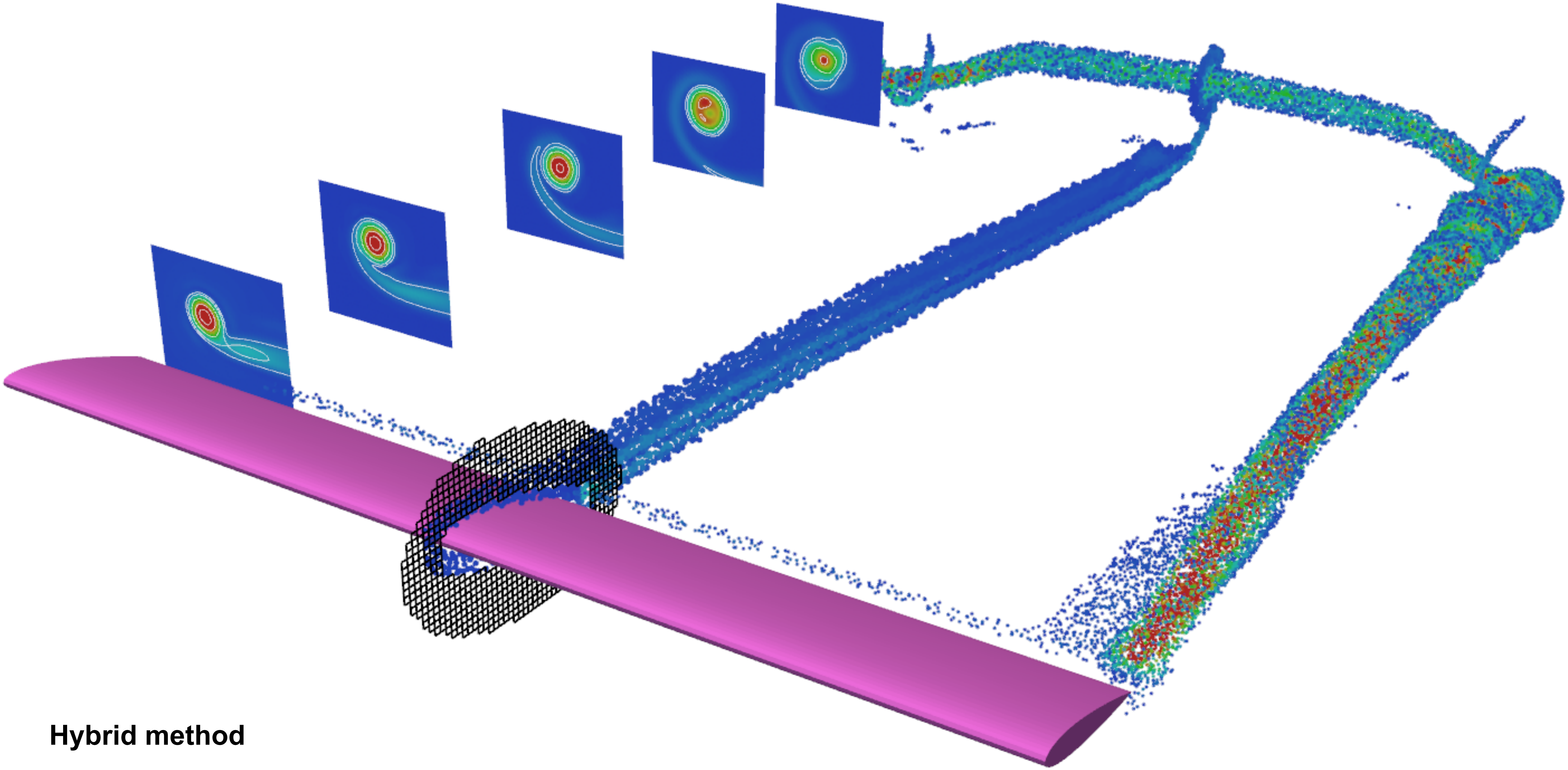
6.6:1 AR wing at 12°



6.6:1 AR wing at 12°

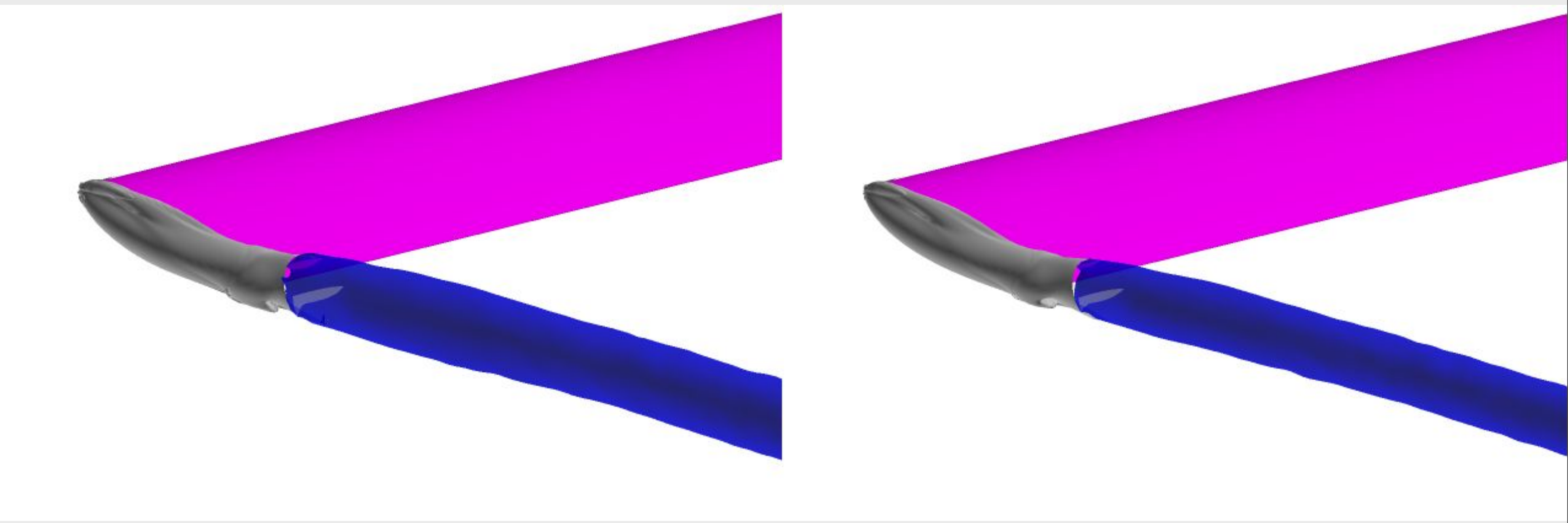
	Primary Δx	Δt	Newton subiterations	Euler grid nodes
Full OVERFLOW	0.04c to x/c=8	0.05	12	28.5M
Hybrid	0.04c	0.05	12*	4.3M plus 1M particles

6.6:1 AR wing at 12°



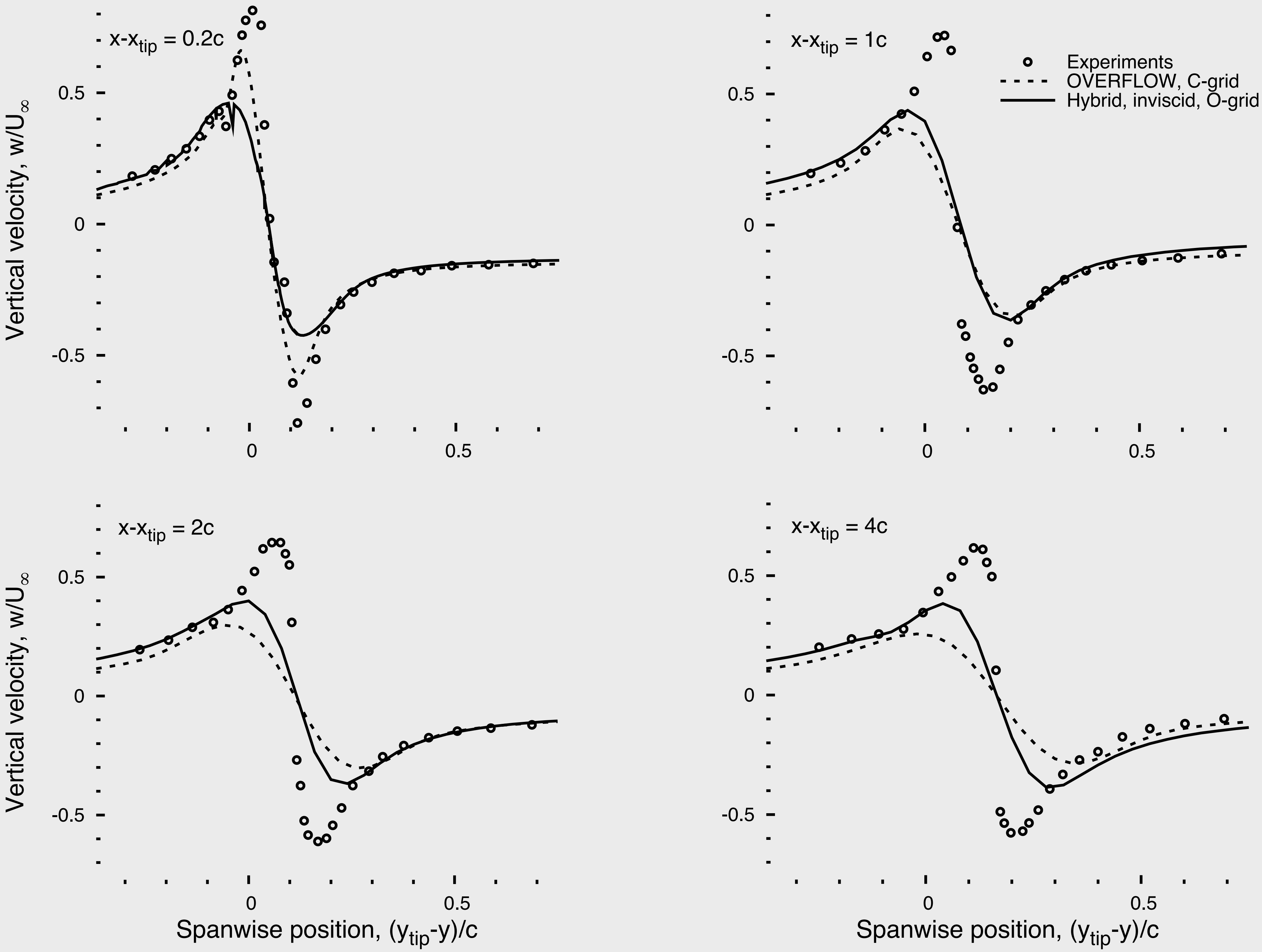
Hybrid method

6.6:1 AR wing at 12°



Hybrid method, ω magnitude 0.3, 0.5

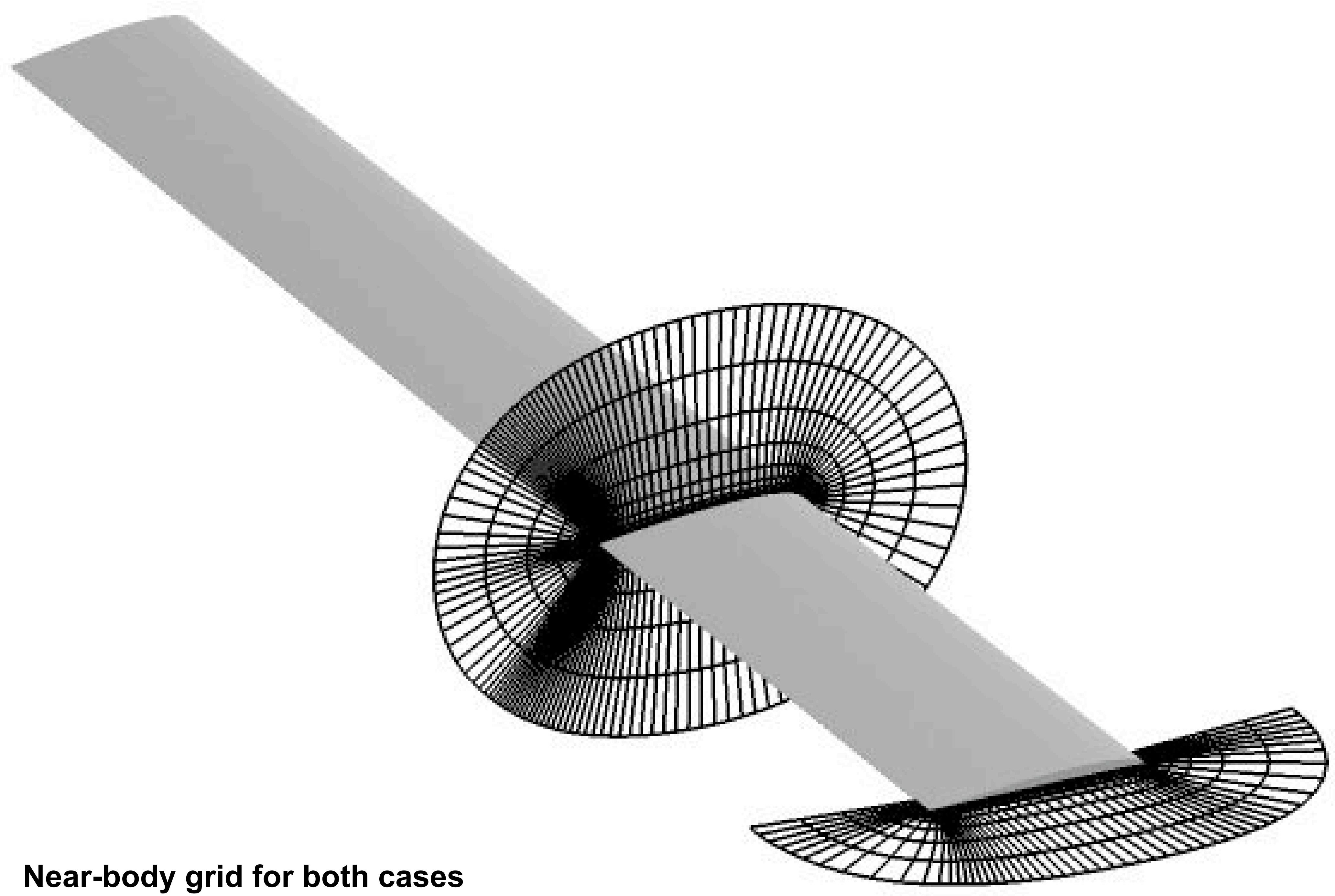
6.6:1 AR wing at 12°



4-Bladed isolated rotor

- NACA 0012 section
- 10.13 AR regular planform, root is 3.17c from hub
- Flat tips
- No cyclic pitch
- Twist is 0° at hub, 8° at tip
- $M_\infty = 0.124$, Re = 860,500
- Advance ratio = 0.2265, $\alpha = -3.04°$
- Similar to Elliot, Althoff, Saily, NASA TM-100542, 1988.

4-Bladed isolated rotor

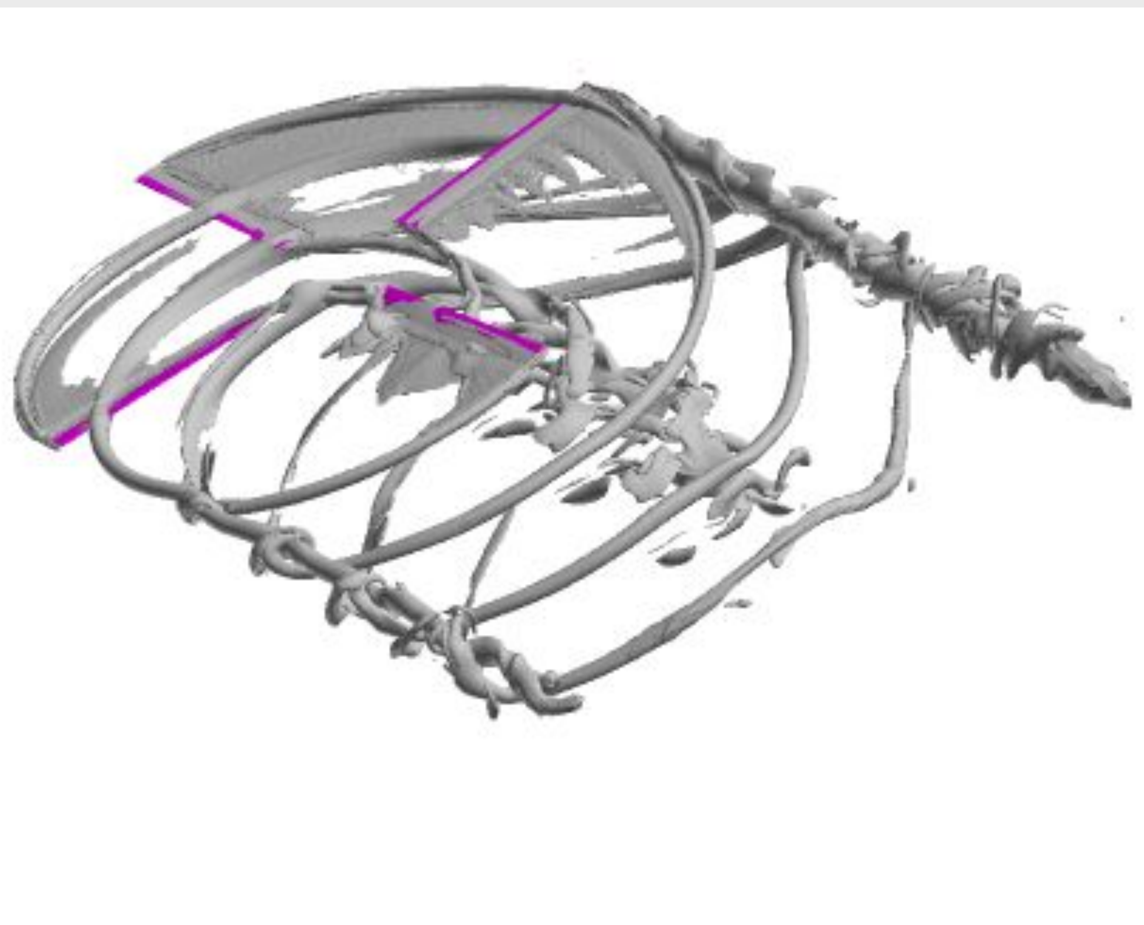


Near-body grid for both cases

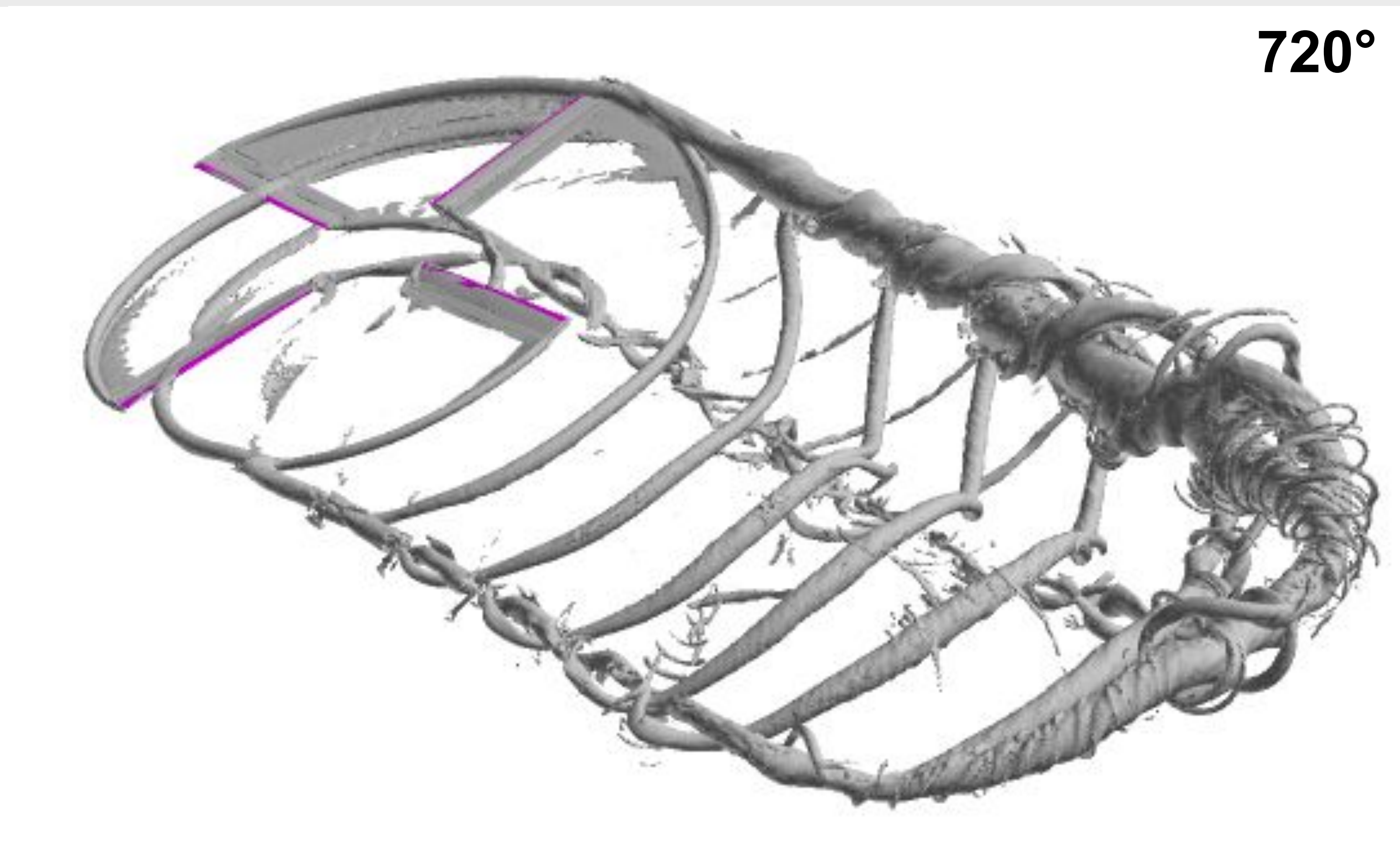
4-Bladed isolated rotor

	Primary Δx	Δt	Newton subiterations	Euler grid nodes
Full OVERFLOW	0.06c to x/c=26	1/2° per step	9	46.2M
Hybrid	0.06c	1° per step	10*	11.7M plus 55M particles

4-Bladed isolated rotor

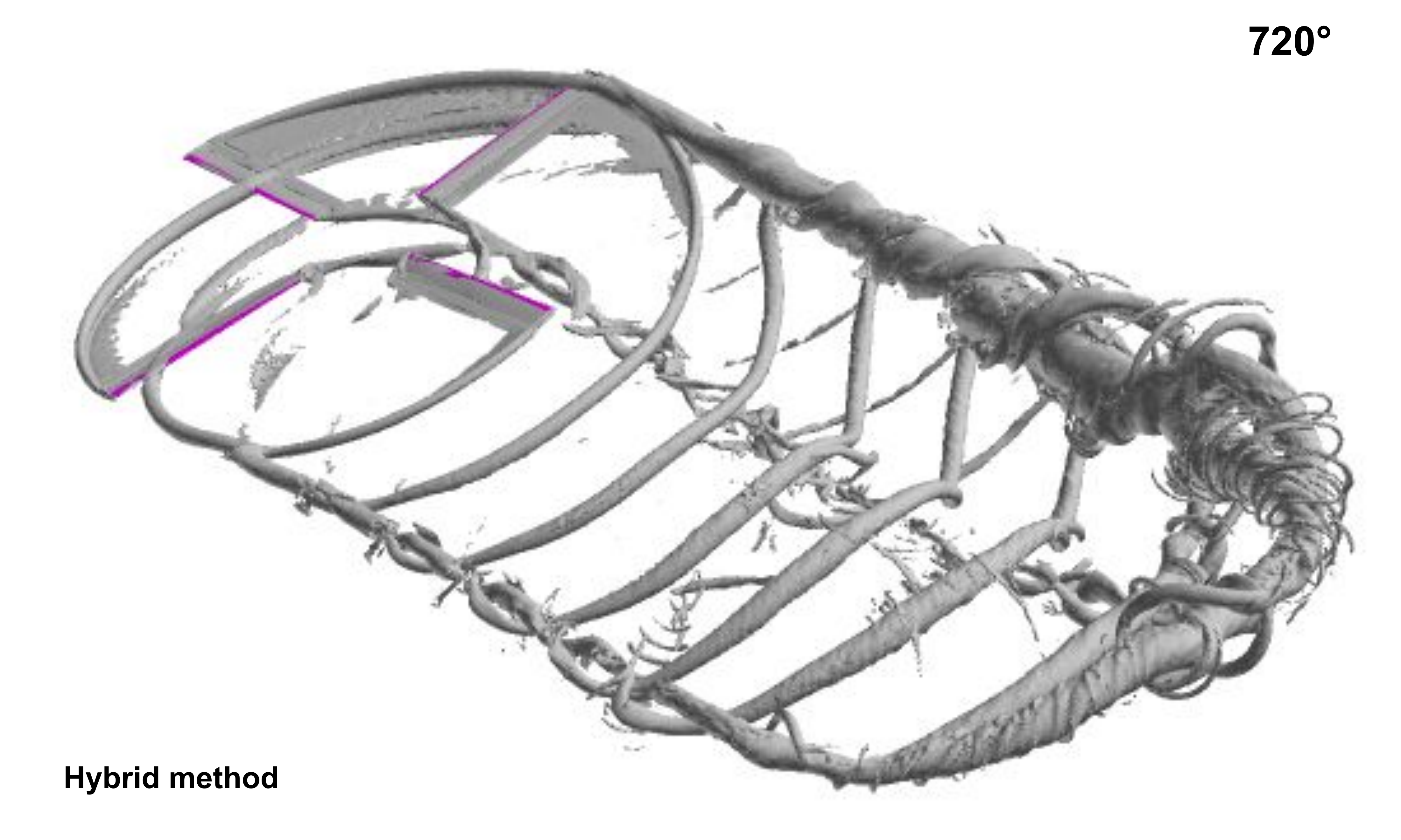


Pure OVERFLOW

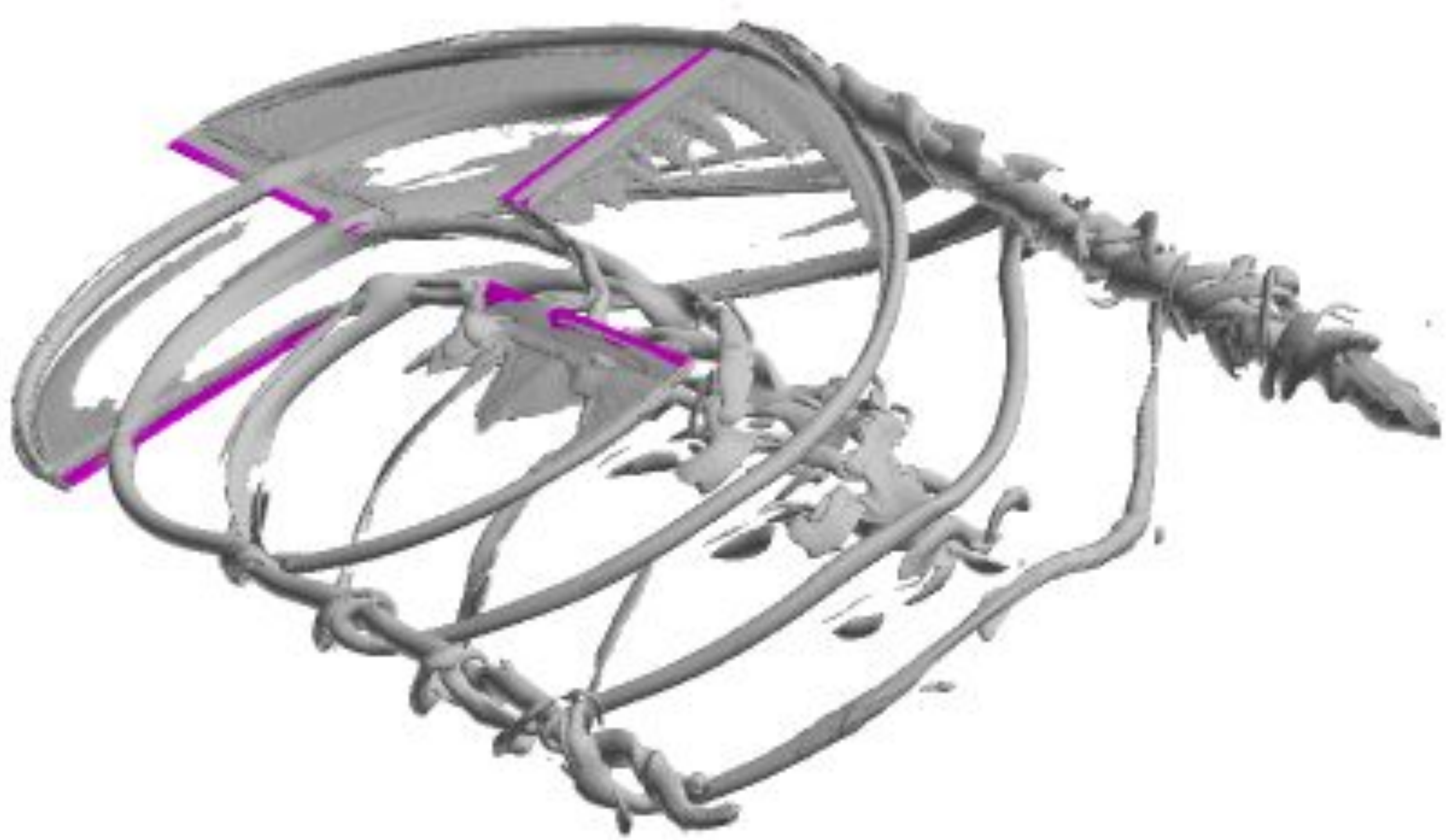


Hybrid method

4-Bladed isolated rotor



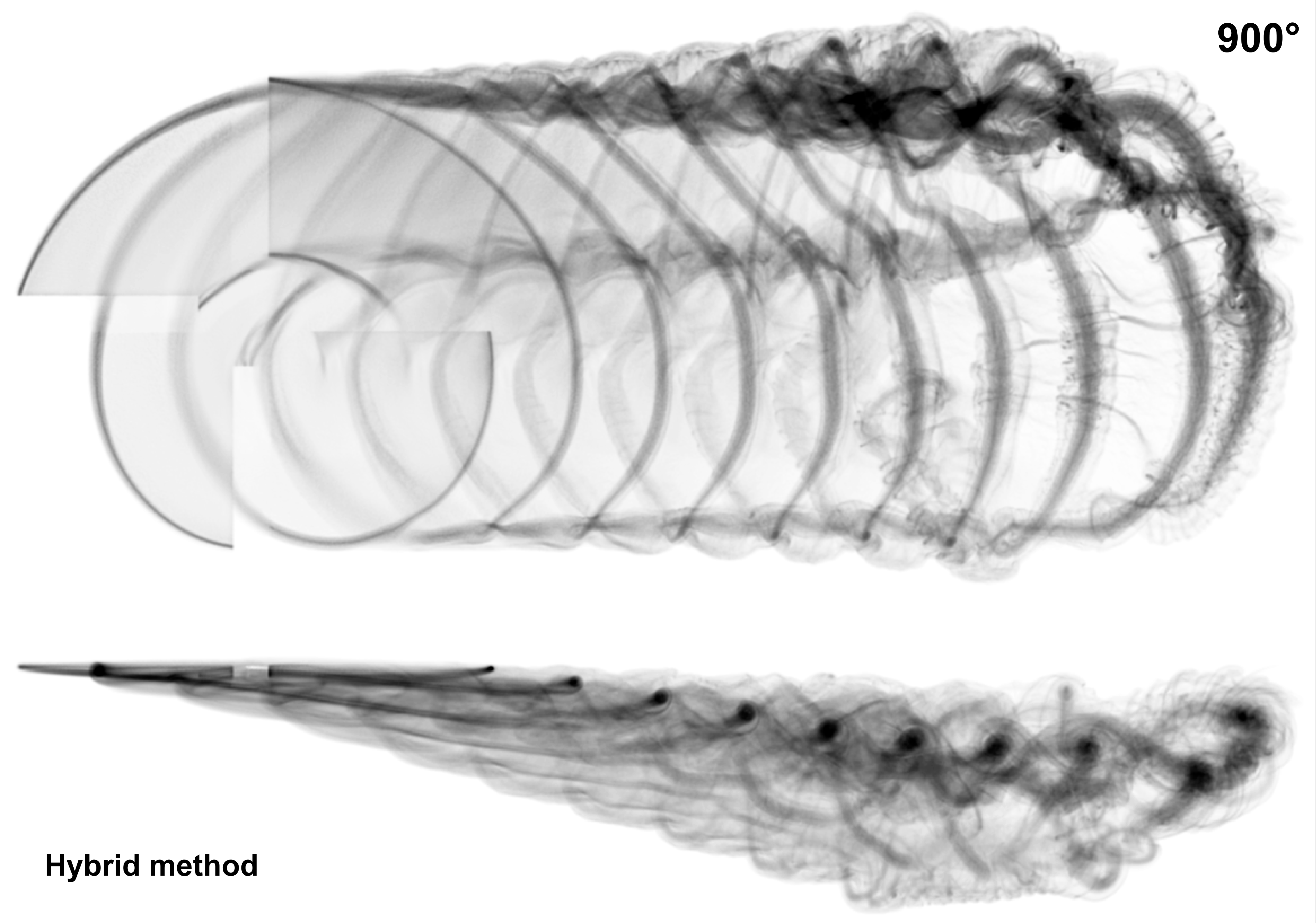
4-Bladed isolated rotor



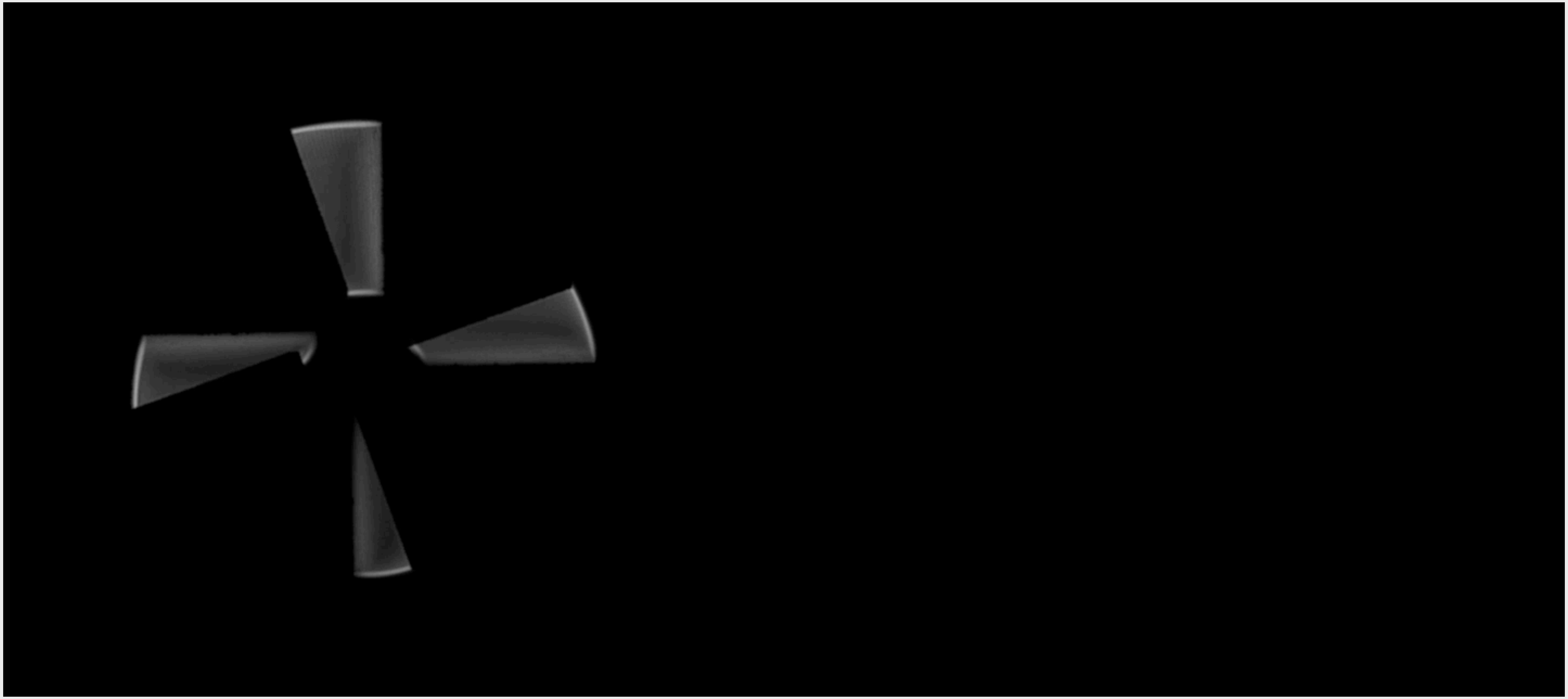
Pure OVERFLOW

720°

4-Bladed isolated rotor

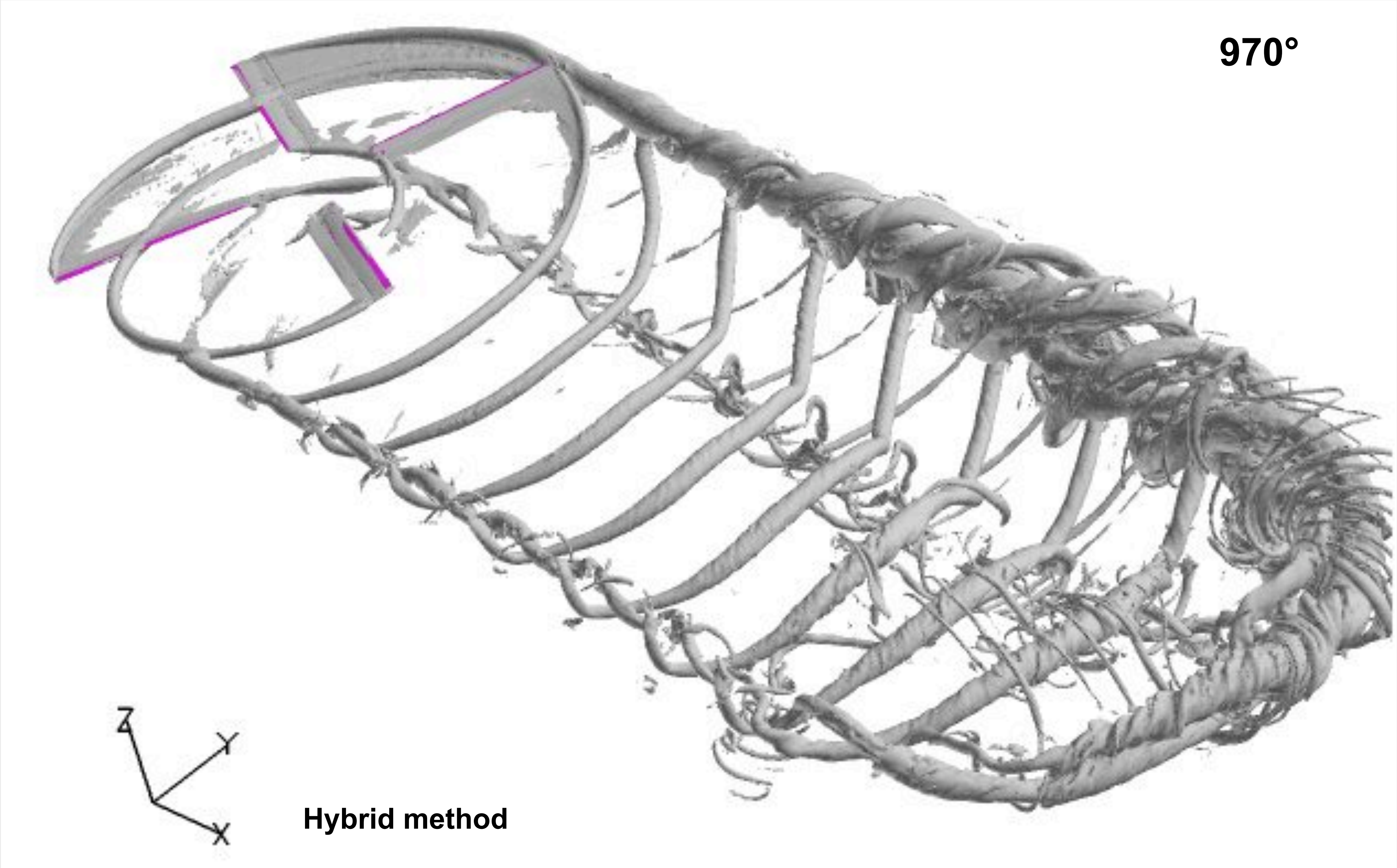


4-Bladed isolated rotor



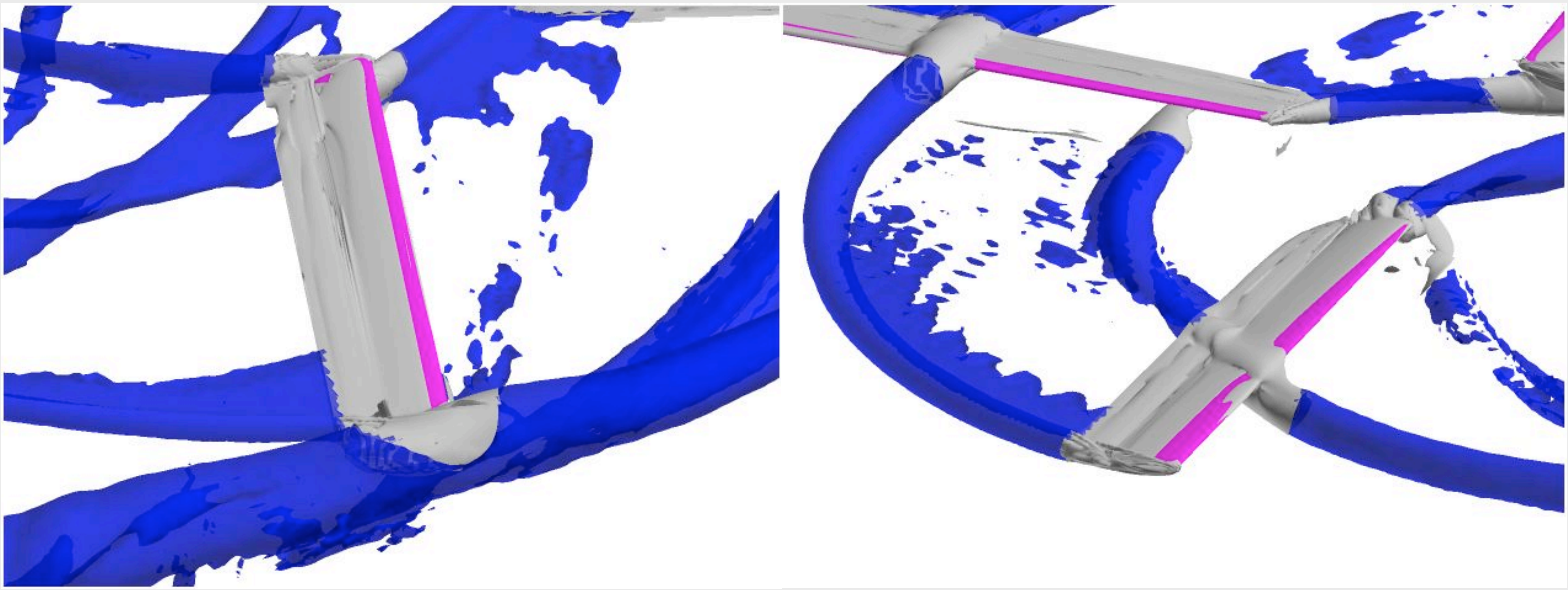
4-Bladed isolated rotor

4-Bladed isolated rotor



4-Bladed isolated rotor

970°

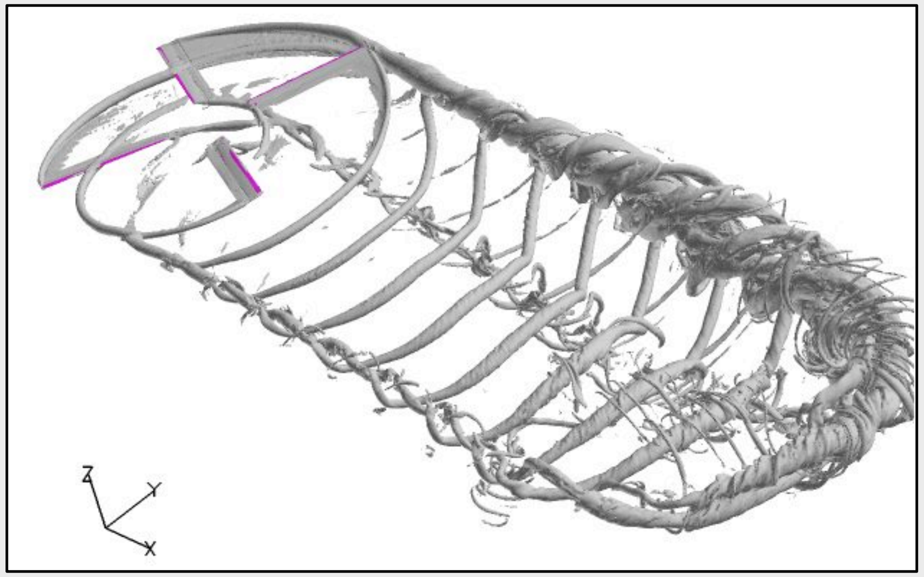


Hybrid method

Conclusions

- Hybrid Lagrangian-Eulerian method created in short time
- Wake maintains all benefits of Vortex Particle Method
- Near-body retains all benefits of Eulerian overset grid method
- Coupling between regimes is fully two-way
- Connected GPU devices allow ~1 TFLOP/s per node

Thank you



- AIAA
- AMRDEC, NSF, NCRR
- You, for your attention

- Please see our other talk: "A GPU-Accelerated Boundary Element Method and Vortex Particle Method" AIAA-2010-5099, Thursday, 1100 hrs, room 23B

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