"VISVE – A VIScous Vorticity Equation model applied to cylinders, hydrofoils, propellers"

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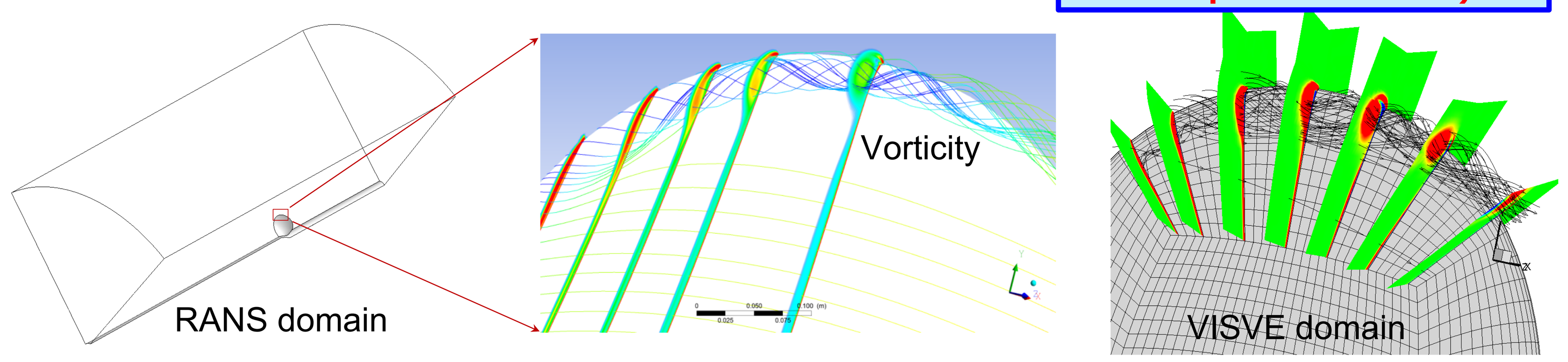
Introduction

Unlike velocity, the vorticity is a locally concentrated quantity. So, solving for the vorticity can results in significantly reduction in computational domain.

$$\frac{\partial \boldsymbol{\omega}}{\partial t} + \nabla\times(\boldsymbol{\omega}\times\mathbf{q}) = -\nu\nabla\times(\nabla\times\boldsymbol{\omega})$$

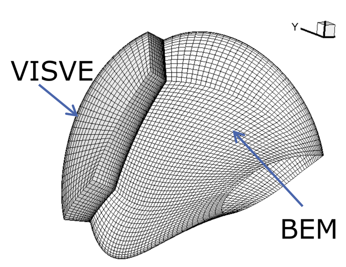
In VISVE, ω is d istributed continuously (i.e. this is NOT a vortex particle method)

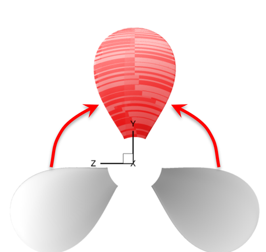


Objectives

To develop an accurate and computationally efficient numerical tool, VISVE, to predict the viscous flow around hydrofoils, cylinders, shperes and propellers at on- and off-design conditions.

- A local solver with significantly small computational domain and small number of cells, which results in much less computation time.
- Only the flow on key blade needs to be modeled. The effect of other blades is considered in an iterative manner. For axisymmetric case: duplicate the variables of the key blade. For non-axisymmetric case: use the variables of the key blade at different blade angles.
- Since only the vicinity of the propeller needs to be modeled without using periodic boundary conditions, the grid generation can be significantly simplified. Actually, this process can be made automated.



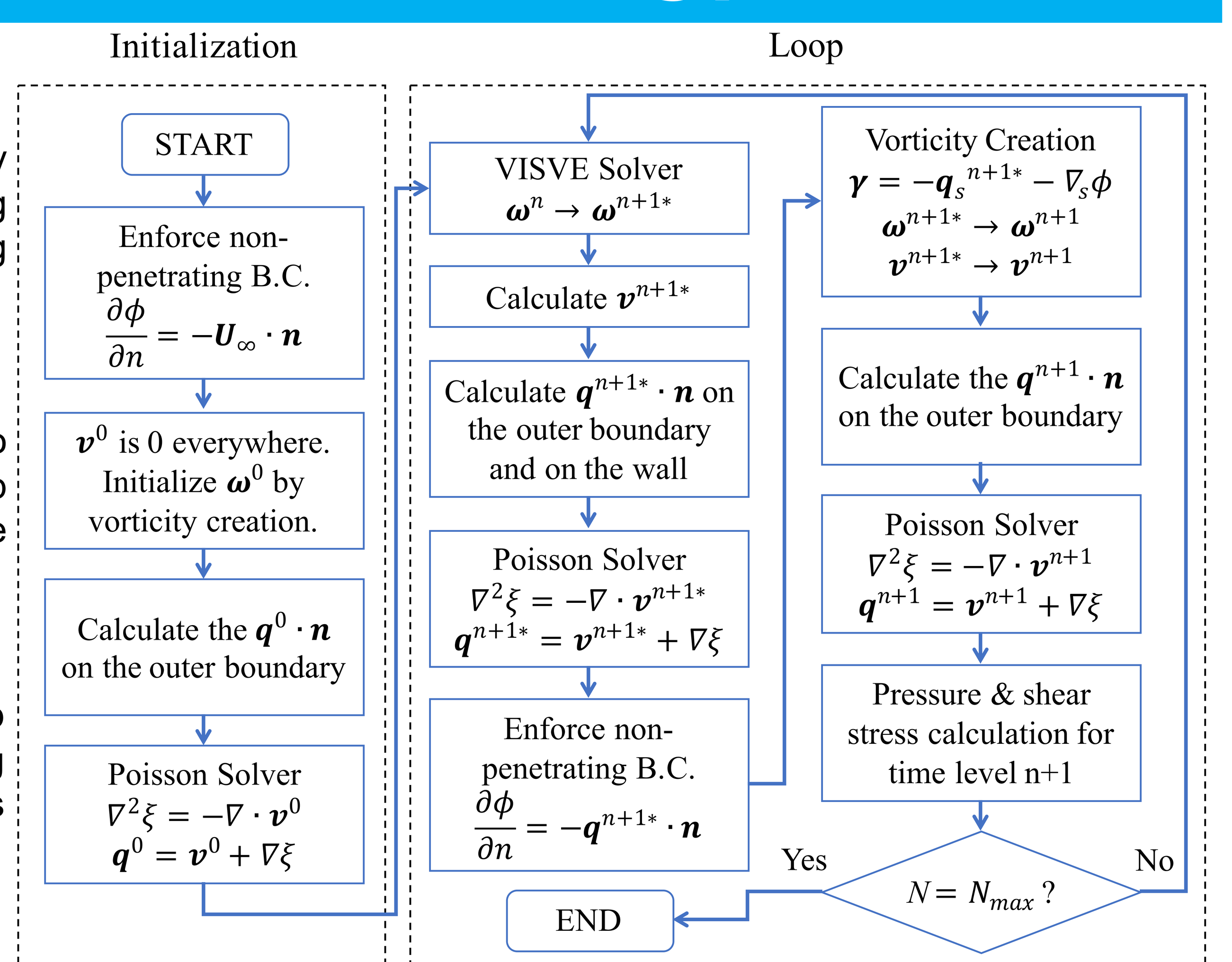


Methodology

Poisson Solver: Given a vorticity field $\boldsymbol{\omega}^n$, computing the corresponding velocity field $\mathbf{q}^n$.

VISVE Solver: Marching vorticity to the next time step by solving the vorticity equation.

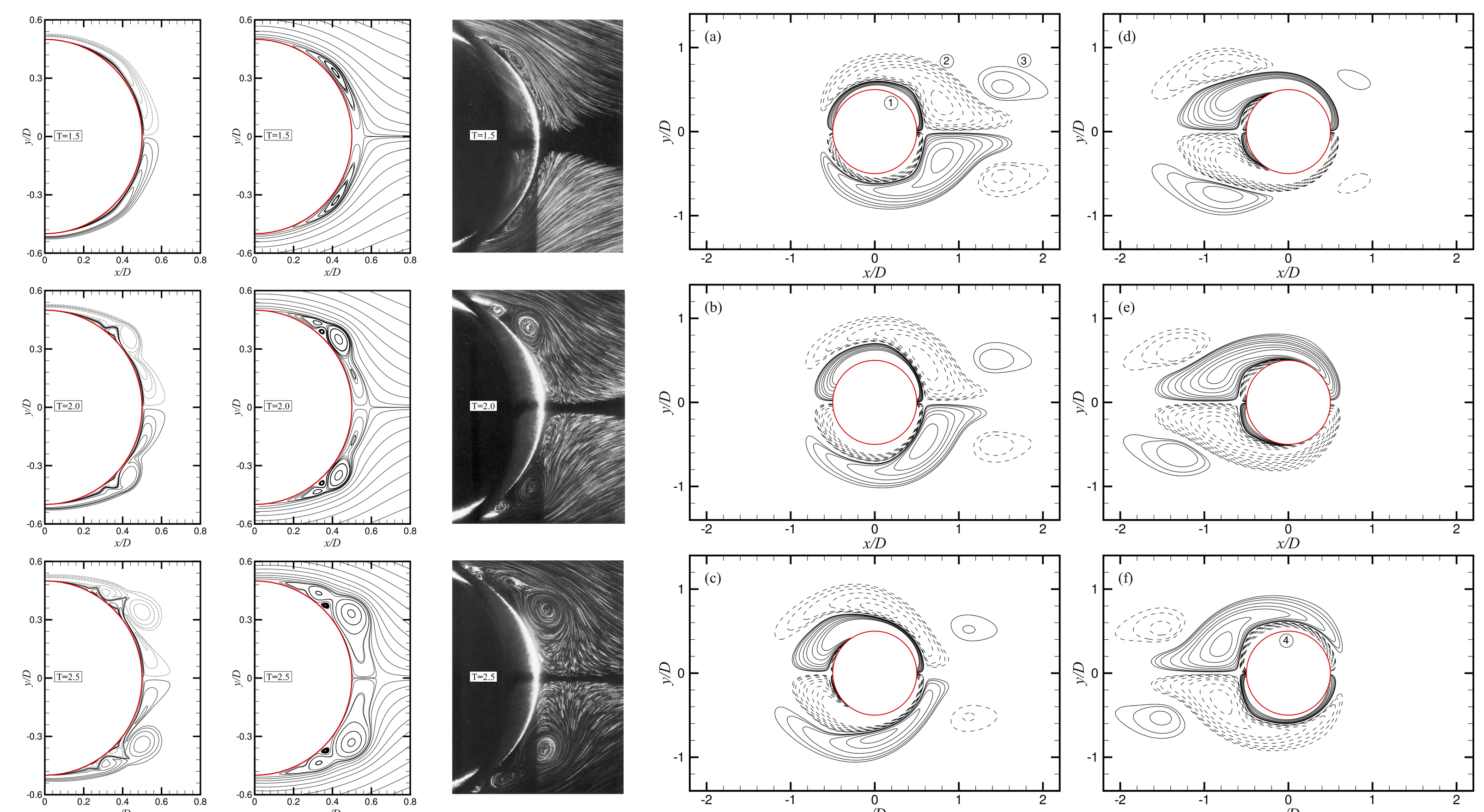
Vorticity Creation: Enforce the no-slip and non-penetrating boundary conditions on the wall.



Applications

Flow past a 2-D circular cylinder

Both the impulsively started unidirectional flow and oscillatory flow around a circular cylinder are simulated using the present method. In this study, an O block mesh is employed for all the simulations, and the grids are orthogonal.



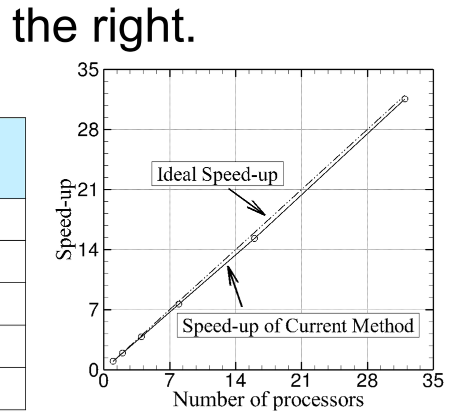
Unidirectional flow at $Re = 9500$: vorticity contours (left column), streamlines (middle column), and experiments by Bouard et al. (right column)

Alternating flows around a cylinder for $KC = 5$ and $Re = 100$ at phase angles: (a) 90°; (b) 126°; (c) 162°; (d) 198°; (e) 234°; (f) 270°.

The efficiency of the correct method is compared with N-S methods as shown in the table. The most time-consuming part is paralleled using Open-MP, and the scaling is shown in the figure below on the right.

The comparison of domain size and number of cells in mesh.

Authors	Method	Domain size (cylinder diameter D)	Number of mesh cells
Russell and Wang	N-S	Rectangular $32D\times16D$	204,800
Linnick and Fasel	N-S	Rectangular $46D\times16D$	180,121
Taira and Colonius	N-S	Rectangular $30D\times30D$	106,250
Chiu et al.	N-S	Rectangular $40D\times20D$	245,000
Present	VISVE	Circular (Radius) $17D$	42,000

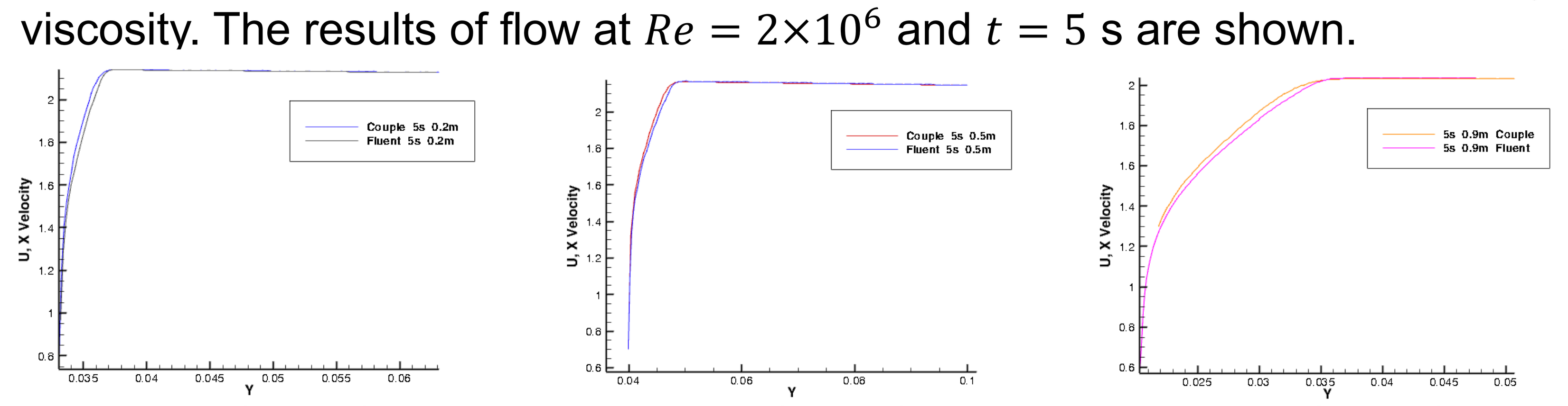


The speed-up in terms of strong scaling

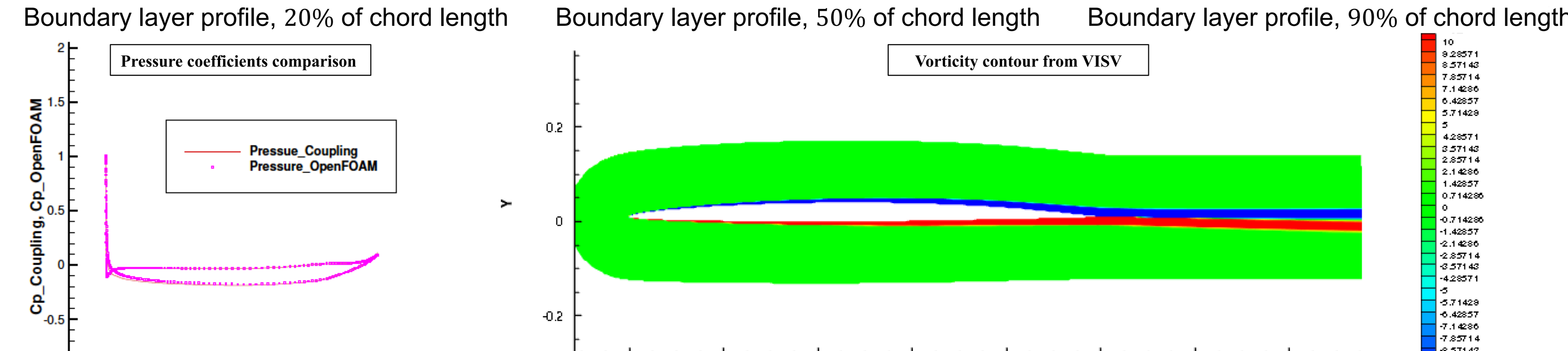
For more results about cylinder flow, see Wu, C., Kinnas, S. A., Li, Z., & Wu, Y. (2019). A conservative viscous vorticity method for unsteady unidirectional and oscillatory flow past a circular cylinder. Ocean Engineering, 191, 106504.

Turbulent Flow past a 2-D Hydrofoil

The turbulent flow is simulated by considering the eddy viscosity in the governing equations. A synchronous coupling method was developed to couple VISVE and a turbulence model in OpenFOAM to calculate the eddy viscosity. The results of flow at $Re = 2\times10^6$ and $t = 5$ s are shown.



Boundary layer profile, 20% of chord length | Boundary layer profile, 50% of chord length | Boundary layer profile, 90% of chord length

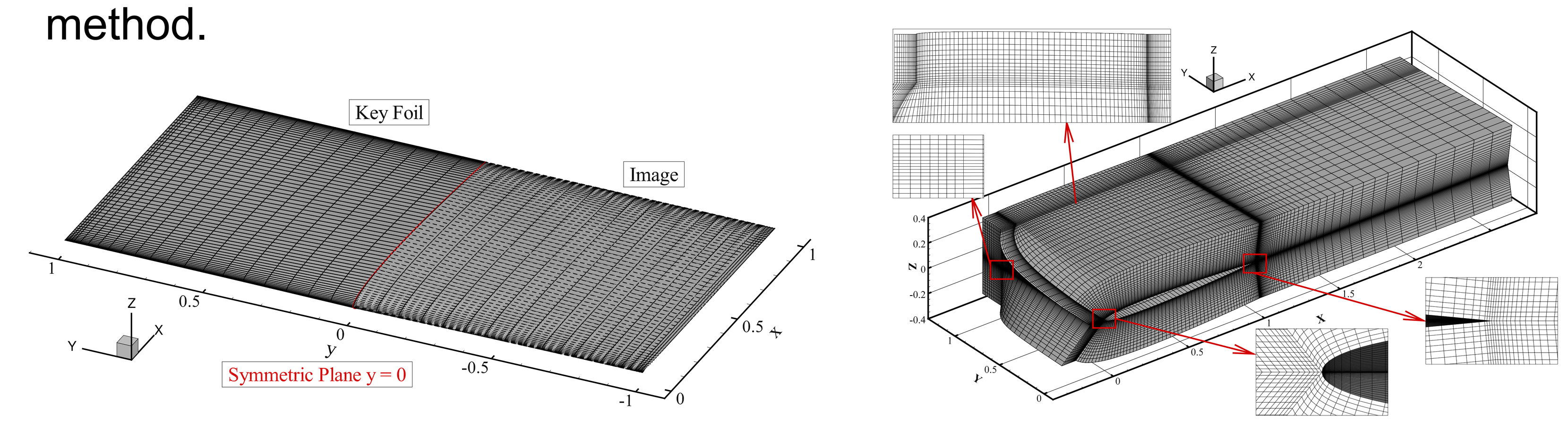


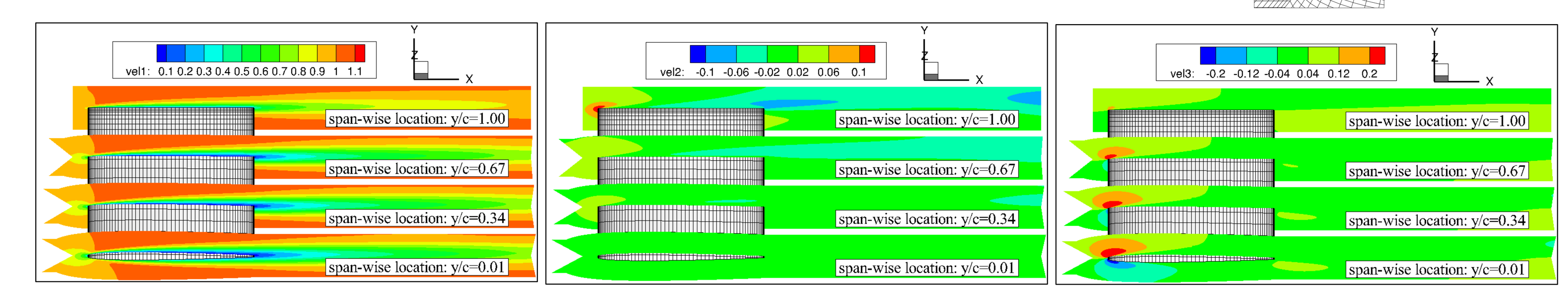
For more results about the applications of VISVE in turbulent flow, see Yao, H., & Kinnas, S. A. (2019, July). Coupling Viscous Vorticity Equation (VISVE) Method with OpenFOAM to Predict Turbulent Flow Around 2-D Hydrofoils and Cylinders. In *The 29th ISOPE Conference*. International Society of Offshore and Polar Engineers.

Applications

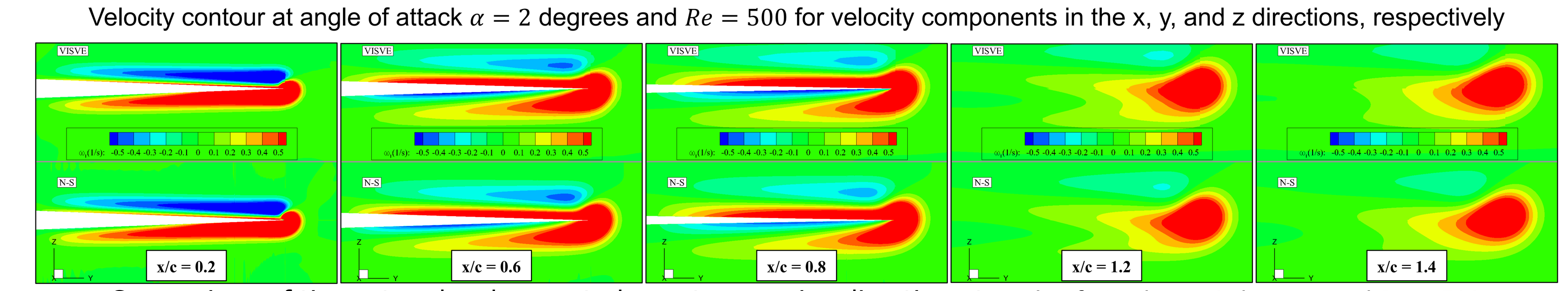
Flow past a 3-D Hydrofoil

The flow past a 3-D naca0012 hydrofoil, which has a maximum thickness of 8% and a closed tip, is also simulated using the proposed VISVE method.

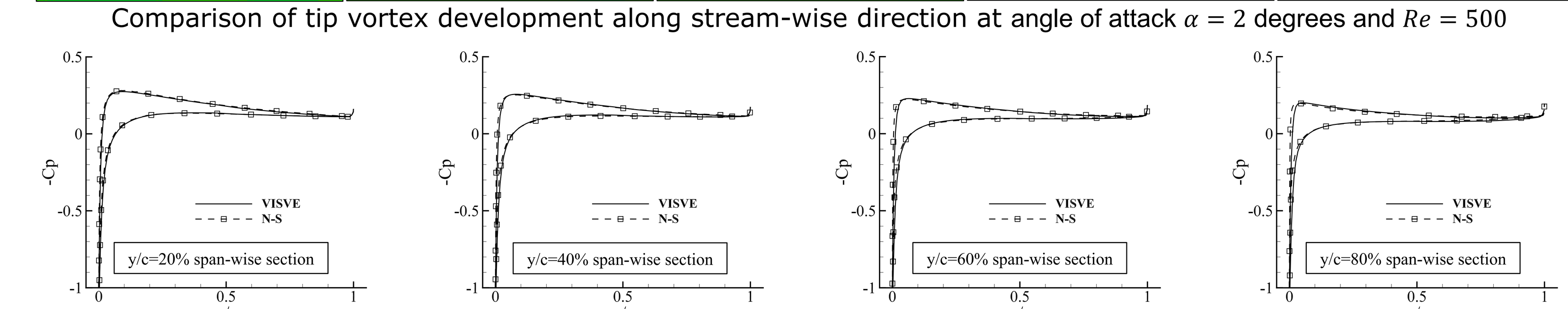




Velocity contour at angle of attack $\alpha = 2$ degrees and $Re = 500$ for velocity components in the x, y, and z directions, respectively



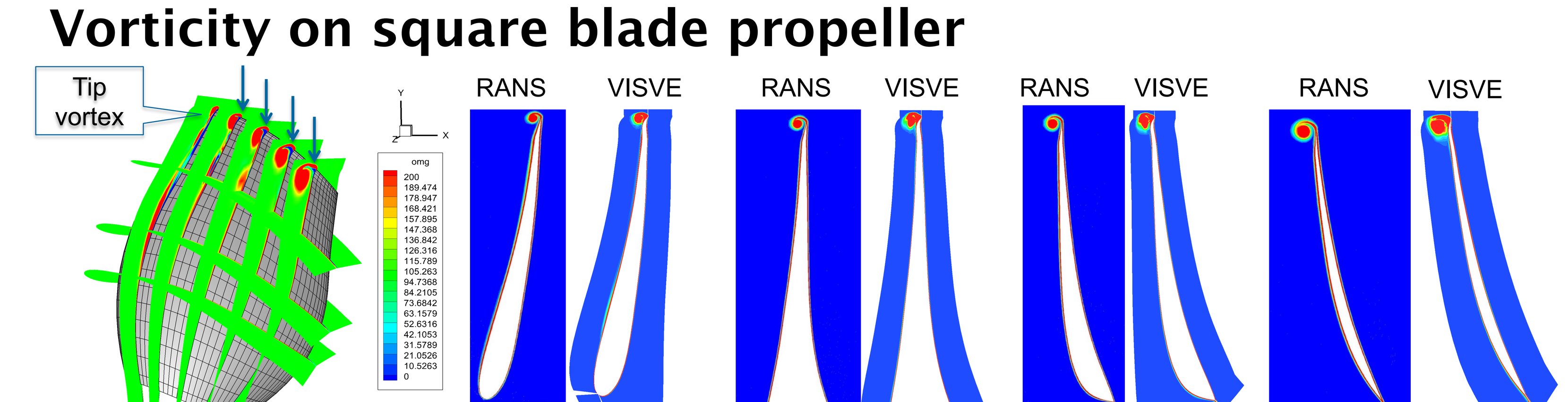
Comparison of tip vortex development along stream-wise direction at angle of attack $\alpha = 2$ degrees and $Re = 500$



Comparison of surface pressure coefficients at angle of attack $\alpha = 2$ degrees and $Re = 500$

This 3-D VISVE method and its applications are under consideration for publication in the Journal of Computational Physics.

Vorticity on square blade propeller



35% of chord length | 50% of chord length | 65% of chord length | 80% of chord length

Conclusions and Future Work

- The results of velocity, vorticity, and pressure from VISVE agree well with the results from other benchmark tests in all cases.
- The computational domain of VISVE is much more smaller than that of the velocity based methods. The grid generation in VISVE can then be made automated since only the vicinity of the wall needs to be modeled.
- VISVE is more efficient than the velocity based methods, especially with proper parallelization of both MPI and Open-MP.
- In the future, the extension to consider turbulence, cavitation the tip gap flow, flow in ducted propeller, propeller in backing condition and flow around riser.