A Moving Mesh Approach for Flow Simulations of an Oscillating Hydrofoil

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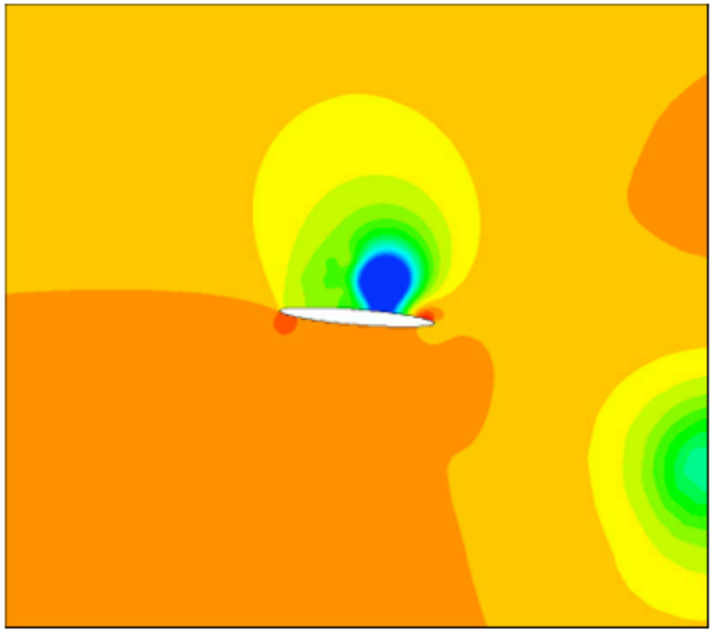
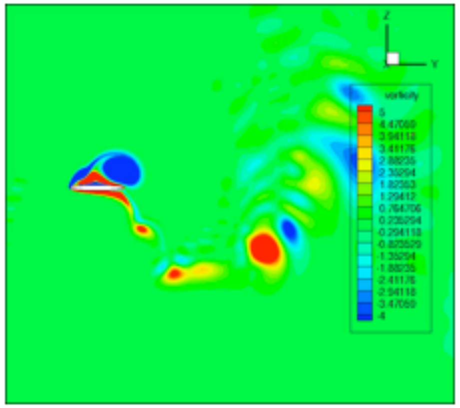
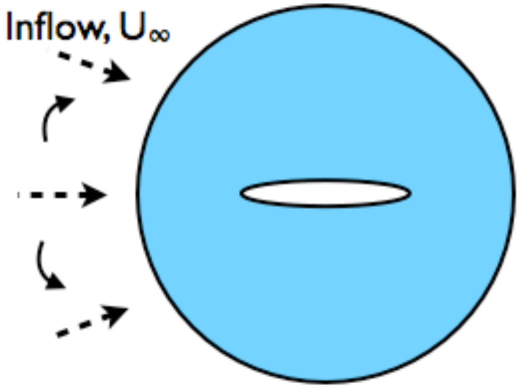
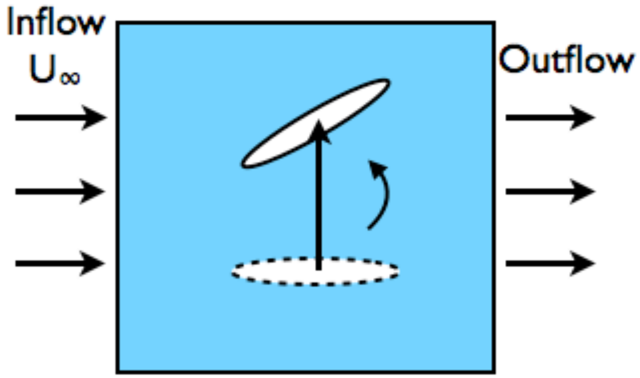


Motivations

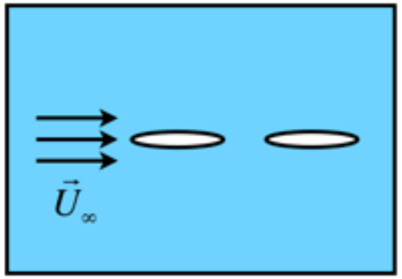
- Potential rich energy source from bodies of water
- A robust infrastructure to study hydrofoil energy extraction
- Limitations of current non-inertial reference frame method

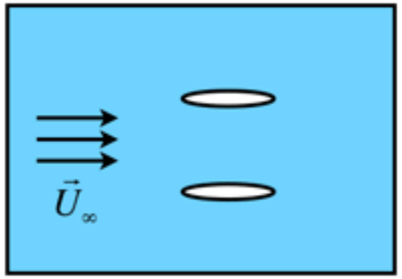


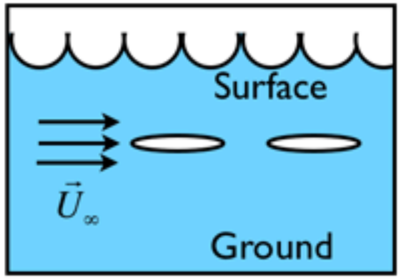




- More complex configurations: tendem, parallel, free surface etc.

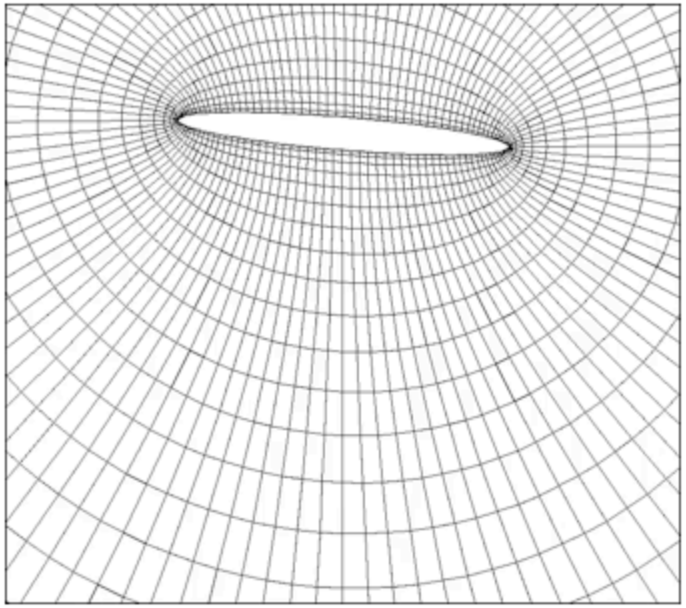






Objectives

- Dynamic mesh deformation method
- Simulate hydrofoil oscillating motion
- Validate the dynamic mesh method:
  - Pressure and velocity field, vortex shedding
  - Drag and lift forces
- Simulation oscillating hydrofoil with the following parameters:



$$h_{max} = 0.5c \qquad \alpha_{max} = 75^{\circ} \qquad \phi = 90^{o} \qquad f = 0.15$$

Computational Method

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- Continuity Equation:

$$\frac{d}{dt}\int_V dV - \int_S \mathbf{v}_b \cdot d\mathbf{S} = 0$$

- Navier-Stokes Equation:

$$\frac{d}{dt}\int_V \rho\mathbf{v}\, dV + \int_S [\rho(\mathbf{v} - \mathbf{v}_b)\mathbf{v} - \mathbf{T}] \cdot d\mathbf{S} = 0$$

- Space Conservation Law:

$$\frac{d}{dt}\int_V dV - \int_S \mathbf{v}_b \cdot d\mathbf{S} = 0$$

- Direct numerial simulation
    OpenFOAM CFD software

Space Conservation Law in Finite Volume Calculations of Fluid Flow: I. Demirdžić et. al., 1988
Finite Volume Method for Prediction of Fluid Flow in Arbitrarily Shaped Domains with Moving Boundarues: I. Demirdžić et. al., 1990

Mesh Cell Motion Approximation

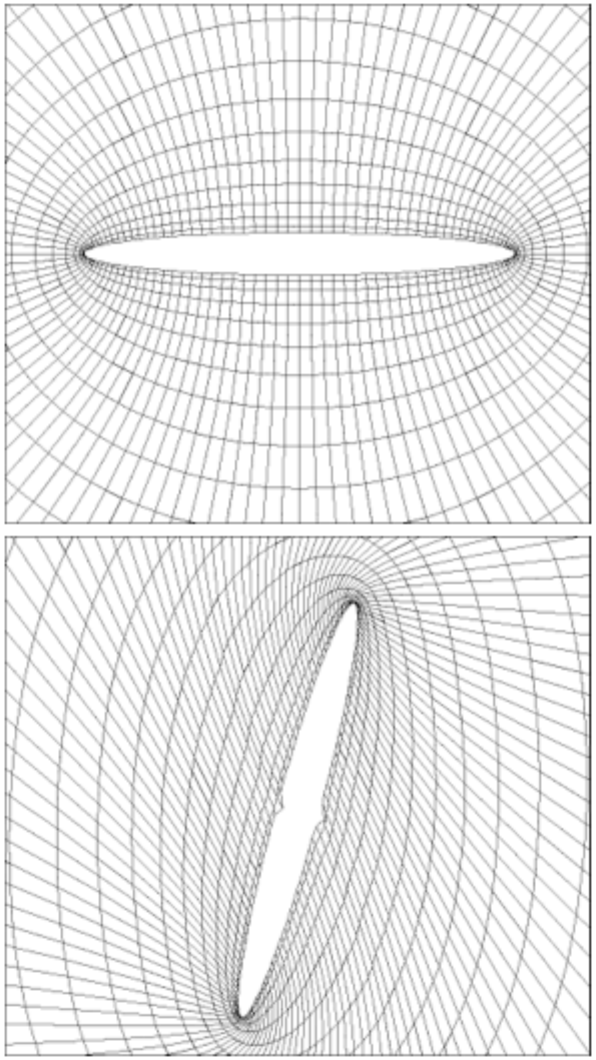
- Laplace Equation of Mesh Cell Velocity:

$$\frac{d}{dt}\nabla\cdot(k\nabla\mathbf{v}_b)=0$$

- Diffusivity Term:

$$k(d)=\frac{1}{d^2}$$

- Quadratic inverse distance based diffusivity



Oscillating Kinematics

- Heaving Motion:

$$\frac{h(t)}{c} = h_{max}\cos(2\pi f t)$$

- Pitching Motion:

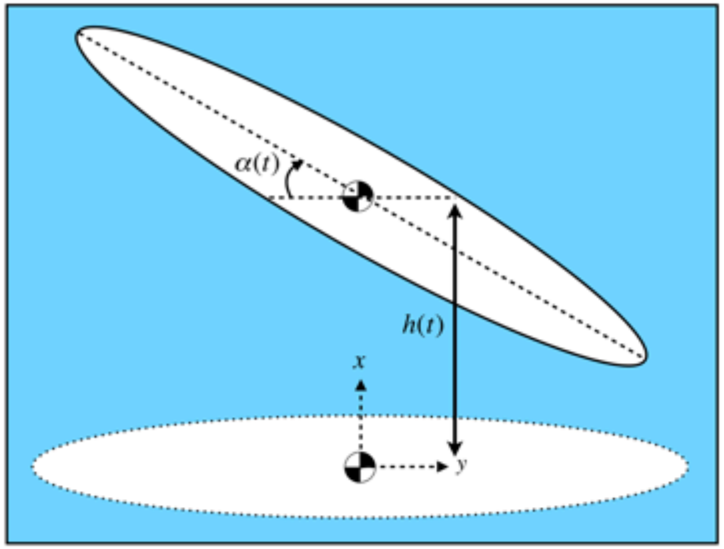
$$\alpha(t) = \alpha_{max}\cos(2\pi f t + \phi)$$

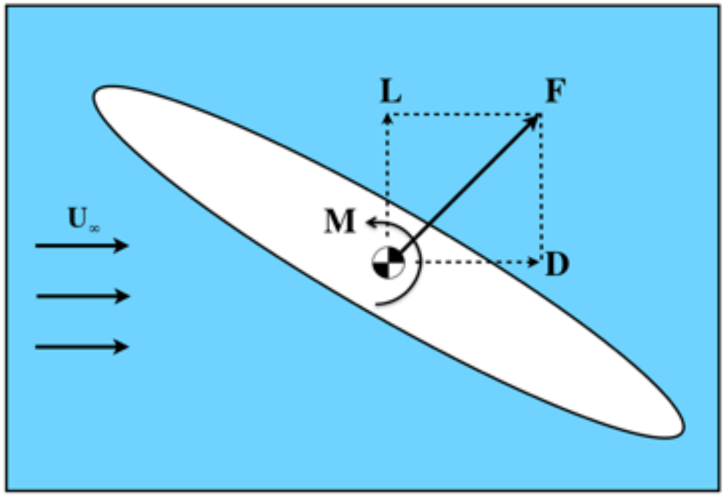
- Non-dimensionalized Frequency:

$$f = \frac{f^{*}c}{U_{\infty}}$$

- Instantaneous Power

$$P(t) = L(t)\frac{dh(t)}{dt} + M(t)\frac{d\alpha(t)}{dt}$$





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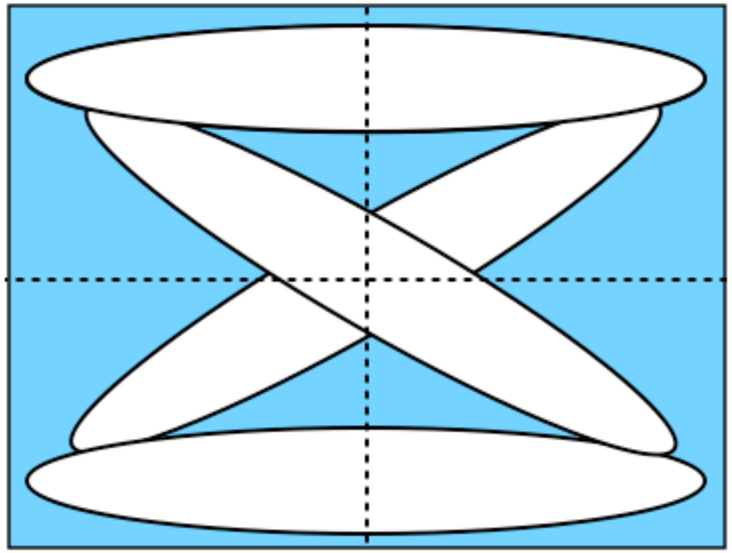
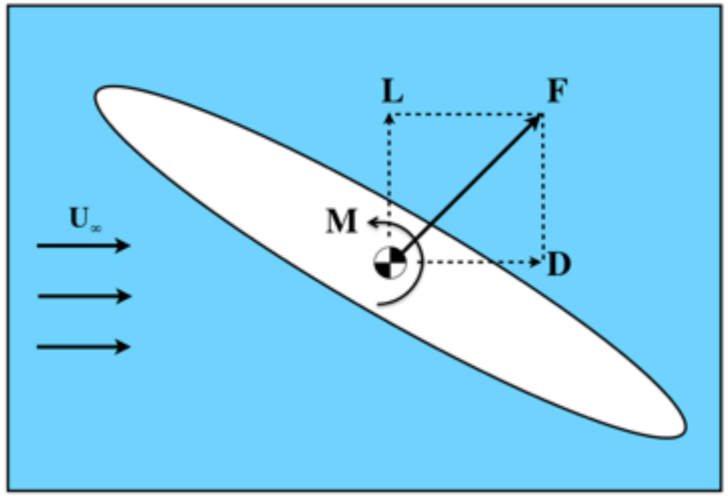
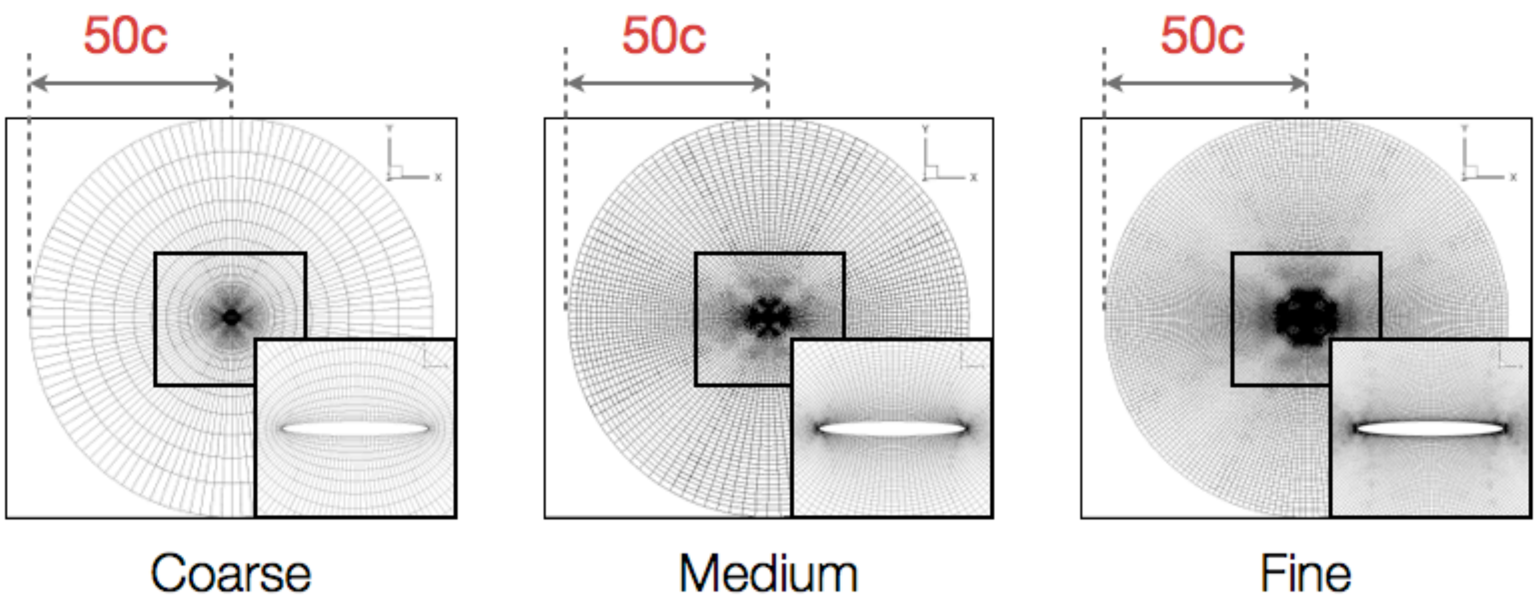




Mesh Resolution

- Three Mesh Resolutions:

Mesh	Total Faces	Nodes on Body	Radial Nodes	Run Time for 1 Oscillating Cycle
Coarse	4,680	120	40	300s
Medium	14,280	120	120	5,000s
Fine	53,760	240	225	30,000s



Static Simulation Validation

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- At 0° Angle of Attack

Parameter	Dynamic Mesh	Static Mesh Method	Percentage Difference
Drag	0.4080	0.4066	0.34%

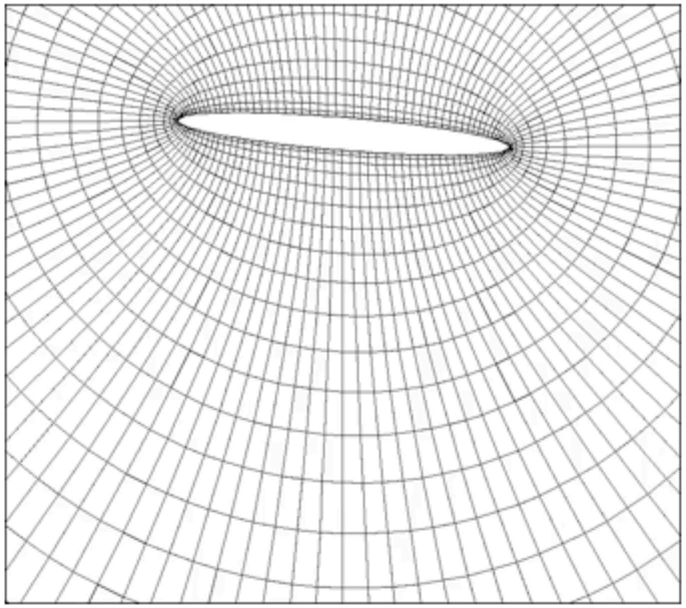
- At 45° Angle of Attack

Parameter	Dynamic Mesh	Static Mesh Method	Percentage Difference
Drag	0.1942	0.1946	-0.2%
Lift	1.5492	1.5512	-0.13%
Moment	-0.0190	-0.0191	0.52%

Dynamic Simulation Validation

- Optimal Case Kinematics Parameters:

$$h_{\max} = 0.5c \qquad \alpha_{\max} = 75^{\circ} \qquad \phi = 90^{o} \qquad f = 0.15$$



Dynamic Simulation Validation

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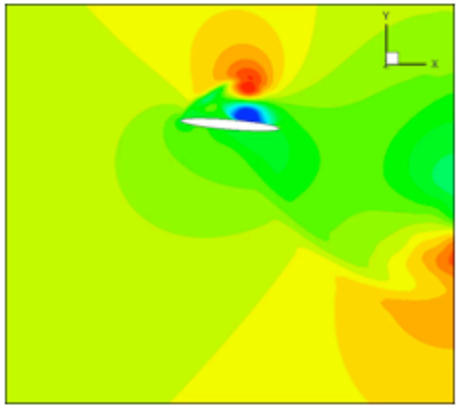
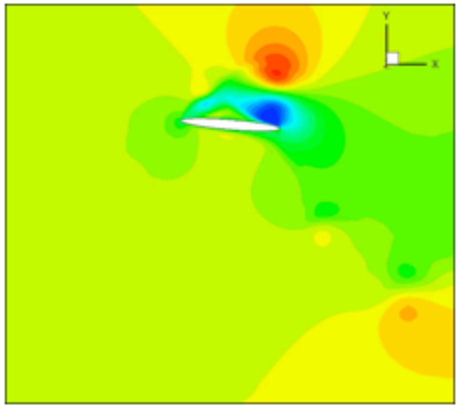
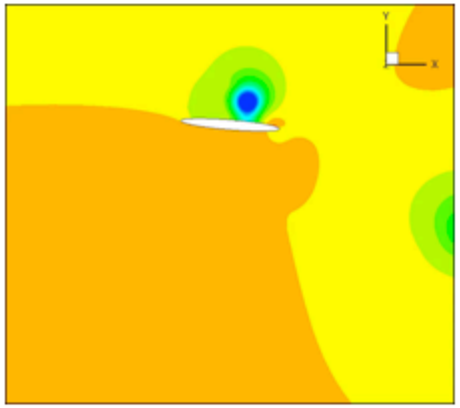
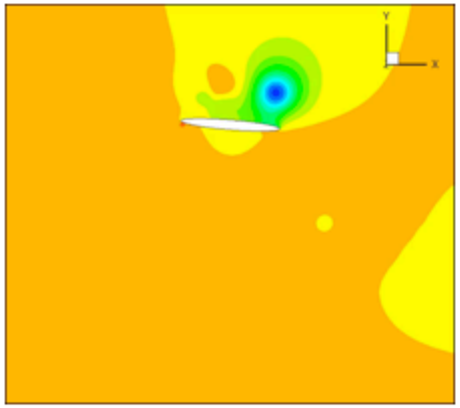
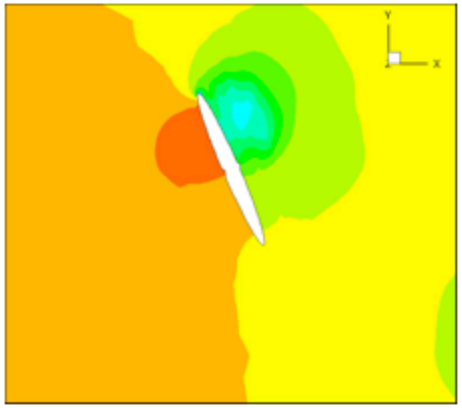
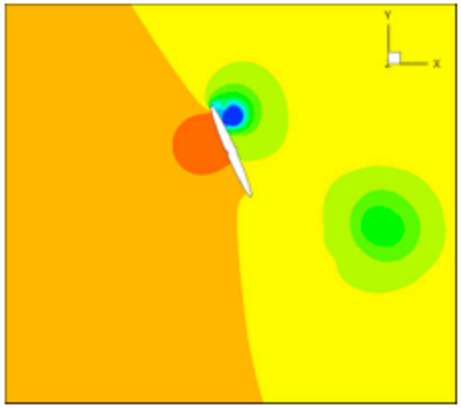
- Velocity and pressure field using fine mesh

	Dynamic Mesh Method	Reference Frame Method
Velocity Field		
Pressure Field		

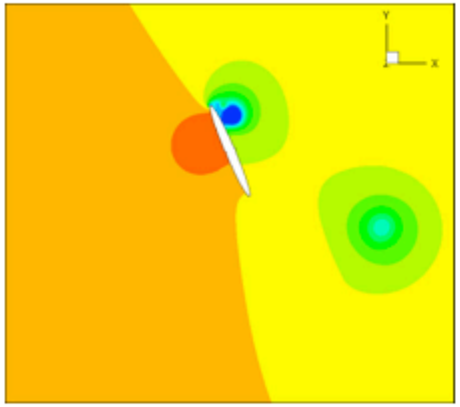
Vortex Shedding



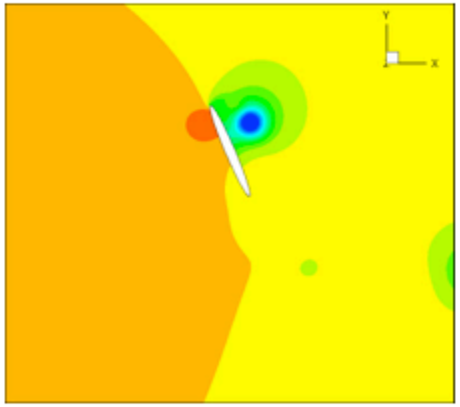
Coarse Mesh



Medium Mesh



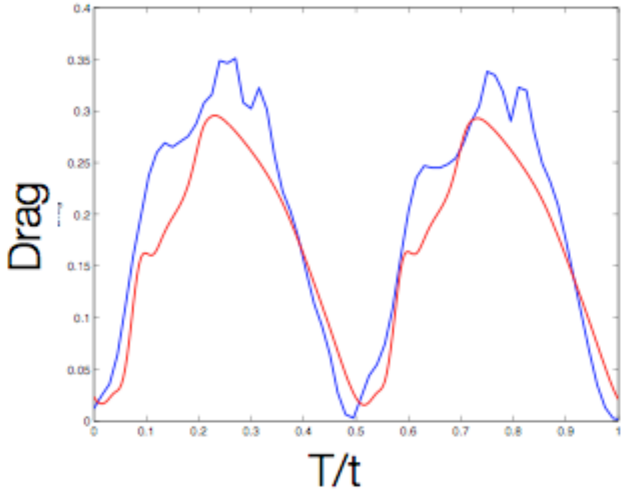
Fine Mesh

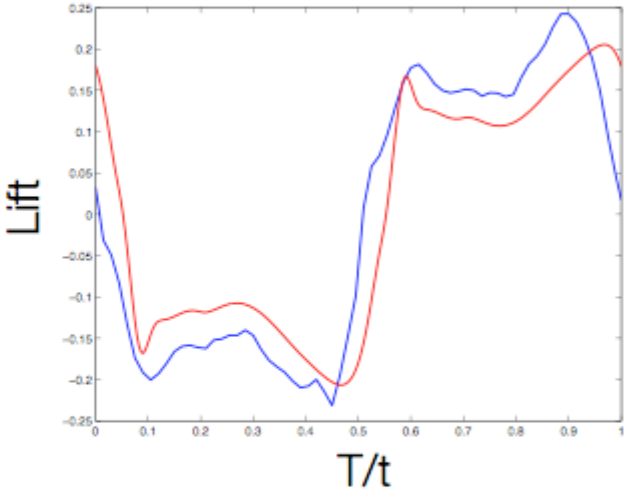


Reference Frame Method

Results

- Table for average drag, RMS lift





	Average Drag	RMS of Lift
Reference Frame Method	0.1603	0.1419

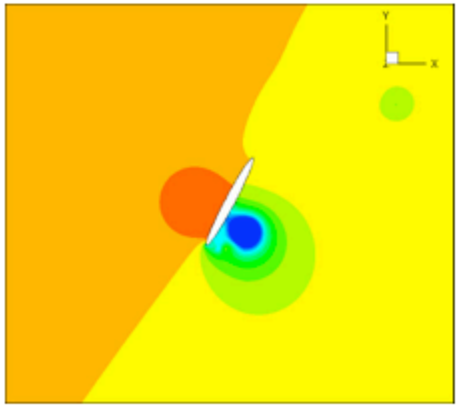
Mesh	Average Drag	% Difference	RMS of Lift	% Difference
Coarse	0.1929	**13.91%**	0.1628	**14.72%**
Medium	0.1876	**10.81%**	0.2044	**44.01%**
Fine	0.1856	**9.63%**	0.2050	**44.47%**

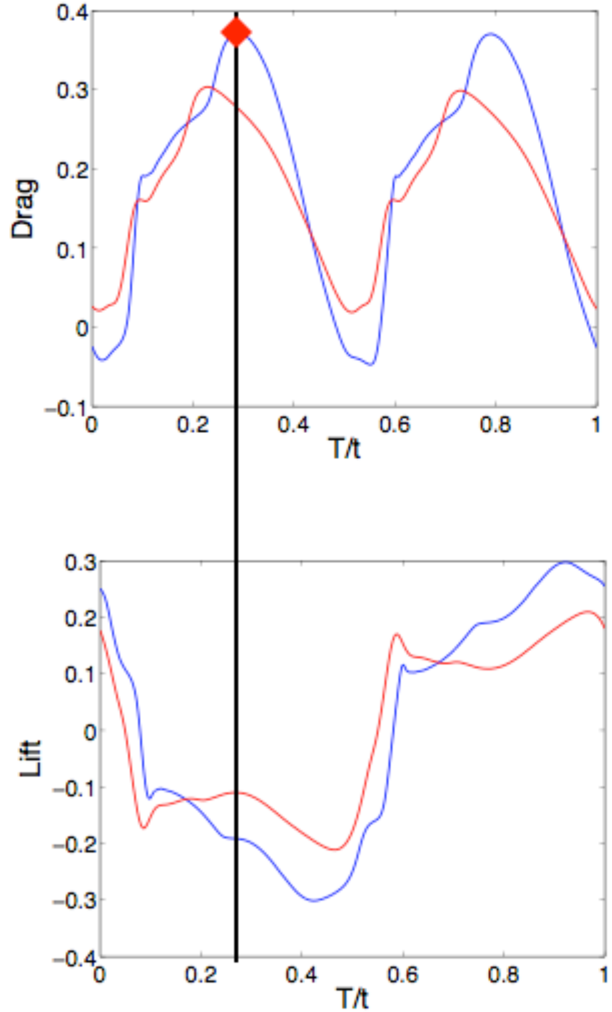
Results - Vortices

T/t = 0.34

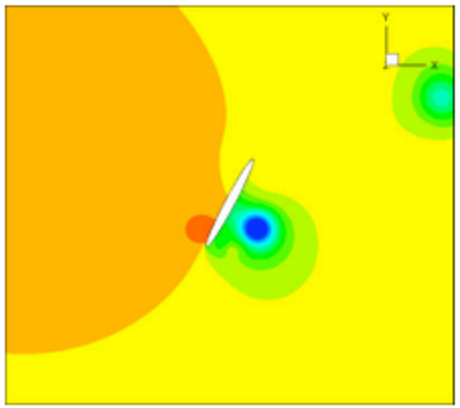
Max. Drag

Dynamic
Mesh Method





Reference
Frame Method

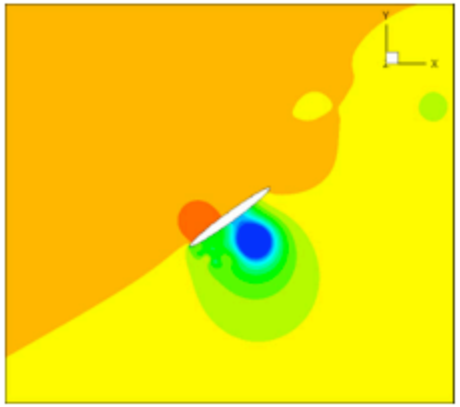


Results - Vortices

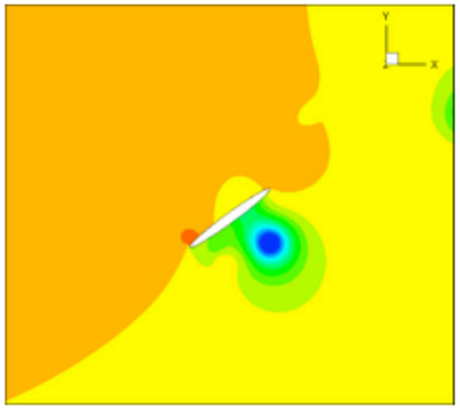
T/t = 0.42

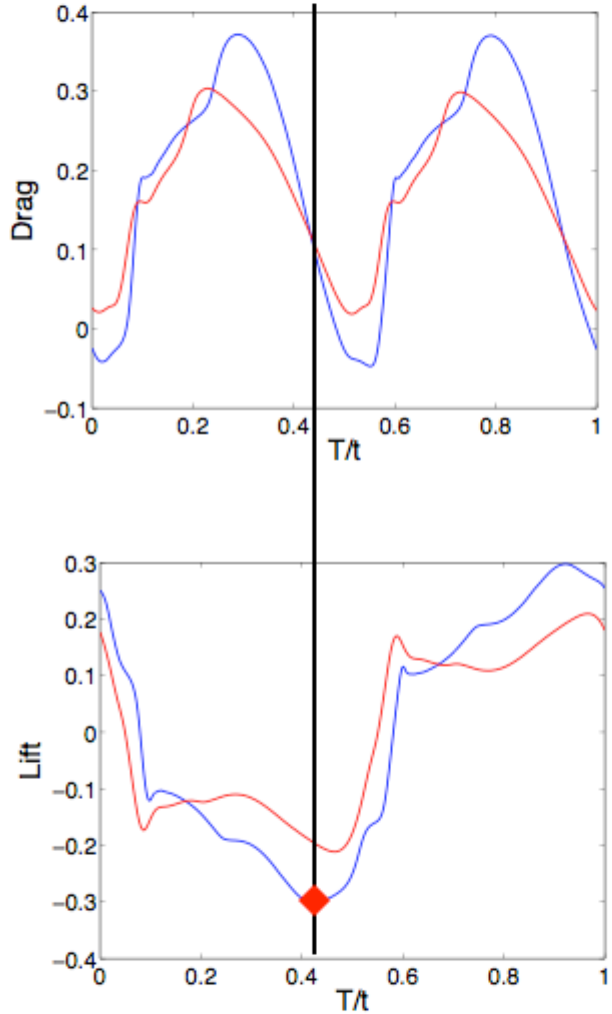
Min. Lift

Dynamic Mesh Method



Reference Frame Method



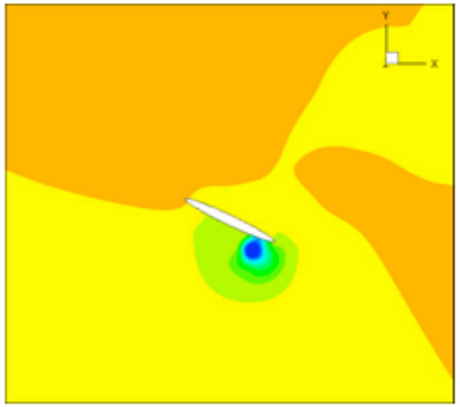


Results - Vortices

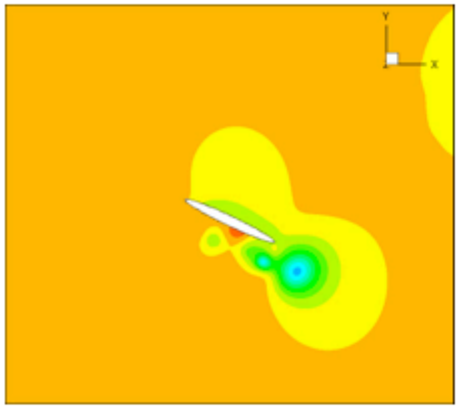
T/t = 0.55

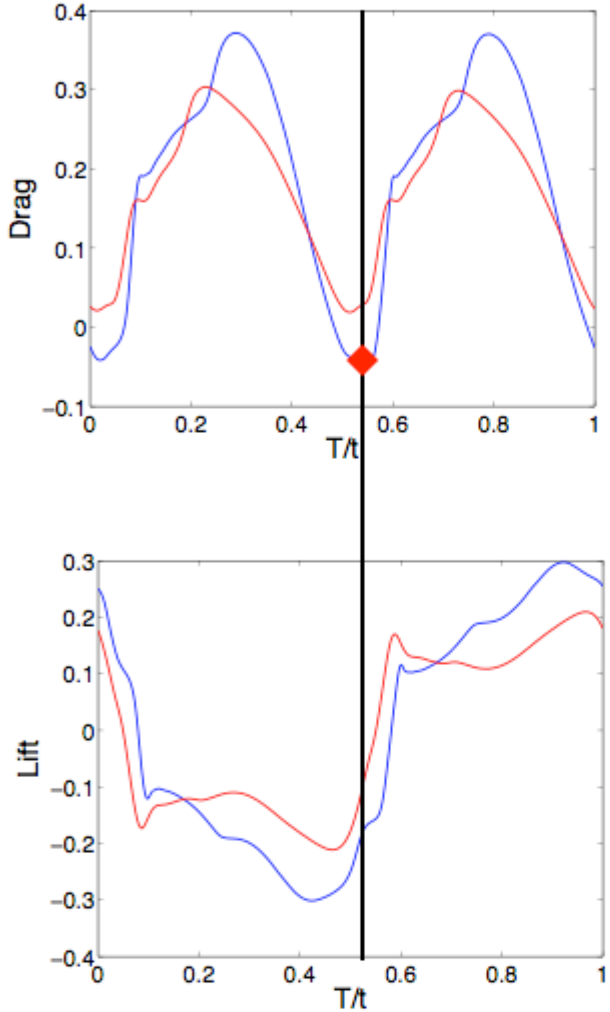
Min. Drag

Dynamic Mesh Method



Reference Frame Method



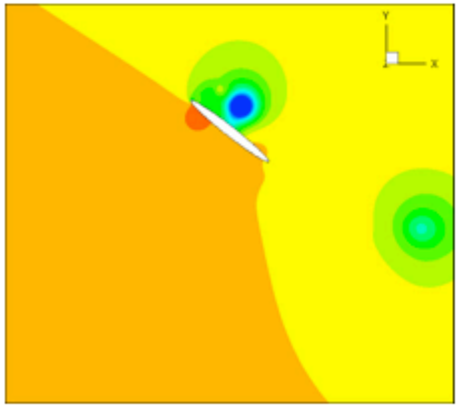


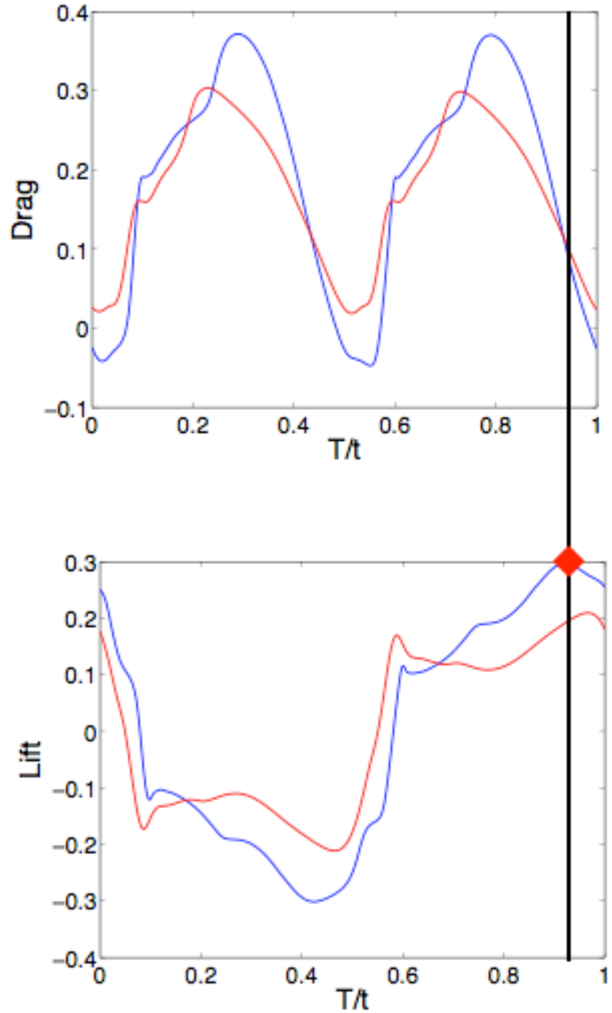
Results - Vortices

T/t = 0.92

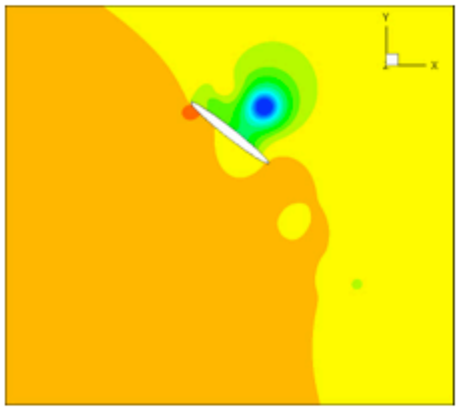
Max. Lift

Dynamic Mesh Method



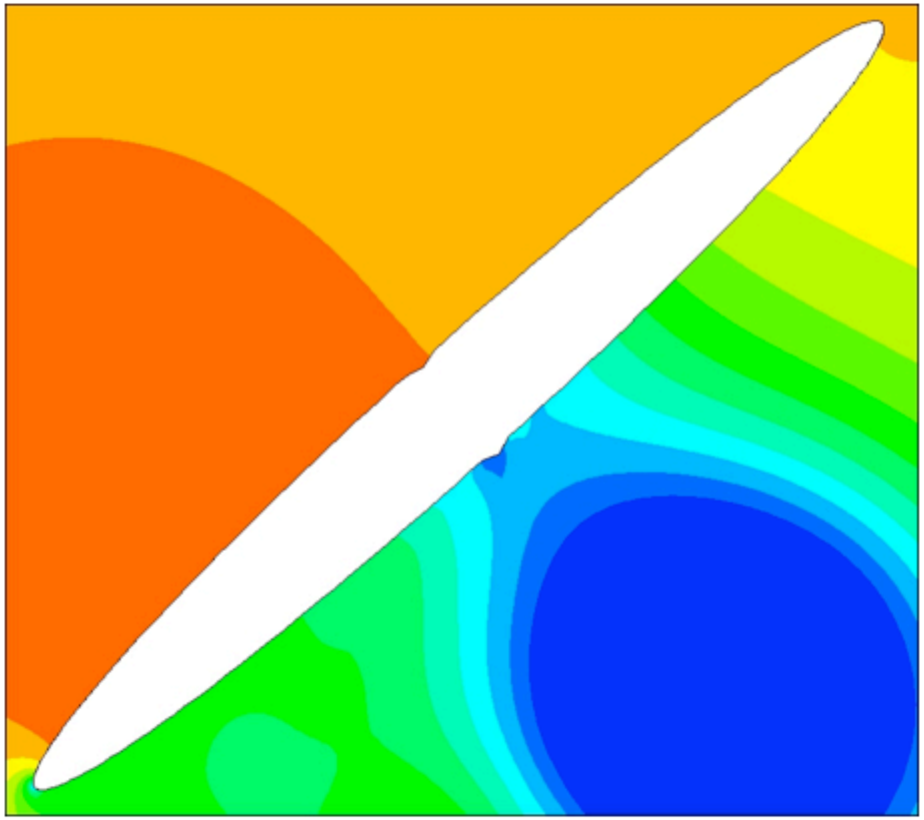


Reference Frame Method



Spur Formation

- Vortices interact with the spur
- Problems with the interpolation of points and faces



Conclusion

- Higher mesh resolution improves vortex formation & drag force
- Vortices fail to leave surface due to the formation of spur
- Model validated
  - Static simulation, oscillating kinematics, dynamic simulation

Future Work

- Solve the interpolation problem of the spur
- Investigate different laplace solver
    - E.g. Laplace solver of mesh nodes displacement
- Explore the function of diffusivity term and the effect of its exponential power
- Try different type of structured and unstructured mesh

References

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Questions?