A Versatile Sharp Interface Immersed Boundary Method with Application to Complex Biological Flows

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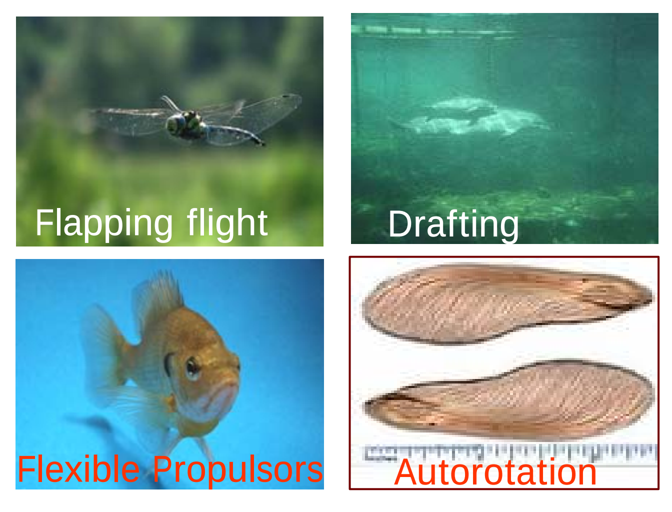
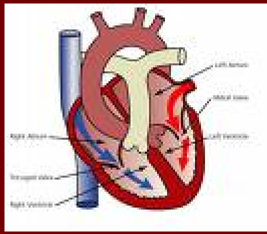
Biological Flows

- Biomimetics and Bioinspired Engineering
  - What can we learn from Nature ?
  - How can we adapt Nature’s solutions into engineered devices/machines ?

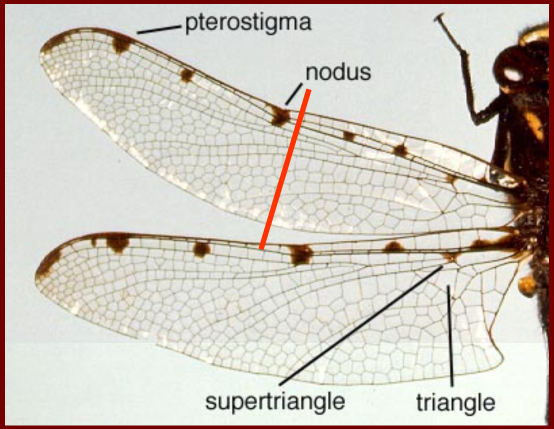


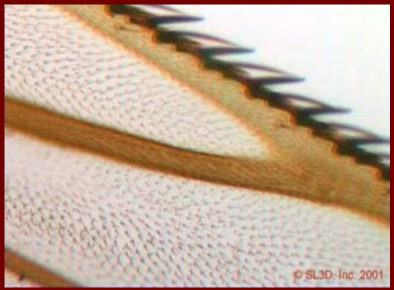
- Biomedical Engineering
  - Cardiovascular flows
  - Respiratory flows
  - Phonatory/Speech Mechanisms
  - Biomedical Devices

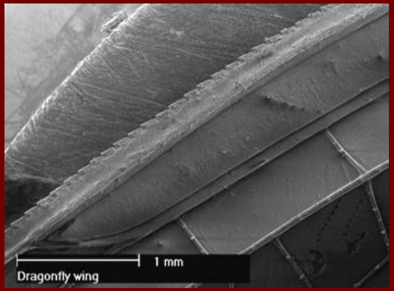


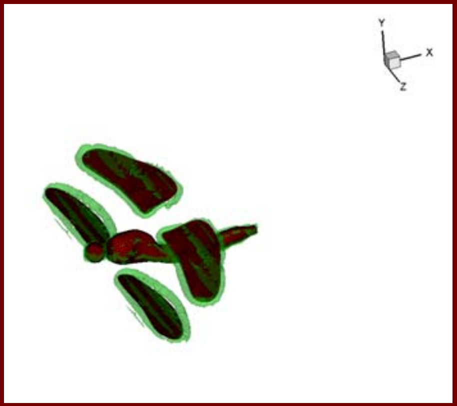
Inspiration from Dragonflies

- Dragonflies
  - Existed for 350 million years
  - Wingspan from 2 – 80 cm
  - Fast and agile
- Wing Design
  - Thin, lightweight
  - Vein reinforced
  - Pleated along chord
  - Pterostigma
  - Microstructure
- Wing Configuration
  - Wing-wing interaction?
- Wing Flexion?



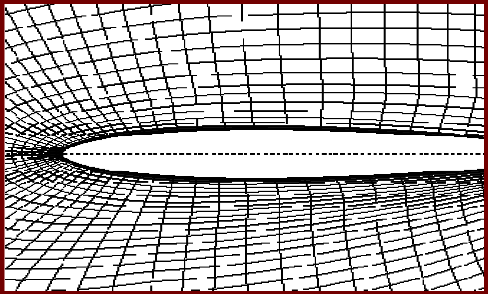


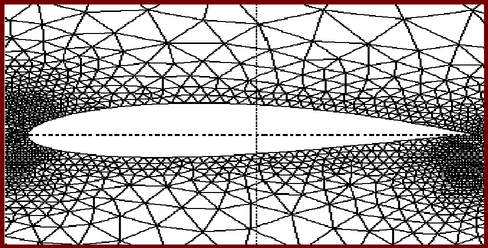




Computational Modeling

- Need to tackle
  - Complex 3D geometries
  - Moving boundaries
  - Fluid Structure Interaction
  - Resolution of vortex dynamics
  - Relatively low Reynolds numbers





- Very challenging for conventional body fitted methods.

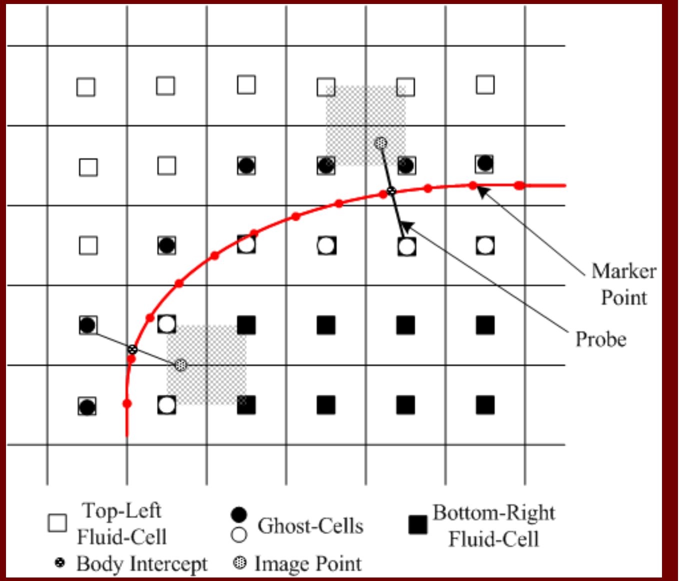
- Immersed Boundary Methods
  - handle these problems in all their complexity.

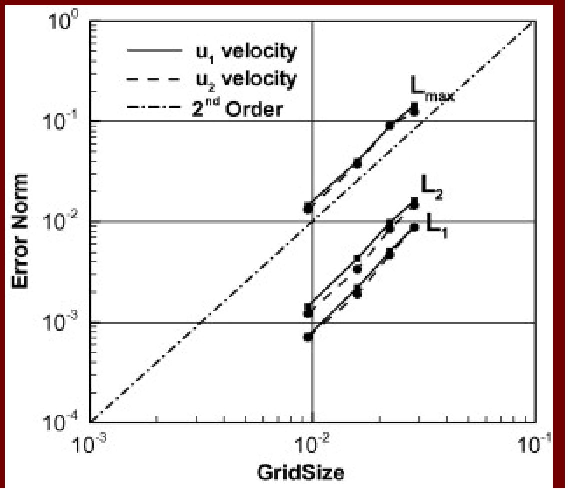
ViCar3D

Journal of Computational Physics
Volume 227, Issue 10, 1 May 2008,
Pages 4825-4852

Viscous Cartesian Grid Solver for 3D Immersed Boundaries

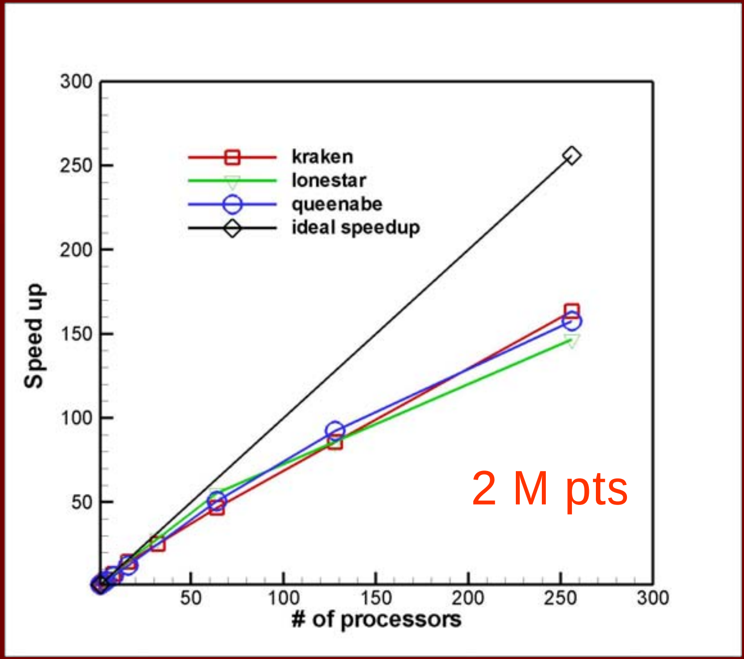
- Simulations on non-conforming Cartesian Grids
  - Stationary/moving boundaries
  - Solids/membranes
- Sharp Interface IBM method
  - No boundary forcing (Peskin et al)
  - 3D ghost-cell methodology
- 2nd Order Fractional Step Scheme
- 2nd Order non-dissipative central difference scheme
  - IBM treatment also 2nd order accurate
- Non-uniform meshes
- Geometric Multigrid for Pressure Poisson
- Global Coeff Dynamic SGS Model (Vreman)

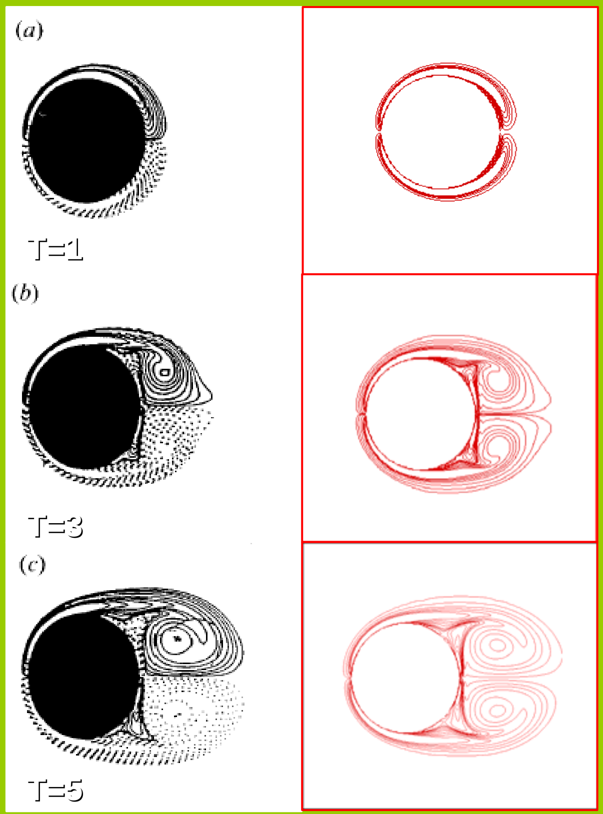




ViCar3D

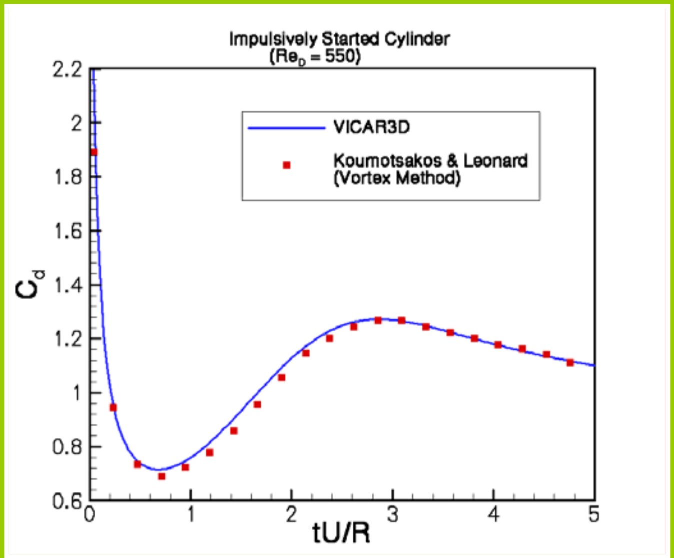
- Parallelized
- Extensively validated





Komoutsakos & Leonard

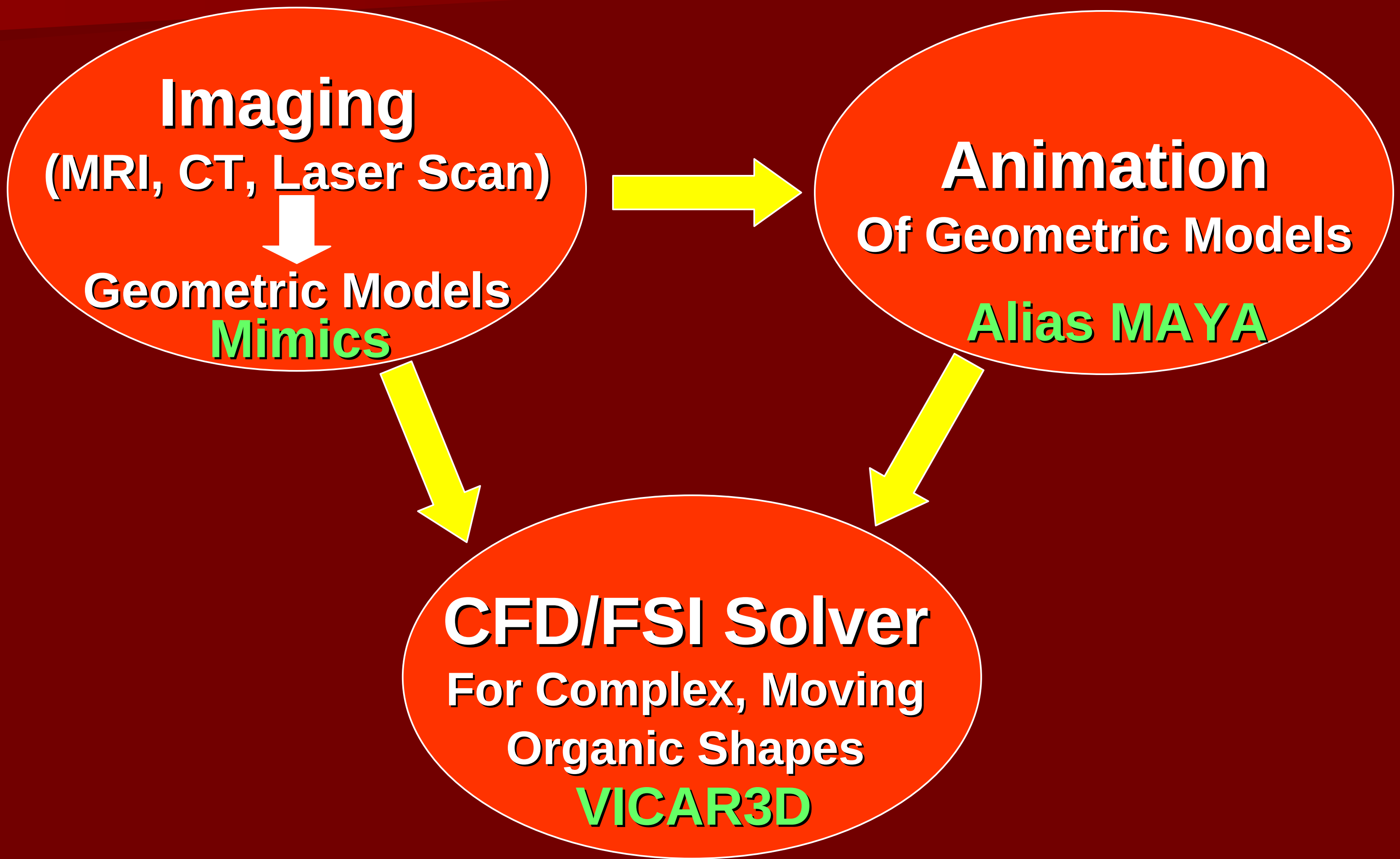
VICAR3D



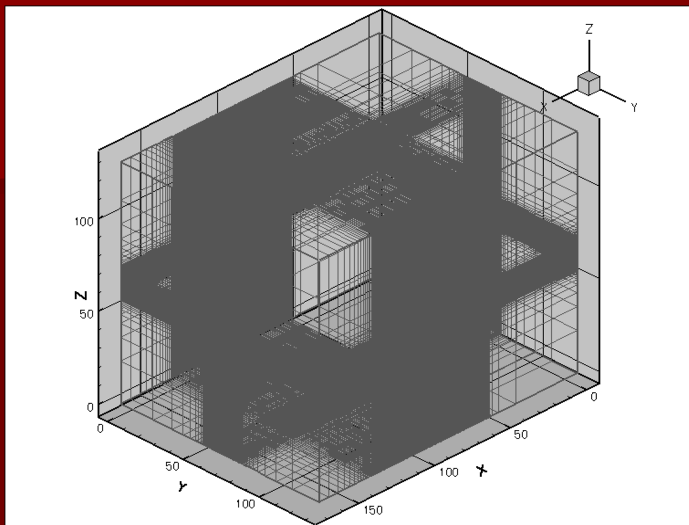
Impulsively Started Cylinder Re=1000

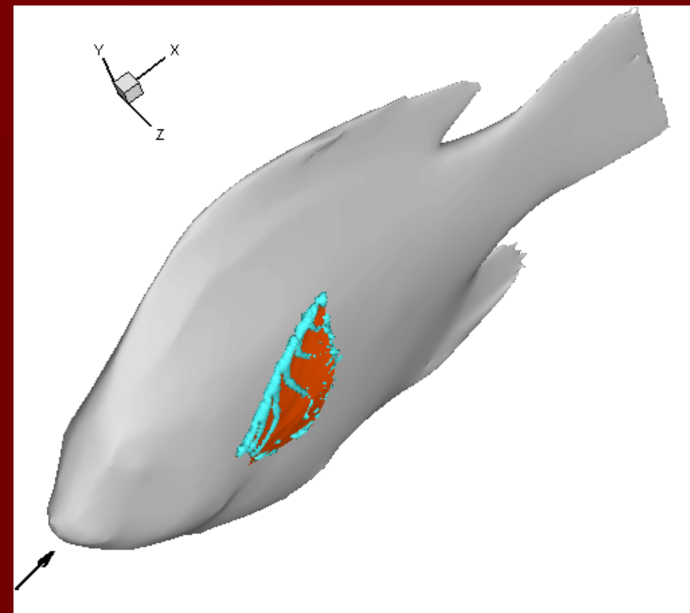
Mittal et al 2008, JCP

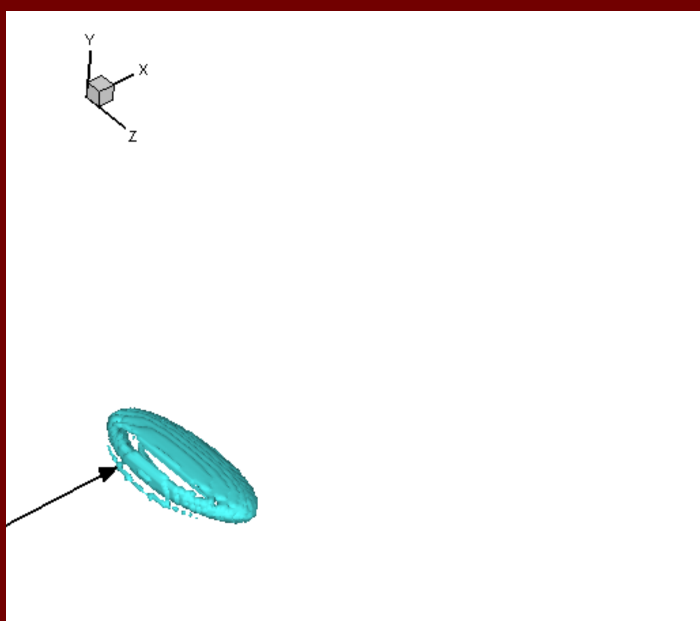
Closing the Loop for CFD in Biology/Biomedical Engineering



ViCar3D-Capabilities





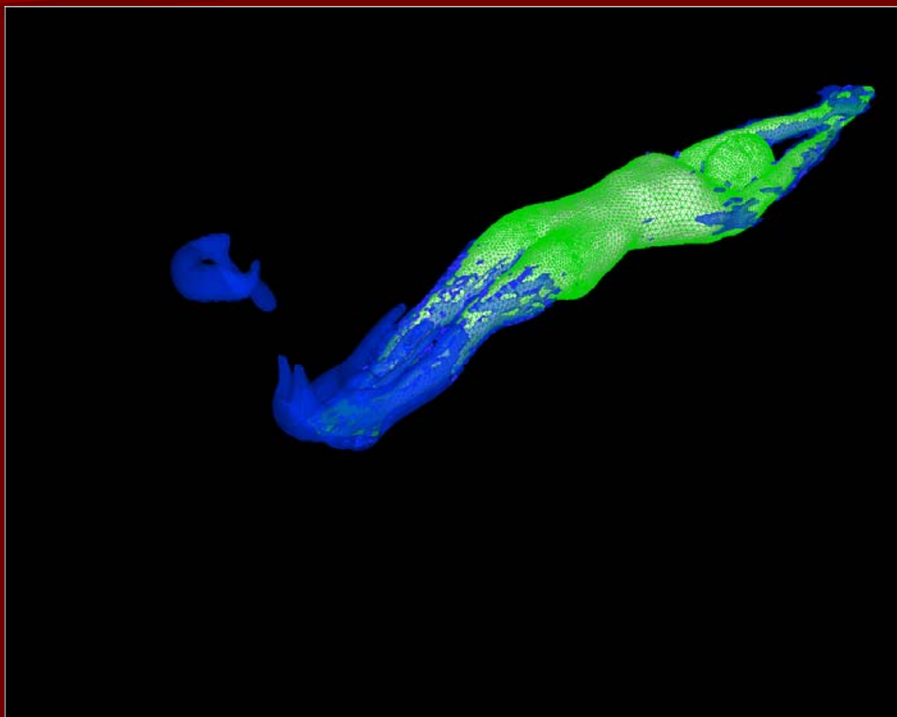


- "Wake Topology and Hydrodynamic Performance of Low-Aspect-Ratio Flapping airfoil", J. Fluid Mechanics (2006) Vol 566 pp 309-343 .

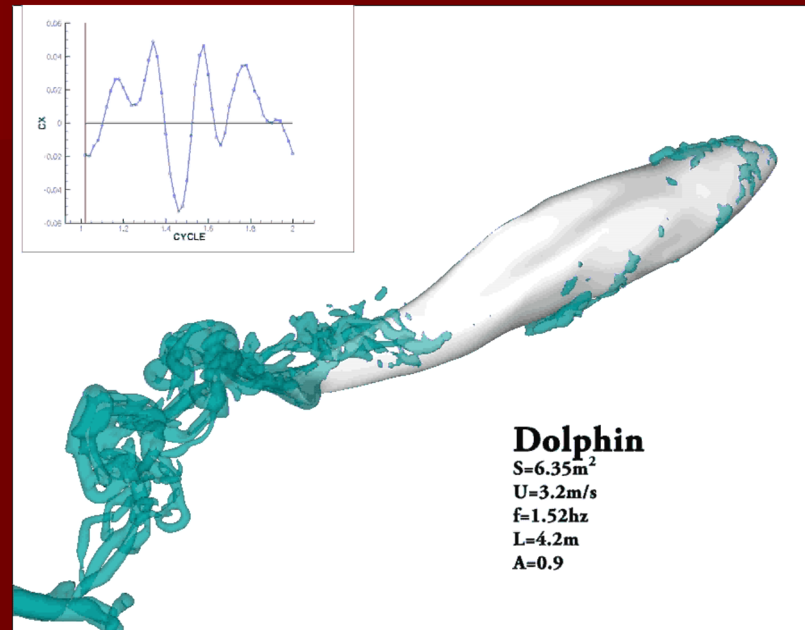
- Low-dimensional models and performance scaling of a highly deformable fish pectoral fin; J. Fluid Mech. (2009), vol. 631, pp. 311–342.

- "Computational modelling and analysis of the hydrodynamics of a highly deformable fish pectoral fin." (2010) , Journal of Fluid Mechanics , doi:10.1017/S0022112009992941.

ViCar3D-Capabilities



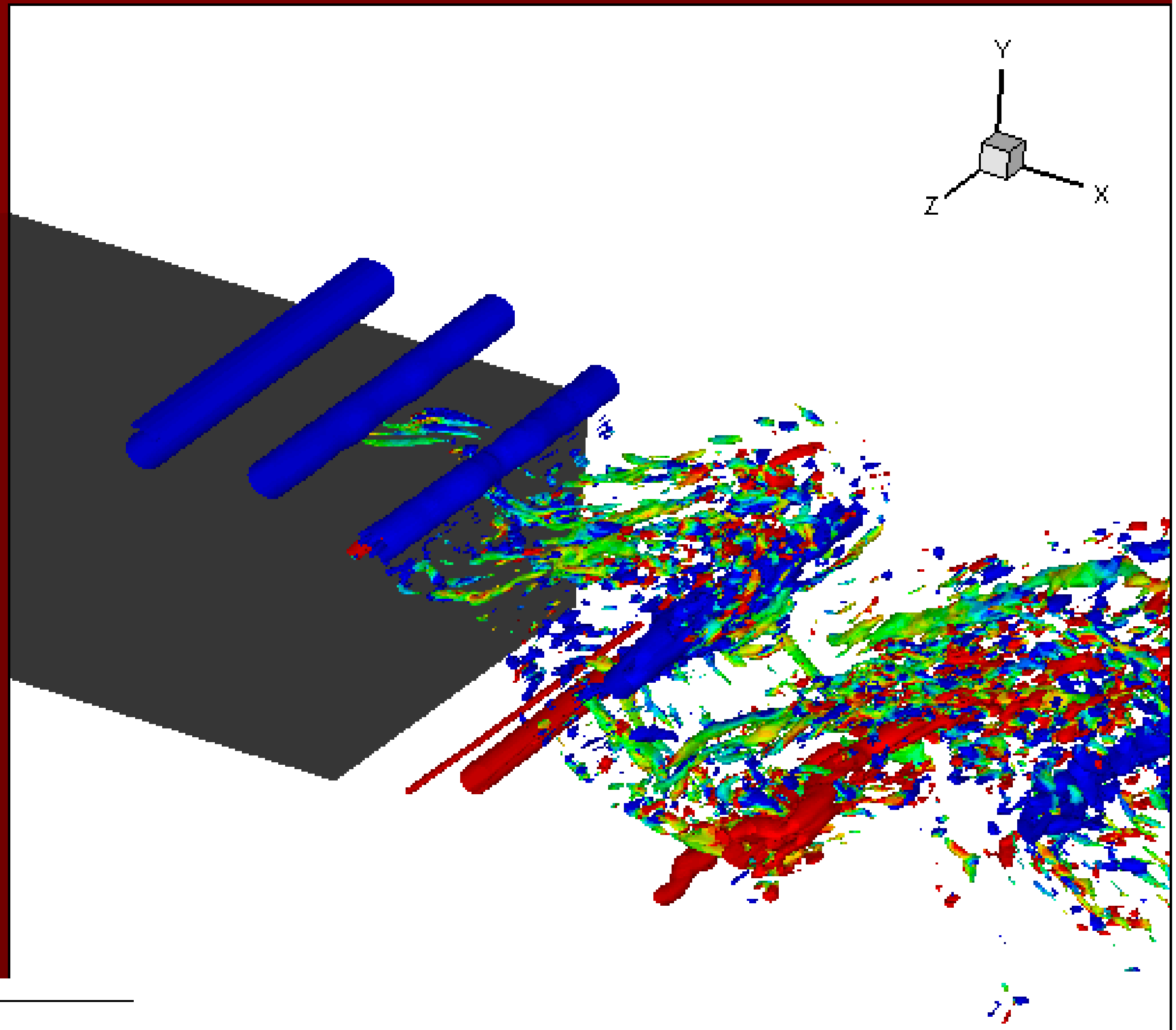
CFD of the dolphin kick

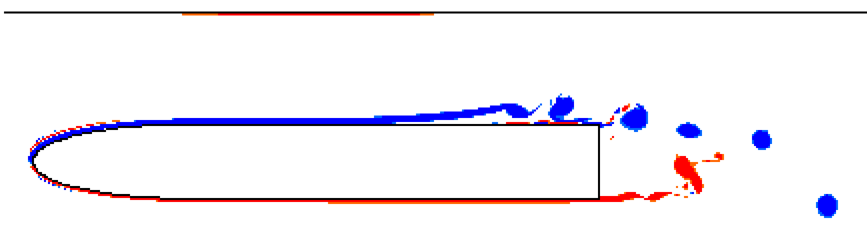


- "Propulsive Efficiency of the Underwater Dolphin Kick in Humans", Journal of Biomechanical Engineering, Vol. 131, May 2009
- "A computational method for analysis of underwater dolphin kick hydrodynamics in human swimming", Sports Biomechanics, 8(1), pp. 60-77, March 2009.
- "A comparison of the kinematics of the dolphin kick in humans and cetaceans", Human Movement Science, Vol.28, pp.99-112, 2009

High Re??

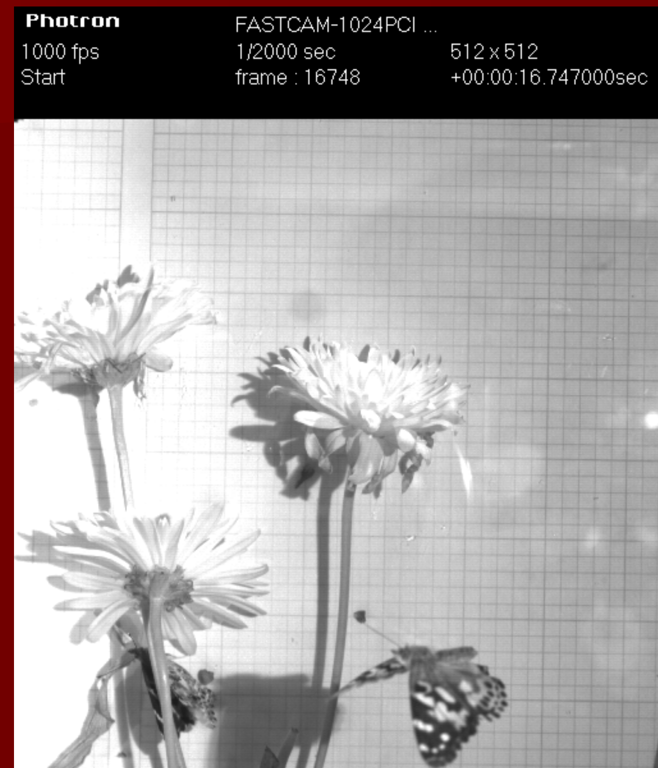
- $Re_c = 10^5$
- 512x256x32
- 128 CPUs





- **Nonlinear dynamics and synthetic-jet-based control of a canonical separated flow. J. Fluid Mech., doi:10.1017/S002211201000042X**

Flight Maneuvers in Insects



Gravity   Side View   Top View

- Maneuver: change in heading and/or speed
- Insects display a large array of maneuvers

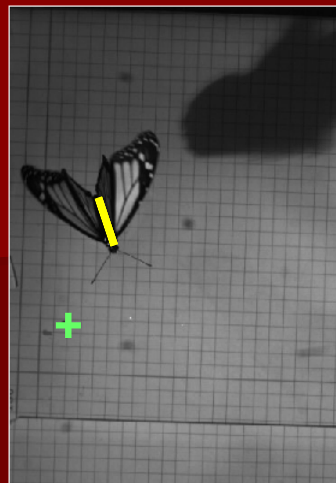
Flapping Frequency and Maneuvering

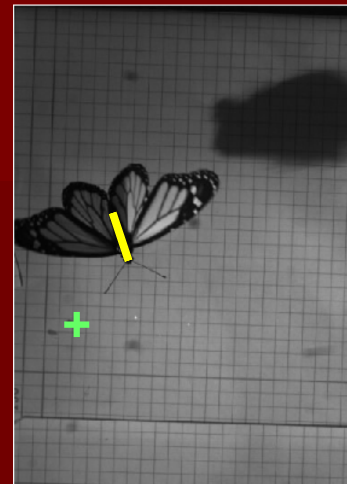
- High frequency flappers (f > 150 Hz)
  - Bees, Flies, wasps etc
  - $\tau_{turn} > 10\tau_{flap}$
  - Minute changes in kinematics required to execute turn. (Dickinson et al)
  - Stroke plane/amplitude/pitch angle

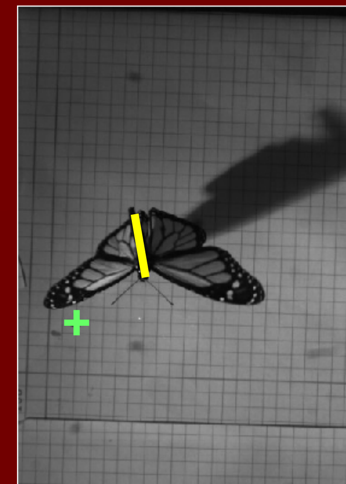
$$T = I_{\theta\theta}\ddot{\theta} + C\dot{\theta}$$

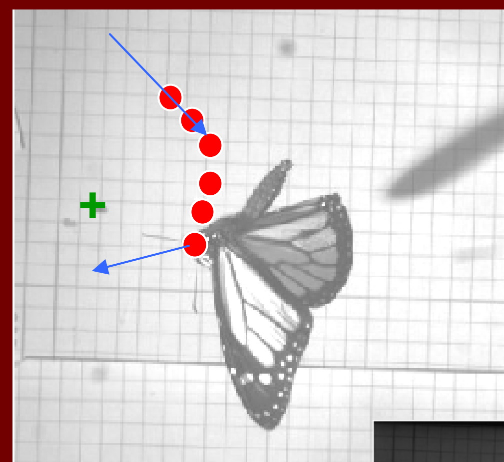
$$\tau_{turn} \sim I_{\theta\theta} / C$$

- Low frequency flappers (f < 50 Hz)
  - Moths, butterflies, locusts etc.
  - $\tau_{turn} \sim \tau_{flap}$
  - Turns can be executed in O(1) flap if wings can produce sufficient turning moments.
  - Does this happen??

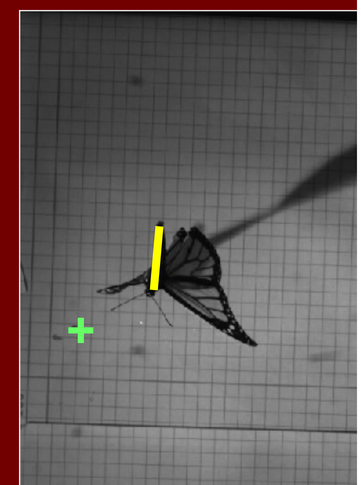


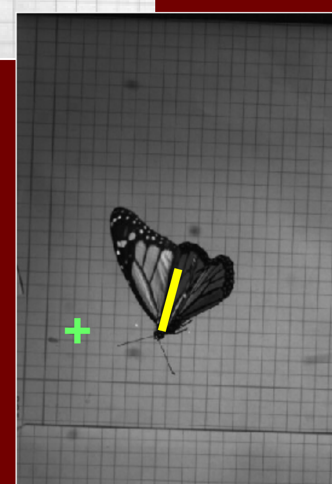






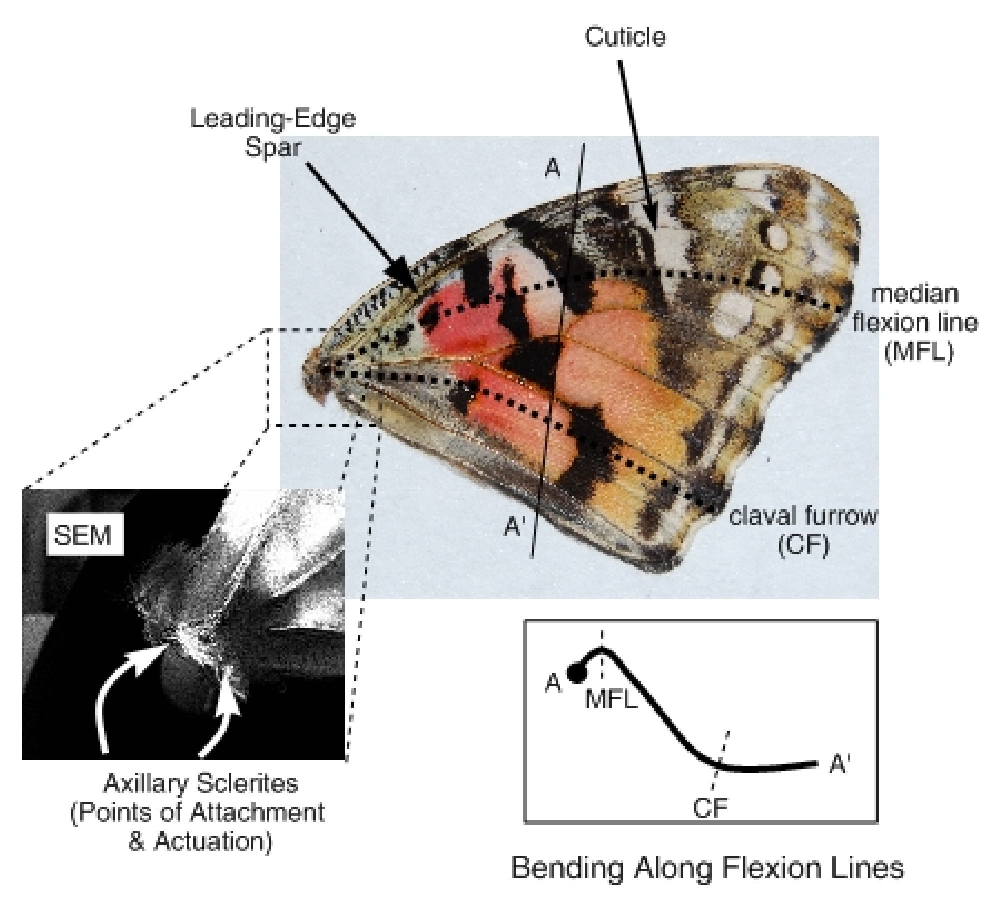
- Turning in a Monarch Butterfly
- Sequence shows 1.5 flaps
- >90º change in heading !
- Turning distance < body size
- Turn on a dime!



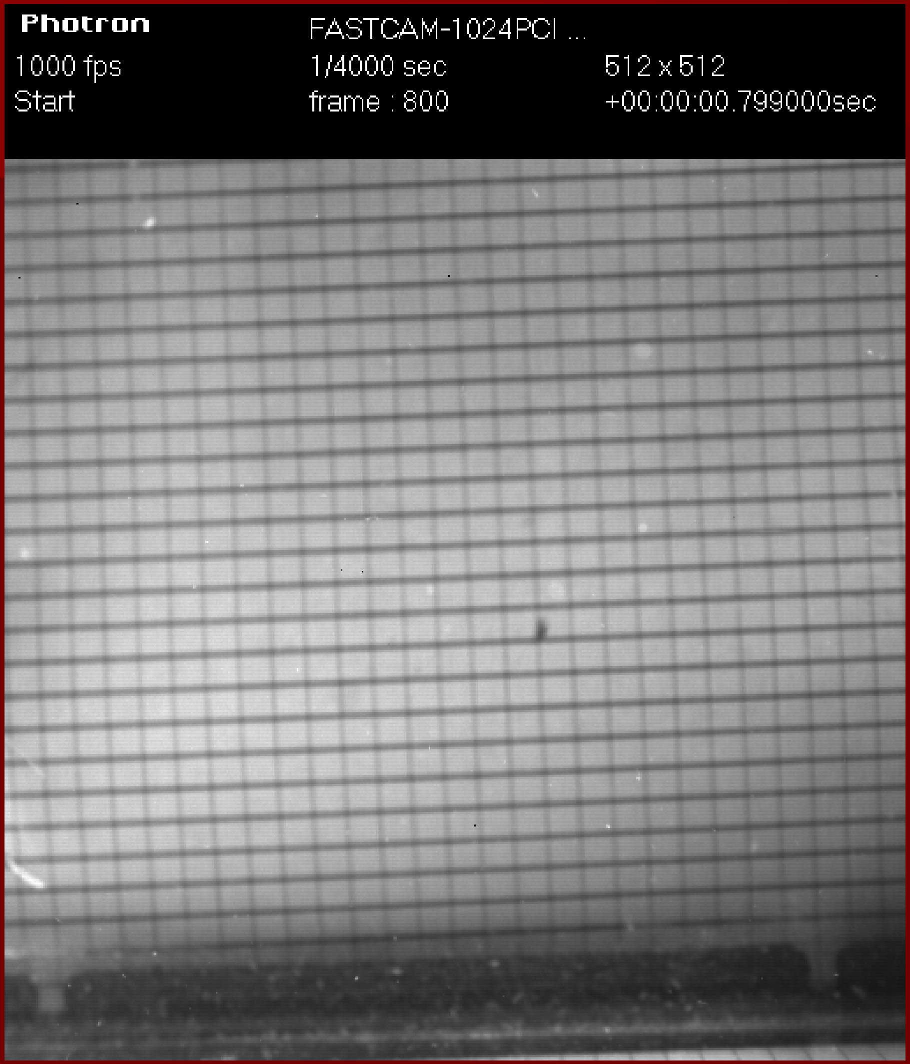


How does the Butterfly do this ? Deformable Wings

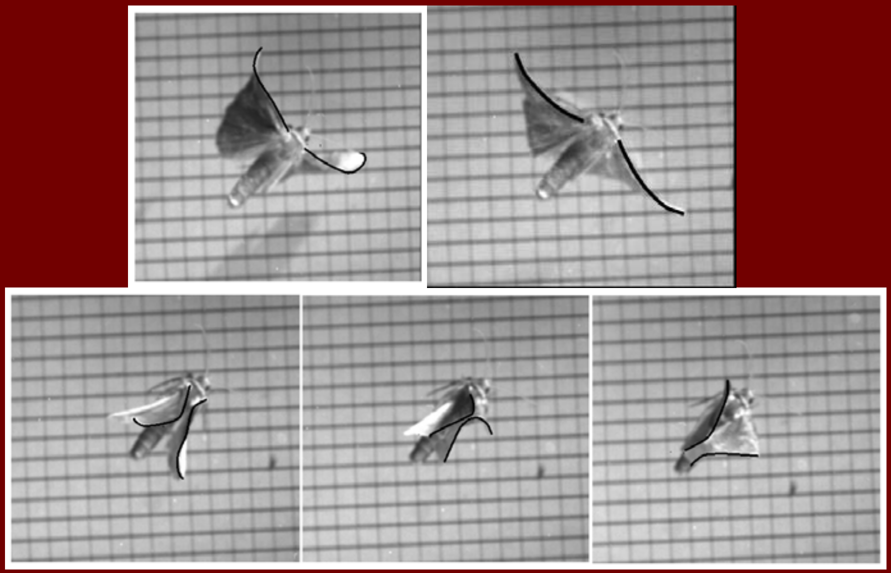
- Wings deform significantly
- Greater repertoire of wing kinematics.
  - Large left-right wing asymmetries
- What causes deformation
  - Flow and inertia induced deformation. (Daniels et al)
  - Also active deformation through action of direct muscles on axillary sclerites (wing joint).
- Perhaps even active control of deformability ??



Wing Flexion: Enabler of other Flight Modes



Moth in Climbing Flight



Clap & peel enabled by wing flexion

COBRE Insect Videogrammetry Lab

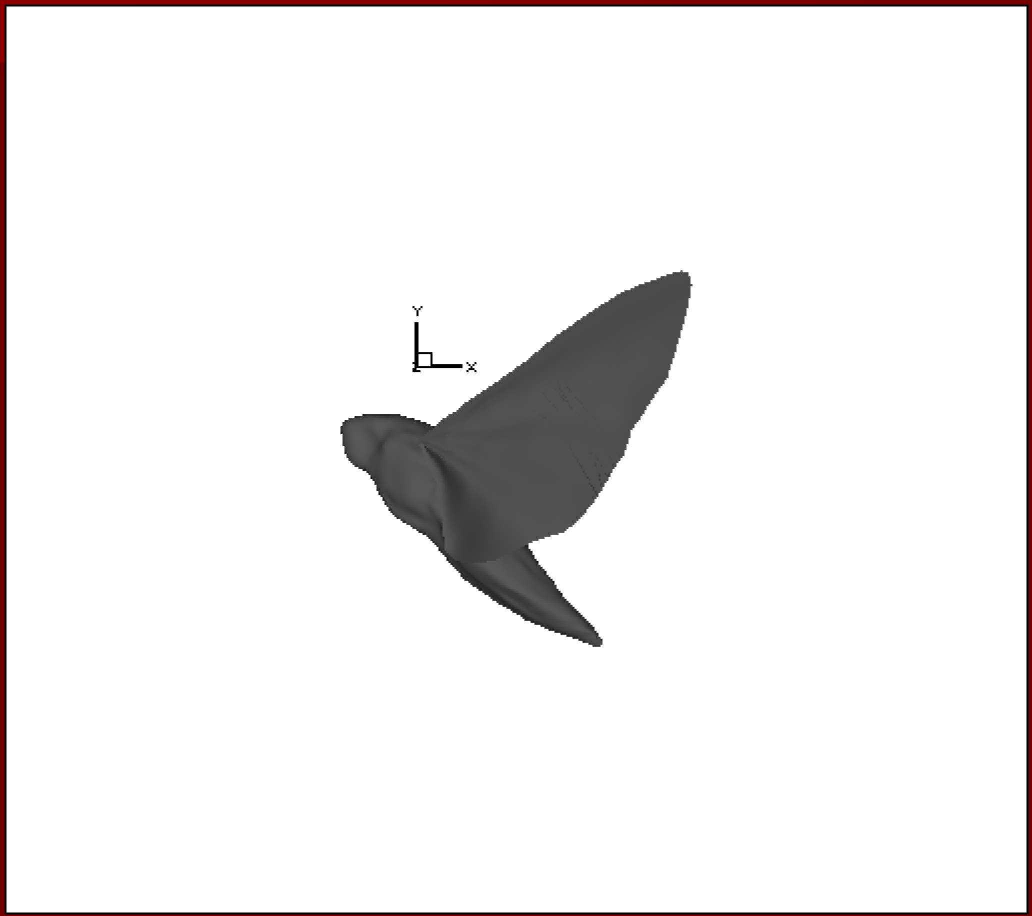
Integrated Approach

- High Speed Videogrammetry
  - JHU Laboratory for Bioinspired Engineering
  - Tyson Hedrick Lab (UNC)
- Structural parameterization (Vallance Lab, GWU)
  - Wing
  - Body
- High Fidelity Computational Modeling of Aerodynamics and Aero-Structural Interaction
  - Sharp Interface Immersed Boundary Method
  - Direct and Large-Eddy Simulation
  - Wing deformation modeling using FEM

Hawkmoth in Hover

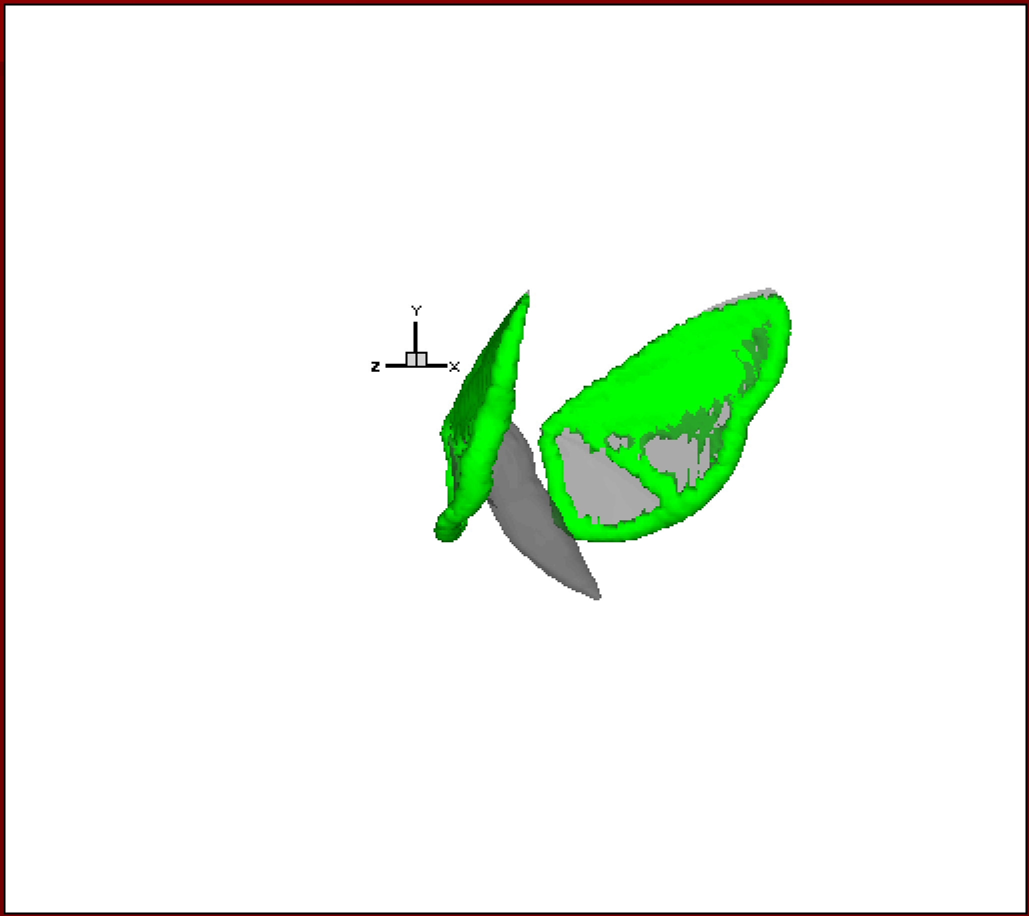
Hedrick Lab (UNC)

Animated Model Rendered for CFD



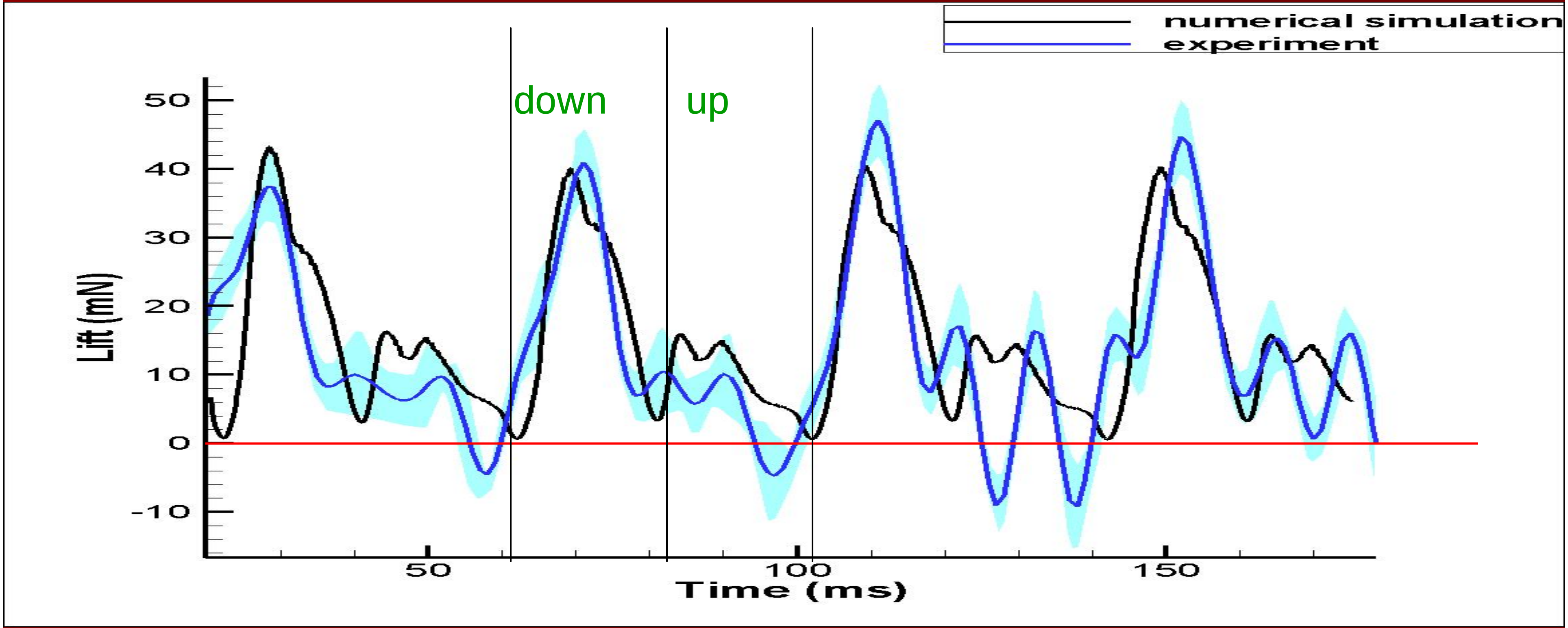
- Moth body based on high-res laser scan.
- Animation created in MAYA by matching high speed video.

Vortex Dynamics



- Strong spiral LEV on downstroke.
- Vortex ring shed at the end of downstroke from each wing.
- Weak LEV on upstroke

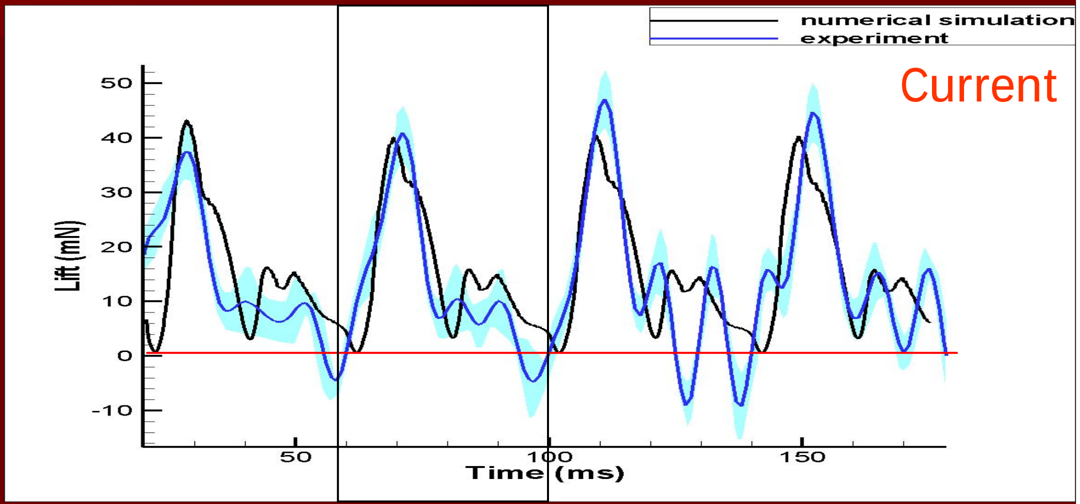
Lift Prediction



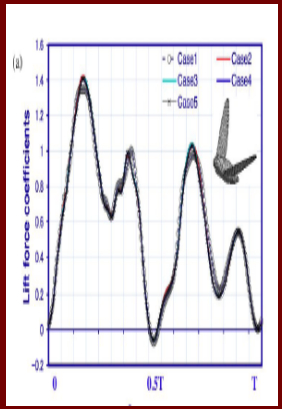
- Fairly good prediction of peak thrust during downstroke.
- Some mismatch during upstroke
  - Larger cycle-to-cycle variations in upstroke
- Interestingly, upstroke is found to be quite ineffective!

Comparison with Past Models

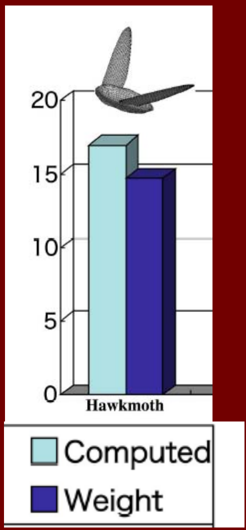
- Liu et al (Chiba University)
- Hawkmoth in hover
- Rigid wings
- Kinematics based on Ellington's data.
- Average lift is comparable



- However simulations show significant lift generation during up (back) stroke.

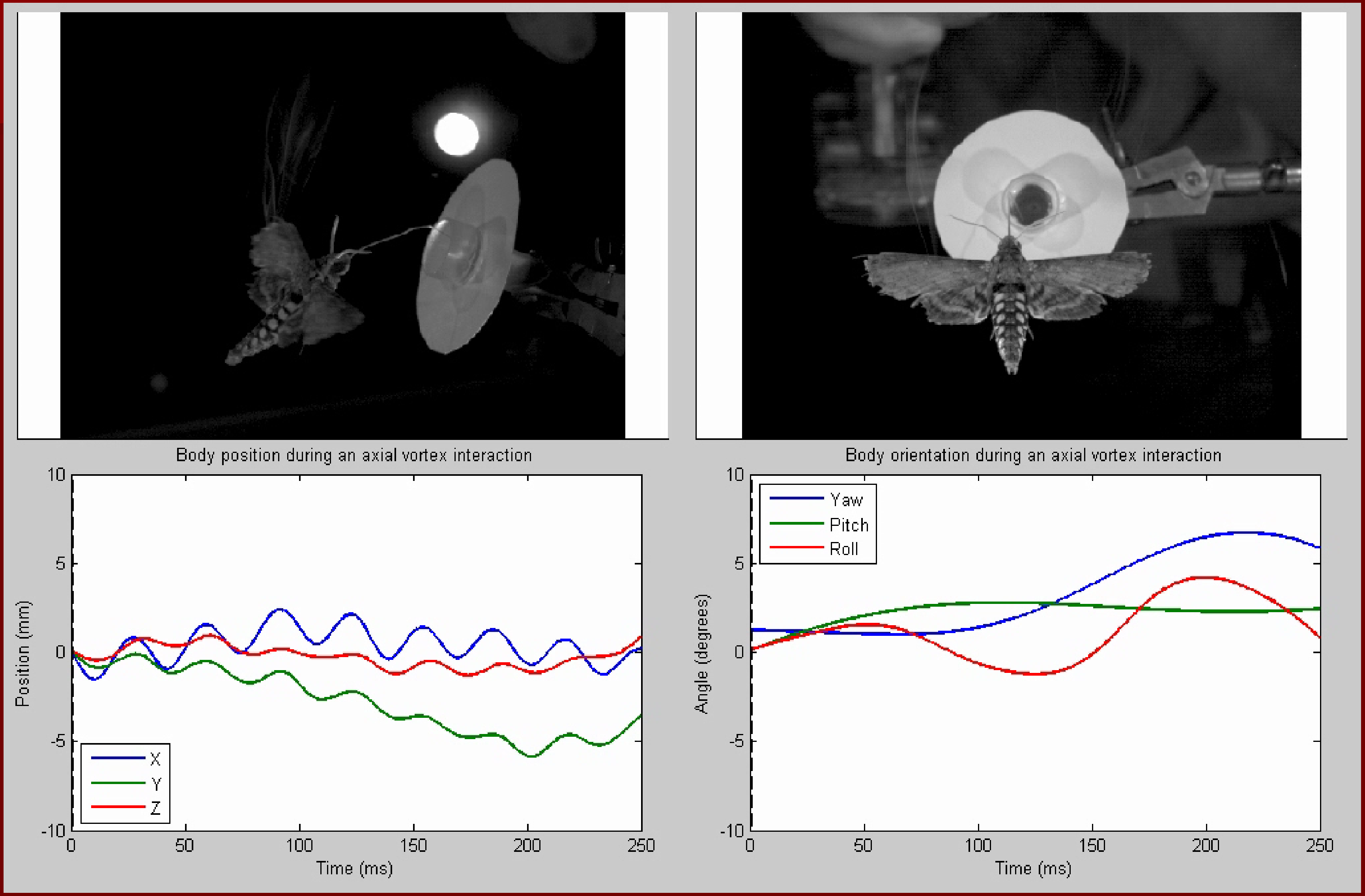


Liu et al.

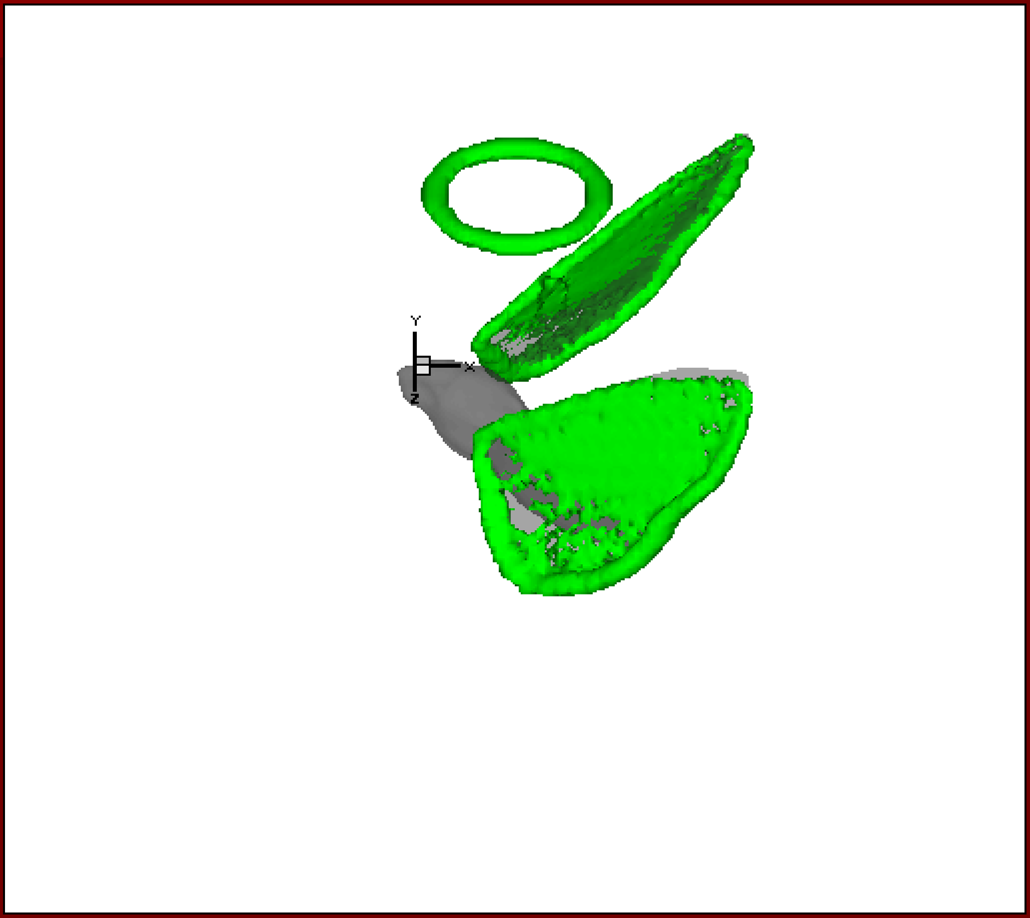


- Possibilities?
  - Discrepancy in kinematics
  - Rigid versus deformable?

Vortex Ring Impingement Experiments



Vortex Ring Impingement: CFD



Biophysics of Phonation

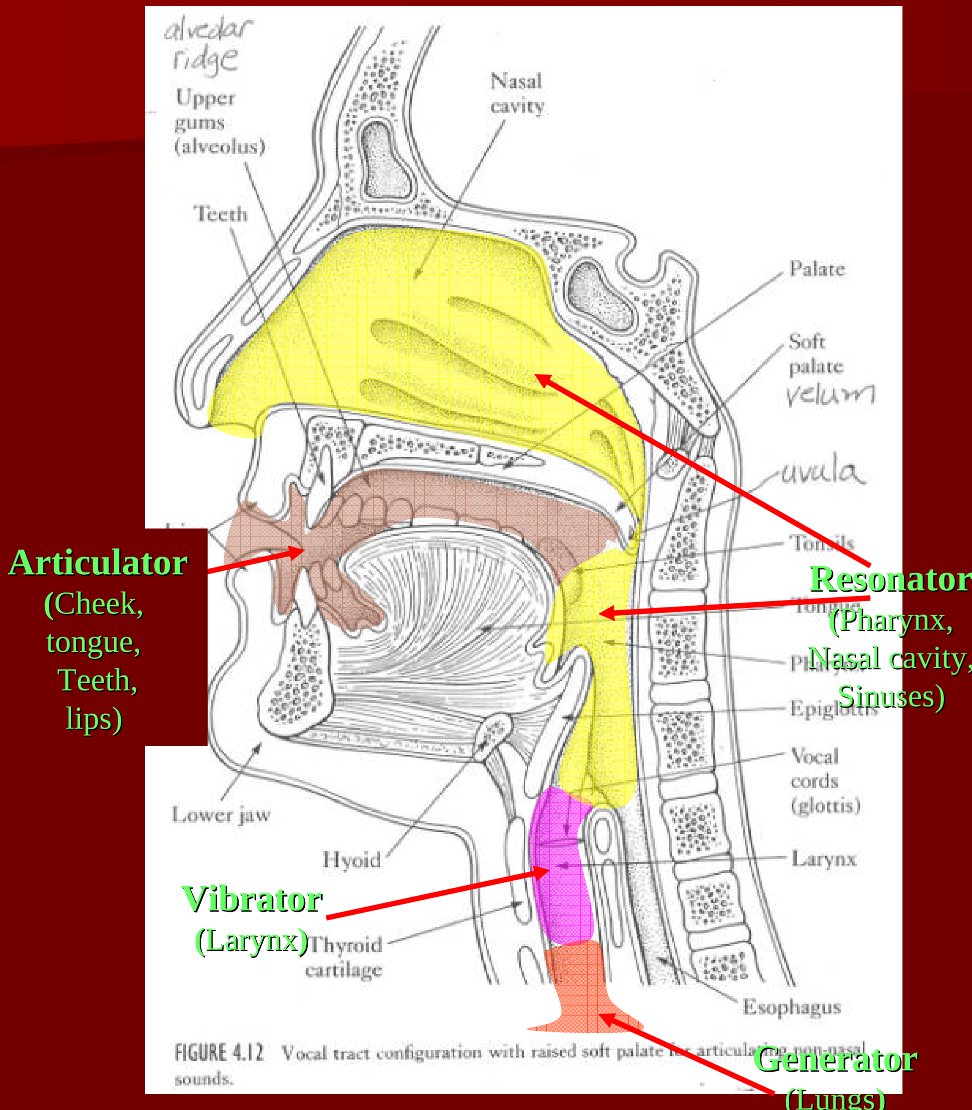
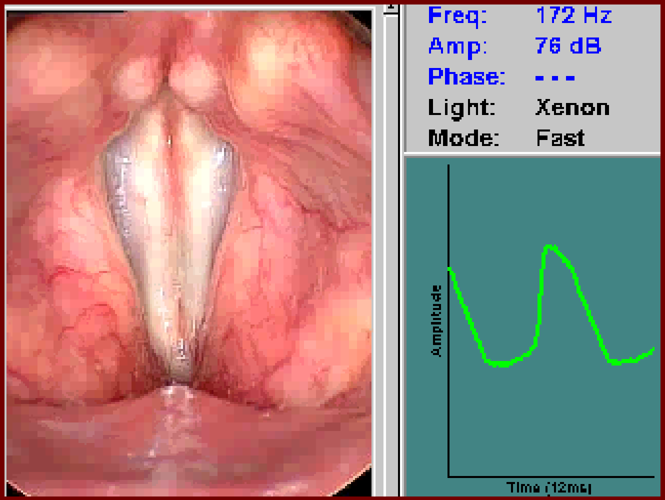


FIGURE 4.12 Vocal tract configuration with raised soft palate for articulating non-nasal sounds.

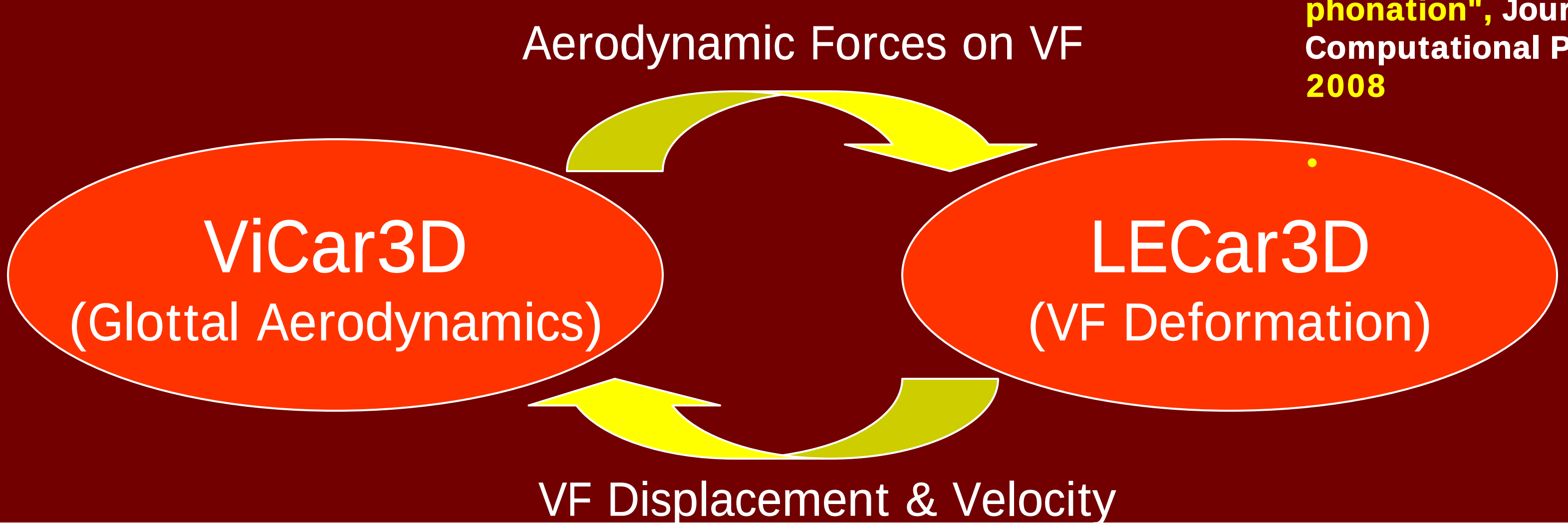


- NIH R01 grant focused on flow-structural interaction in larynx
- Understand the FSI mechanisms
- Apply knowledge to enhance laryngeal surgical procedures.

Modeling of Fluid-Tissue Interaction

- ViCar3D coupled to another solver that computes deformation of elastic structures
- Two approaches used for elastic structures
  - Finite-Element approach
  - Cartesian grid based approach (LECar3D)

- **"An immersed-boundary method for flow-structure interaction in biological systems with application to phonation", Journal of Computational Physics, 2008**



Structural Dynamics of VF

- Governing equations

$$\frac{\partial \sigma_{ij}}{\partial x_j} + b_i = \rho \frac{\partial v_i}{\partial t} = \rho \frac{\partial^2 u_i}{\partial t^2}$$

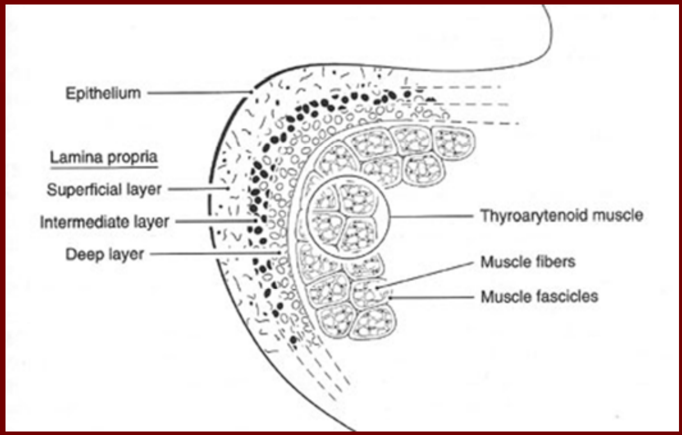
$$\sigma_{ij} = C_{ijmn} e_{mn}$$

$$u_i = u_{b_i} \qquad \sigma_{ij} n_j = T_i$$

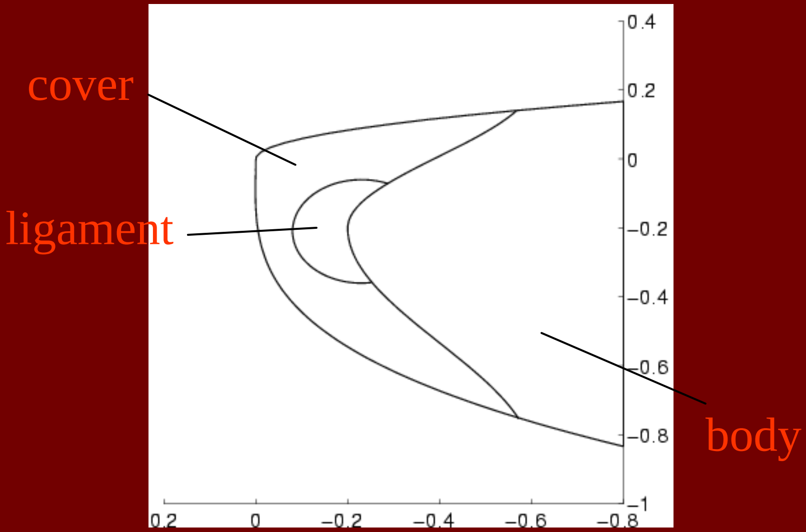
•The tissue materials are assumed to be transversely isotropic.

•Material properties are obtained from experiments (e.g., Titze *et al* 2000).

•Multi-property, non-homogeneous structure



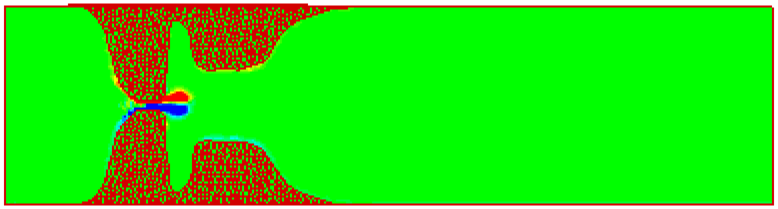
Schematic showing VF substructure



Model assumed in current study

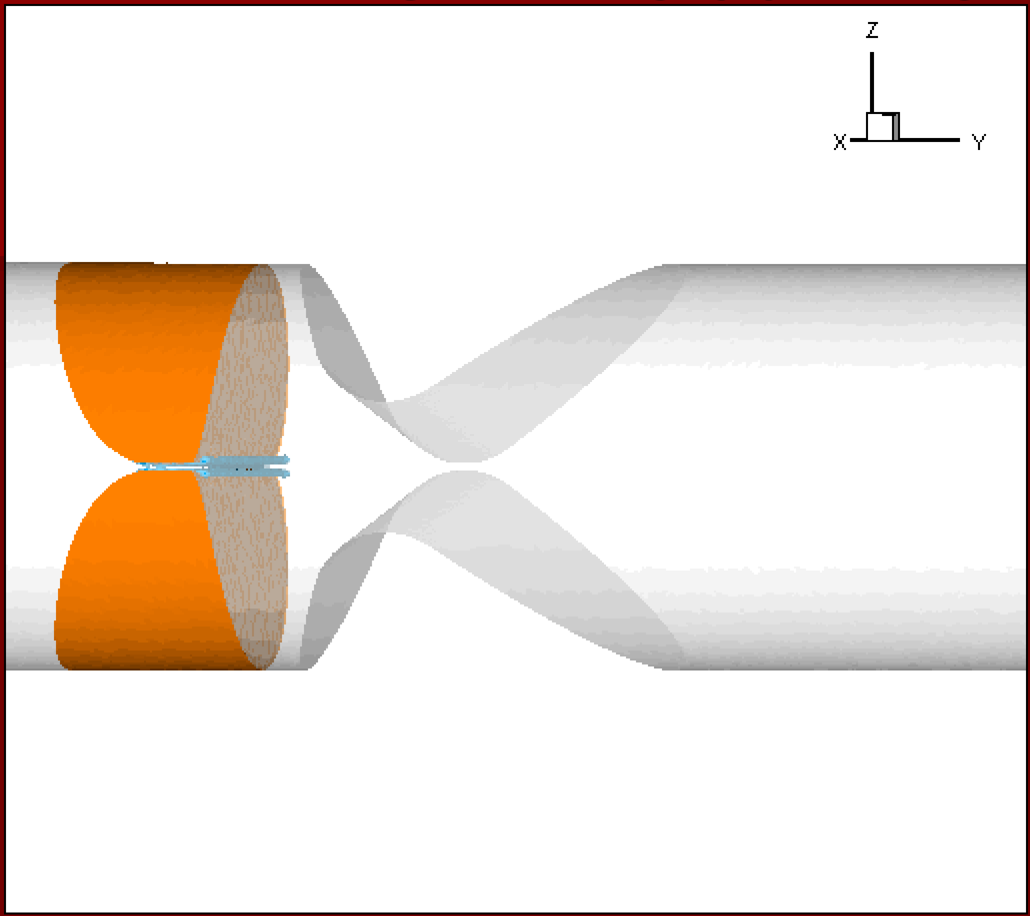
Flow-Induced Vibration (FEM)

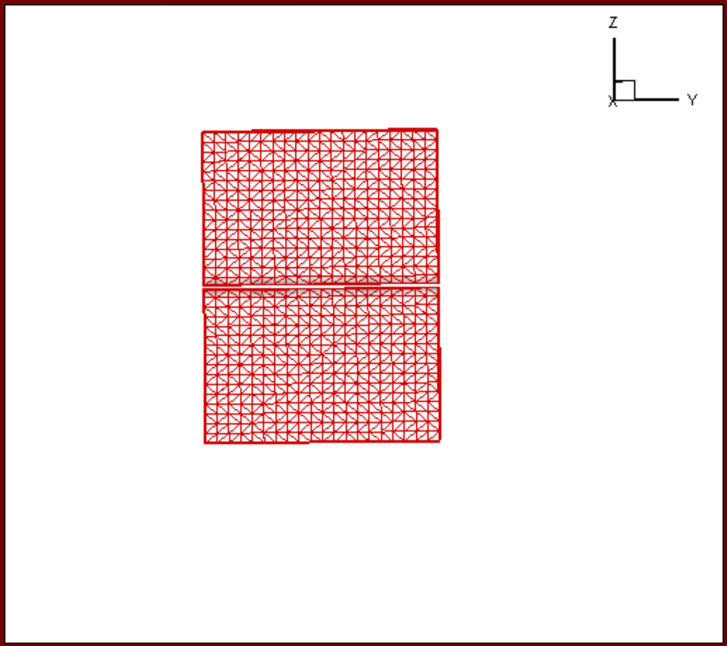
- Simulation Details
  - 2D Simulation
  - Geometry based notionally on CT scan of human larynx
  - ViCar3D for air-flow
  - Finite-Element for VF
  - VF not fully adducted
- Observations
  - Kelvin-Helmholtz vortices
  - Bistable Jet
  - Sustained vibrations of vocal folds.

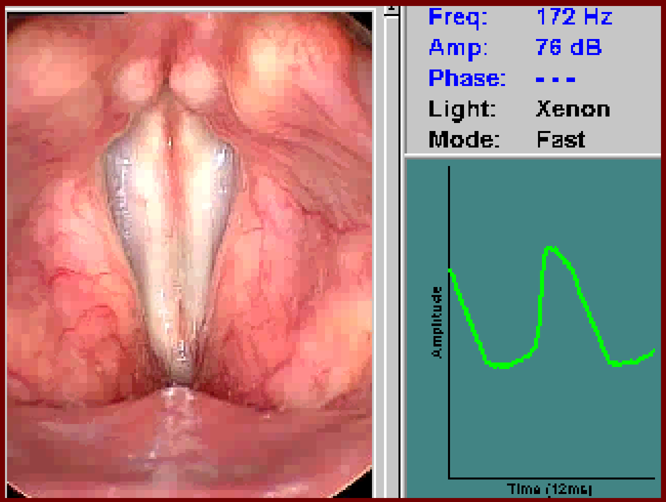


(400K points)

3D Vocal Fold Model





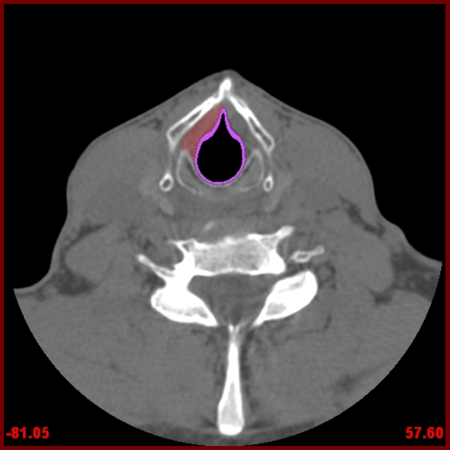


- Analysis of flow-structure interaction in the larynx during phonation using an immersed-boundary method; J. Acoust. Soc. Am. 126 2 , August 2009.

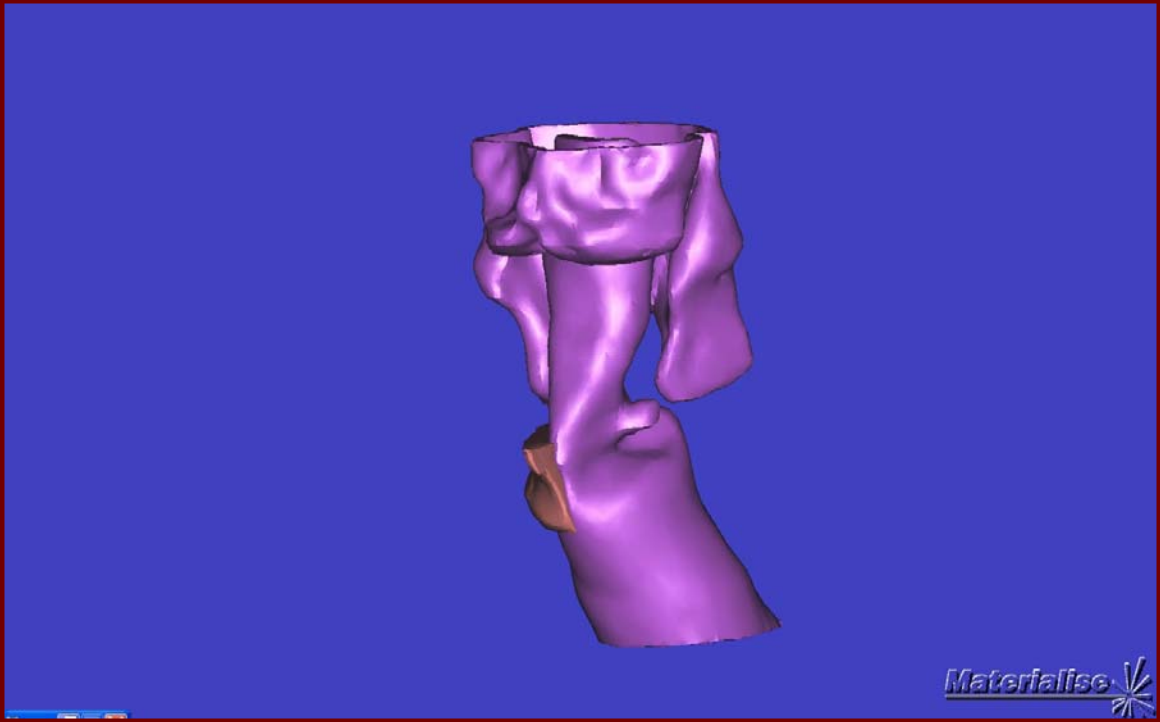
- Computational Study of the Effect of False Vocal Folds on Glottal Flow and Vocal Fold Vibration During Phonation," Annals of Biomedical Engineering, Vol. 37, No. 3 pp. 625-642 March 2009

Towards Patient-Specific Models

Sagittal View



Axial View



Direct Computation of Low-Mach Number Sound
Linearized Perturbed Compressible Equations (LPCE)

$$\rho(\vec{x},t) = \rho_0 + \rho'(\vec{x},t)$$
$$\vec{u}(\vec{x},t) = \vec{U}(\vec{x},t) + \vec{u}'(\vec{x},t)$$
$$p(\vec{x},t) = P(\vec{x},t) + p'(\vec{x},t)$$

Subtracting INS from CNS

Linearization and suppressing the generation and evolution of vortical component on the acoustic field.

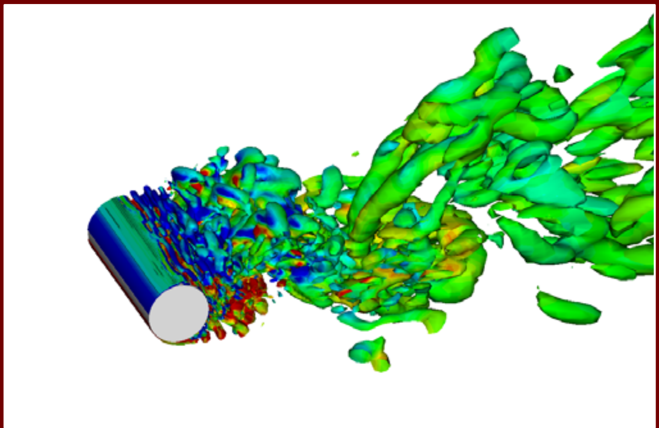
$$\frac{\partial \rho'}{\partial t} + (\vec{U}\cdot\nabla)\rho' + \rho_0(\nabla\cdot\vec{u}') = 0$$

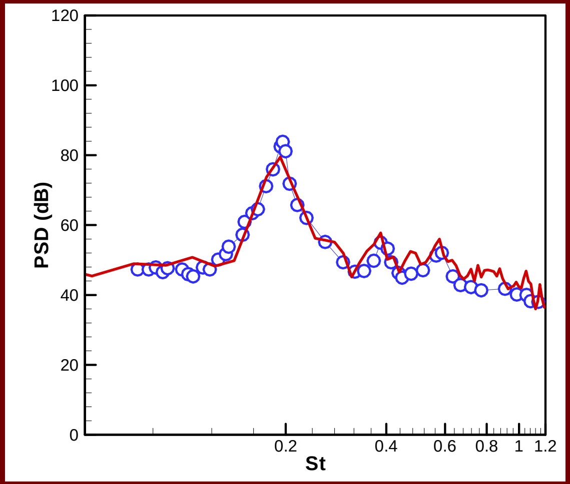
$$\frac{\partial \vec{u}'}{\partial t} + \nabla(\vec{u}'\cdot\vec{U}) + \frac{1}{\rho_0}\nabla p' = 0$$

$$\frac{\partial p'}{\partial t} + (\vec{U}\cdot\nabla)p' + \gamma P(\nabla\cdot\vec{u}') + (\vec{u}'\cdot\nabla)P = -\frac{DP}{Dt}$$

LPCE (Seo & Moon, JCP, 2006)

Noise generated by turbulent flow over a circular cylinder at $Re_D = 46000$, M = 0.21





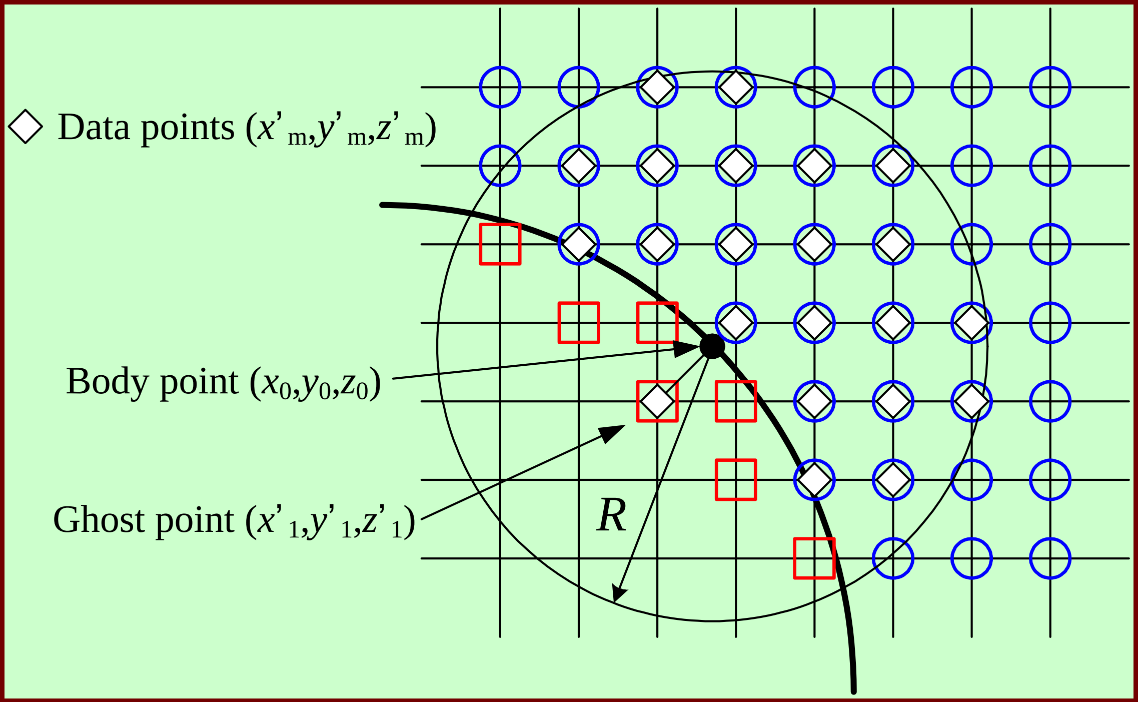
Need to use high (6th) order schemes to accurately model sound propagation

Immersed Boundary Method for LPCE (Approximating Polynomial Method)

(H. Luo et al.)

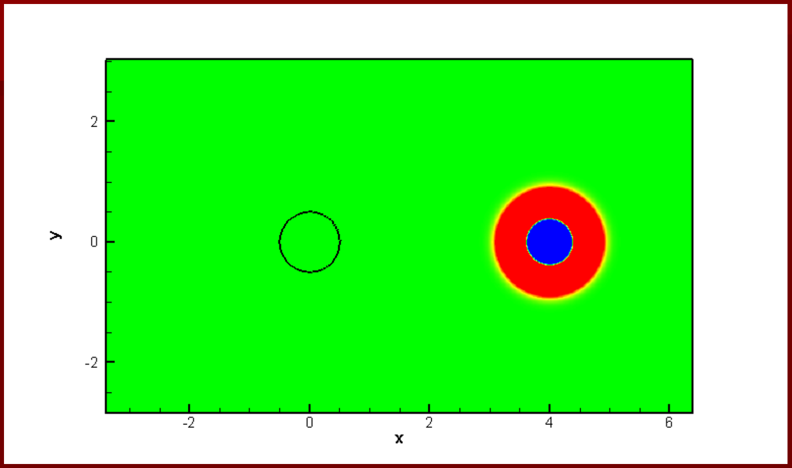
$$\phi(x',y',z') \simeq \Phi(x',y',z') = \sum_{i=0}^{N}\sum_{j=0}^{N}\sum_{k=0}^{N} c_{ijk}(x')^i(y')^j(z')^k, \qquad i+j+k \le N$$

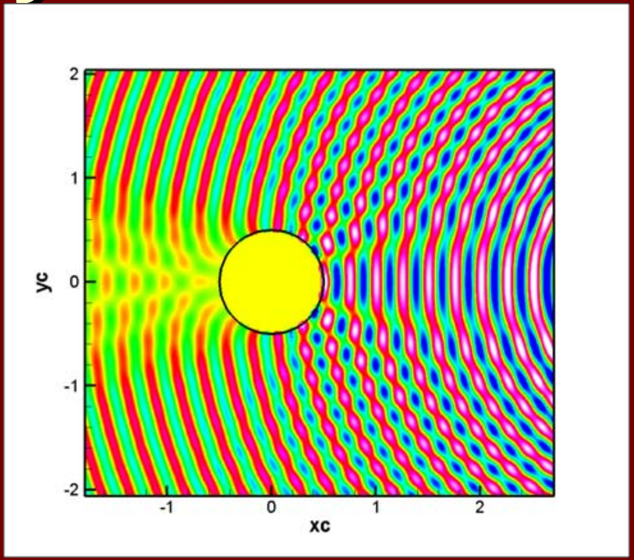
$$\varepsilon = \sum_{m=1}^{M} w_m{}^2 \left[\Phi(x'_m, y'_m, z'_m) - \phi(x'_m, y'_m, z'_m)\right]^2$$

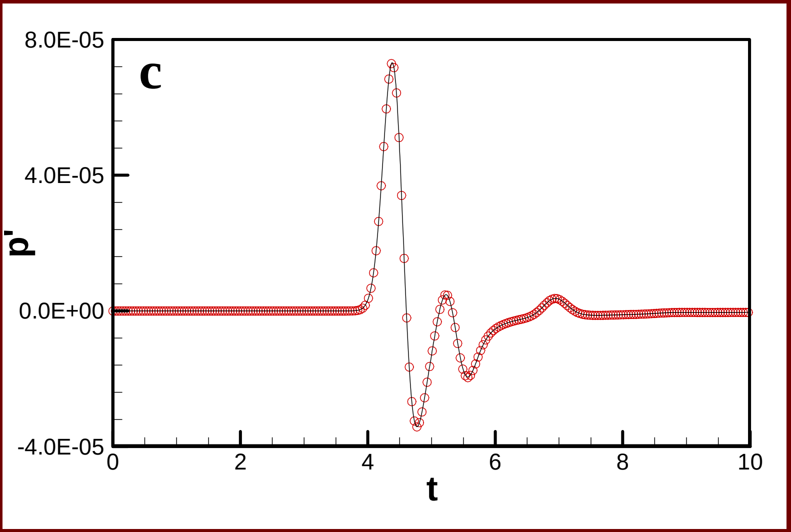


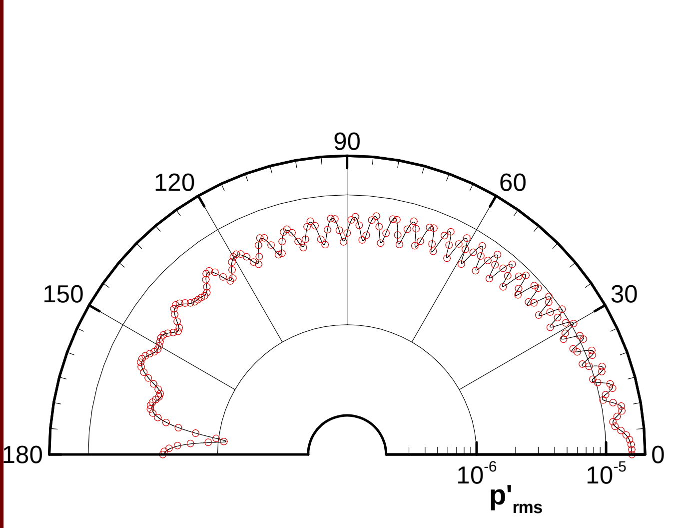
N	Number of coefficients	
	2D	3D
1	3	4
2	6	10
3	10	20
4	15	35

Benchmark: Sound scattering by a Circular Cylinder



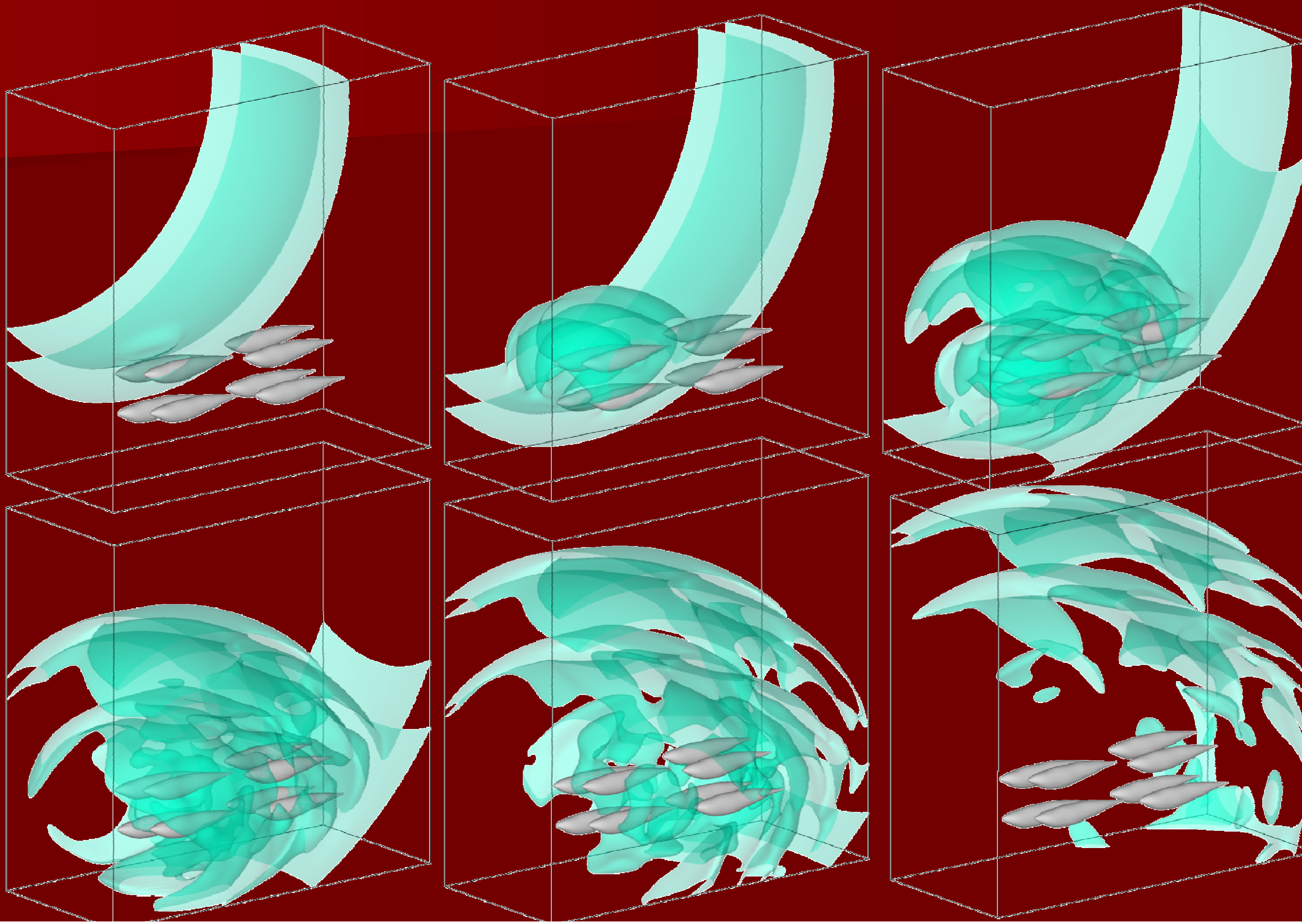






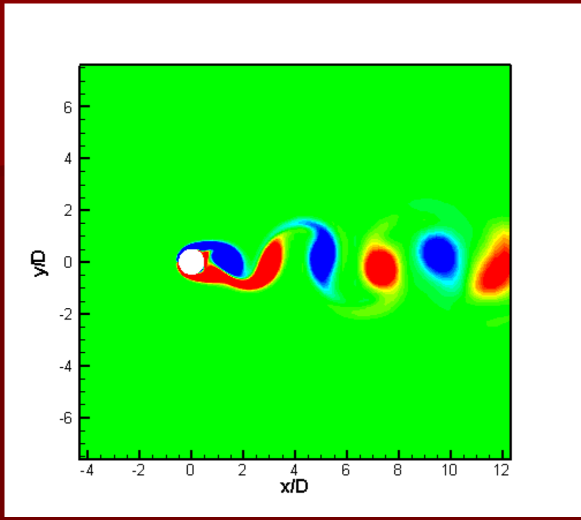
Directivity at r=5

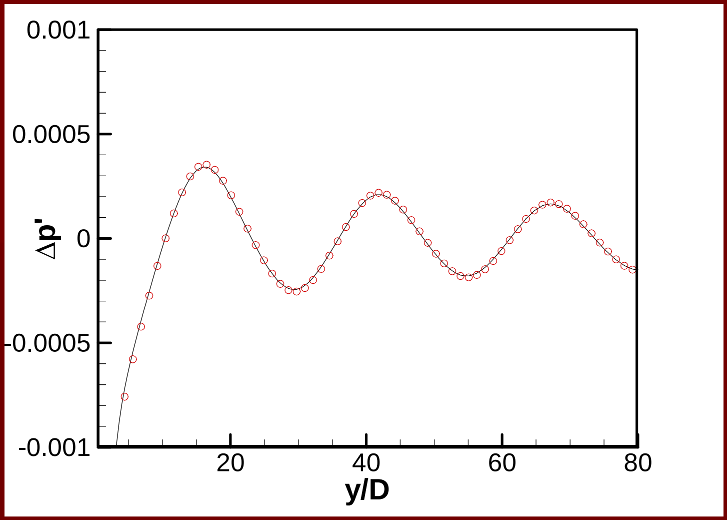
Acoustic Scattering from Complex Geometries

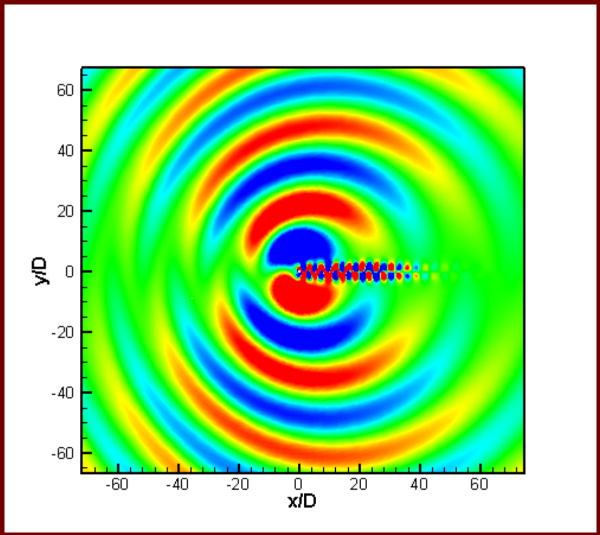


Comparison with DNS

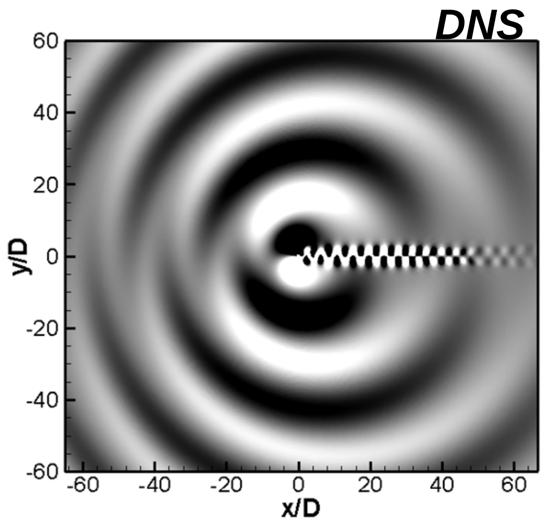
ViCar3D





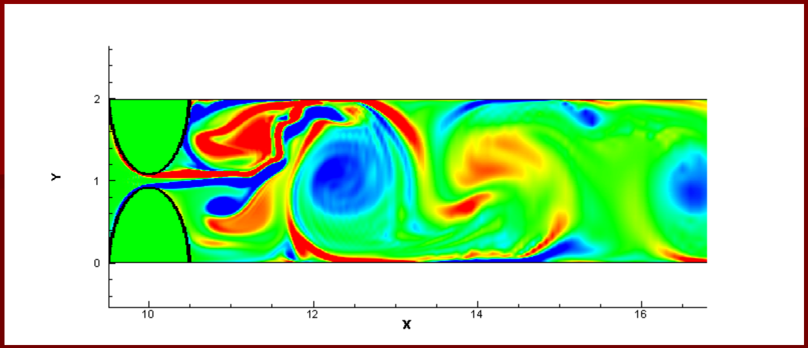


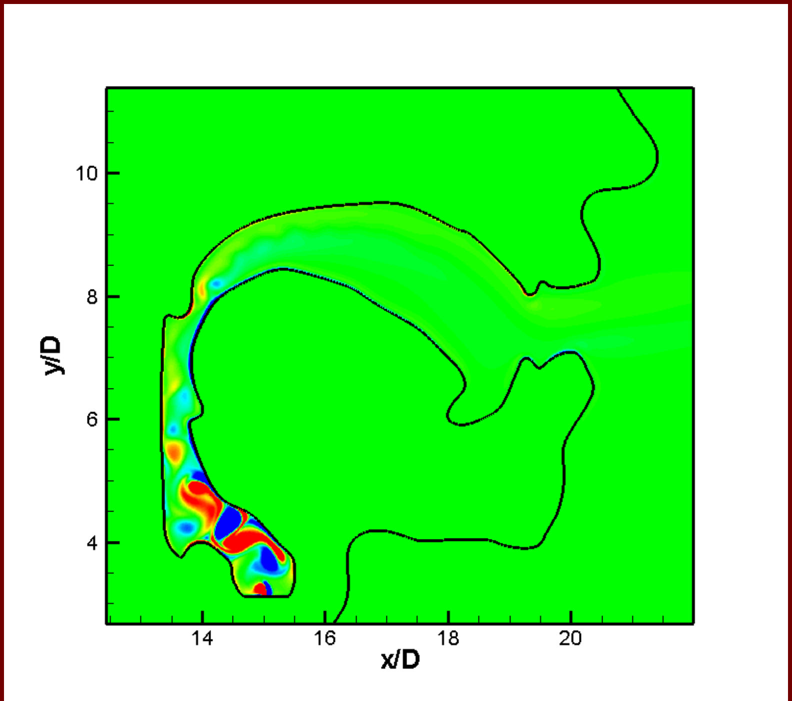
carLPCE

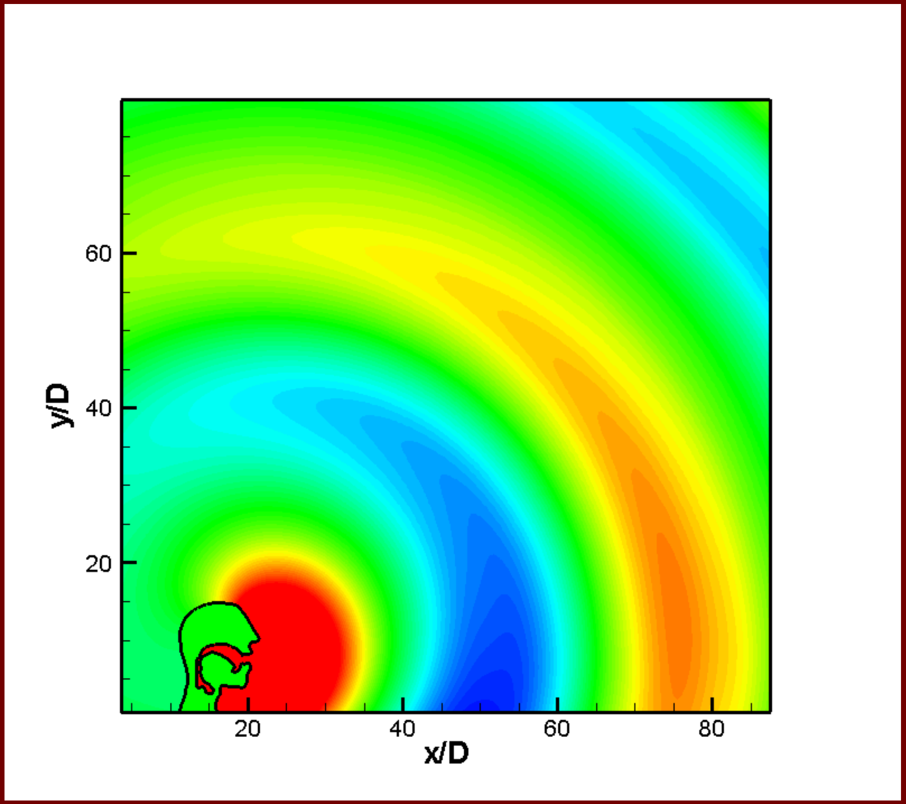


DNS : full compressible N-S Eqs. on a body-fitted O-grid

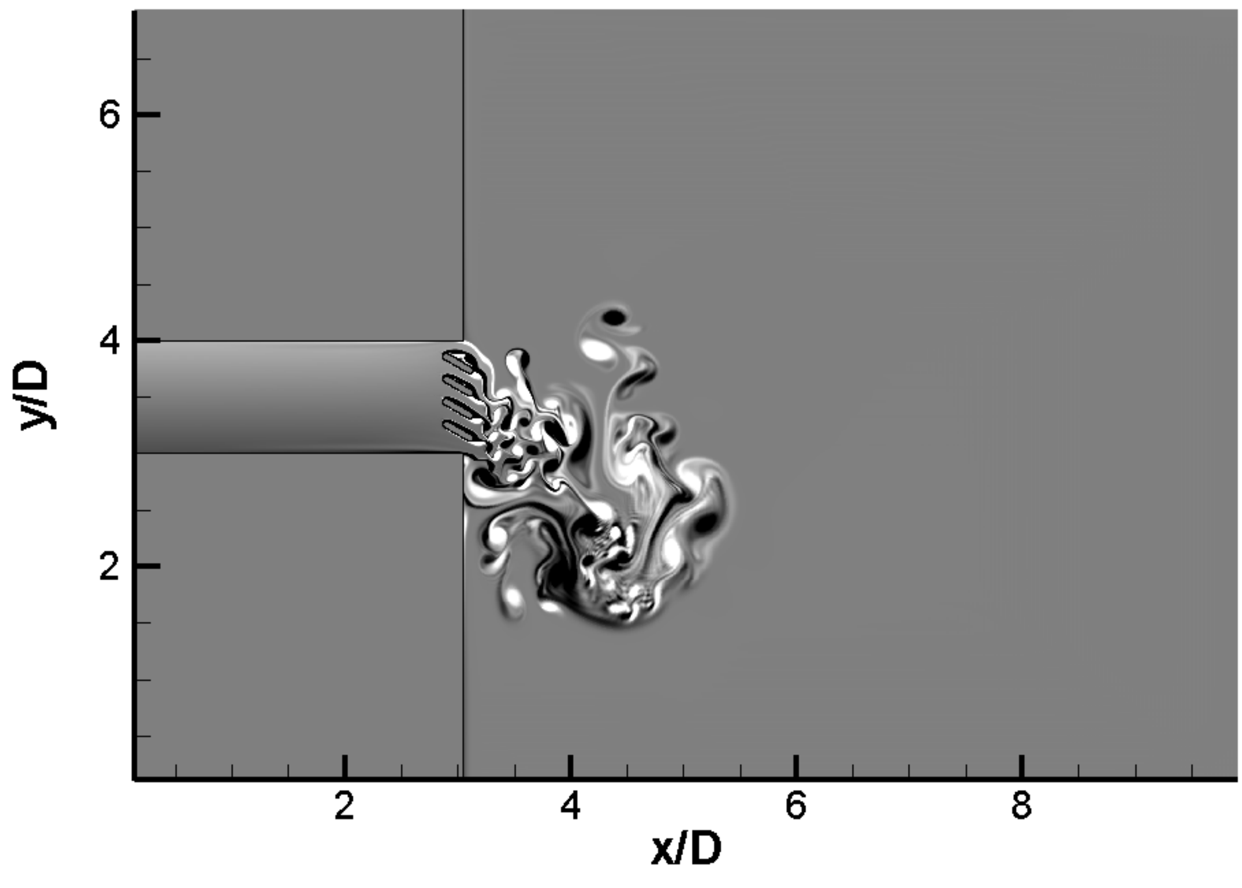
Phonation and Speech



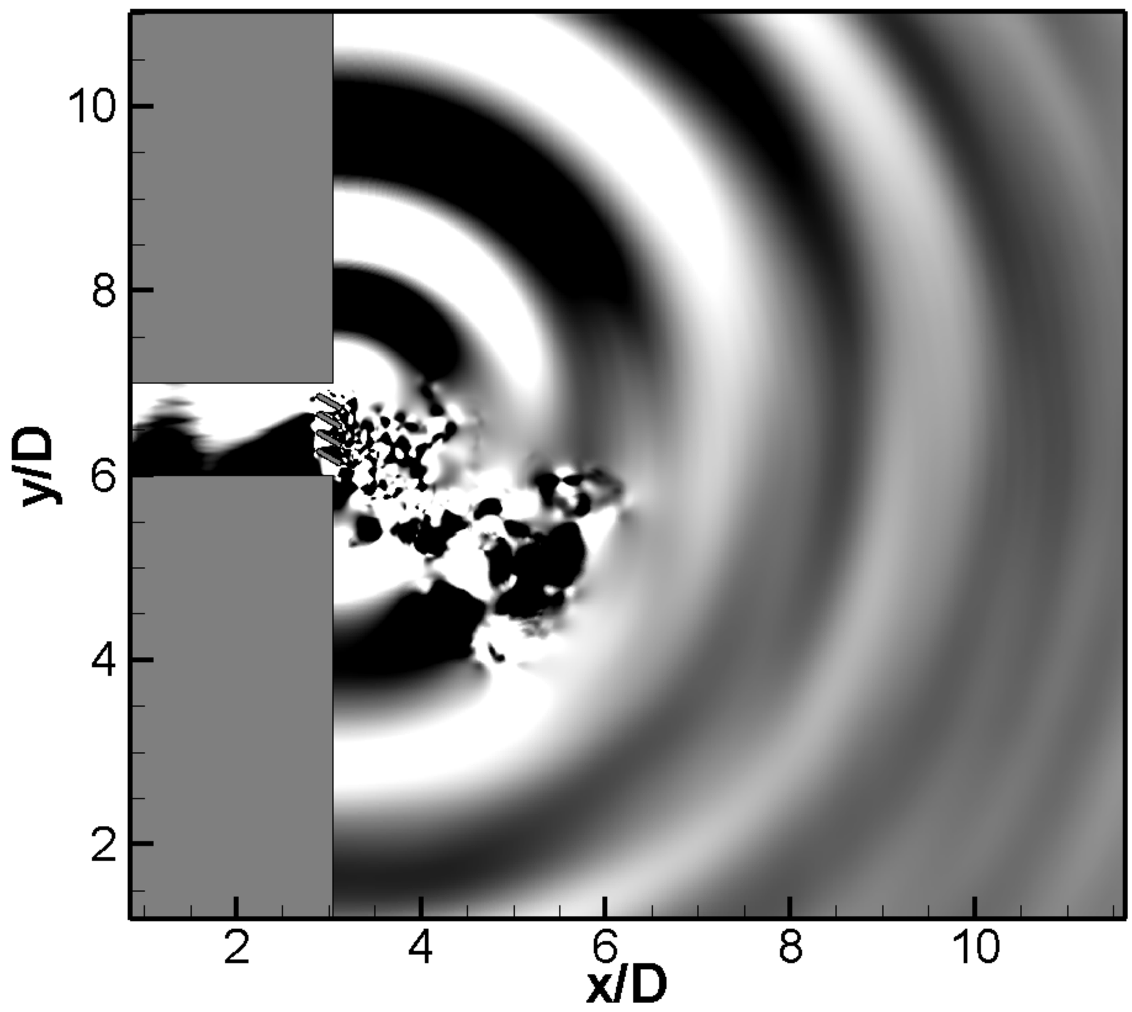




Sound in Complex Configurations



Sound in Complex Configurations



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Questions?