An Immersed Boundary Method for Solving the Compressible Navier-Stokes Equations with Fluid-Structure Interaction*

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Outline

Motivation/Introduction

IBM-FSI & FSI relevant applications

Numerical Methods

Interior scheme, IBM, CSD, and CFD-CSD coupling

Immersed Boundary Method

All aspects of immersed boundary method.

Structural Solver

Element formulation and time-integration.

CFD-CSD Coupling

Displacements and loads transfer.

Validation for Moving Boundary Problems

Oscillating Cylinder, and pitching airfoil.

Validation for Fluid-Structure Interaction Problems

Deforming panel. *plate flutter, and bending tower.*

Results from the AIAA Workshop

Forced oscillation and fluid structure interaction.

Summary and Outlook

What are the next steps?.

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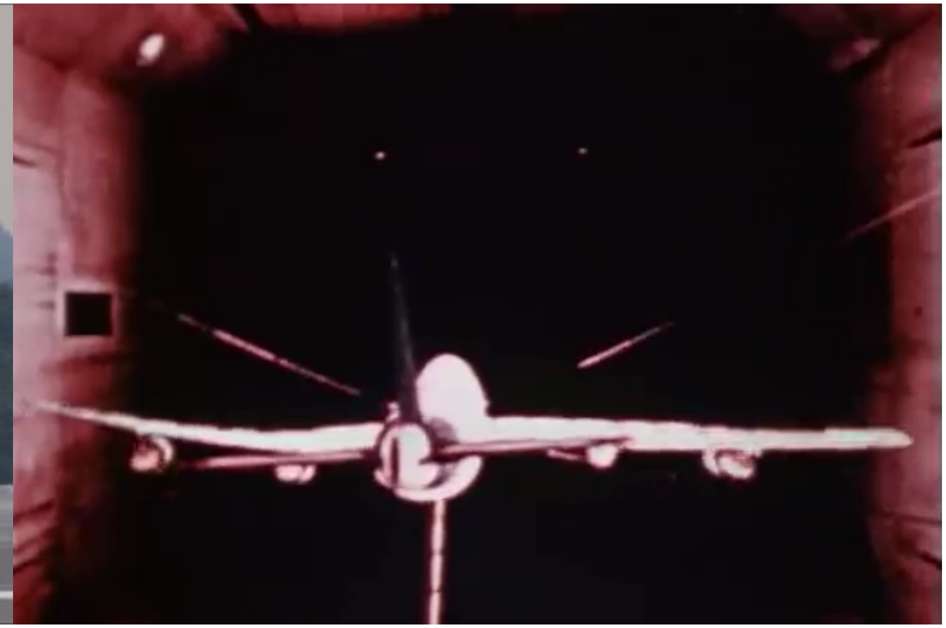
Boeing 787 Landing at Düsseldorf

Flutter at a Glance (NASA-LaRC)



- ❑ There are many relevant FSI applications requiring further attention
- ❑ Limited testing data is available for highly complex FSI problems
- ❑ Presentation focuses on validating newly developed capabilities within the LAVA framework

Introduction

- Different methods are available:
  - Reduced-order models: computationally efficient but lack of generality
  - High-fidelity methods: computationally expensive but usually more general
- Here the focus is on high-fidelity methods
  - Computational Fluid Dynamics (CFD)
    - Curvilinear: significant pre-processing time for mesh generation, large deformations/topology changes are problematic, but provide efficient solution strategies
    - Unstructured: significantly reduce mesh generation pre-processing time for complex geometries, large deformations are problematic
    - Cartesian: automatic volume mesh generation, large deformations no problem, but modeling viscous wall effects may be difficult
  - Computational Structural Dynamics (CSD)
    - Linear/nonlinear geometric and linear/nonlinear material
    - Element types: 1D, 2D, shell elements, and 3D
  - Coupling
    - Partitioned, monolothic, weak, and strong coupling

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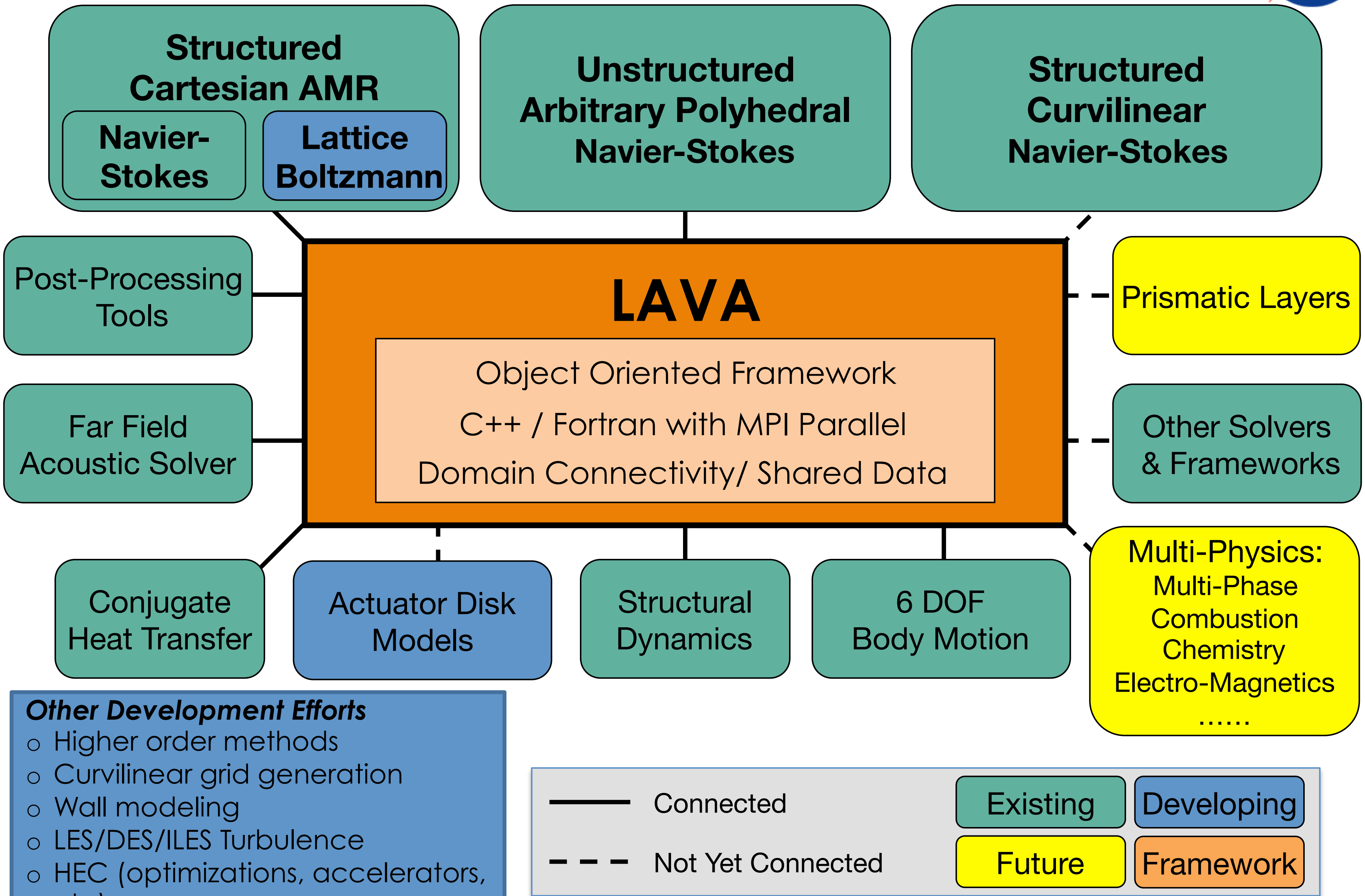
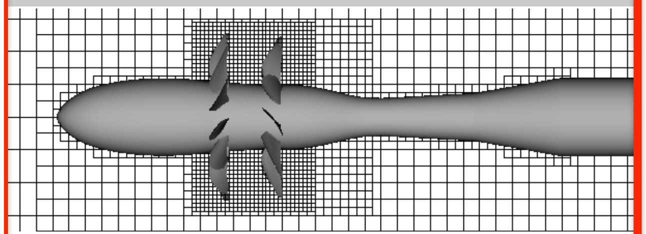
LAVA Framework



Kiris at al. AIAA-2014-0070 & AST-2016

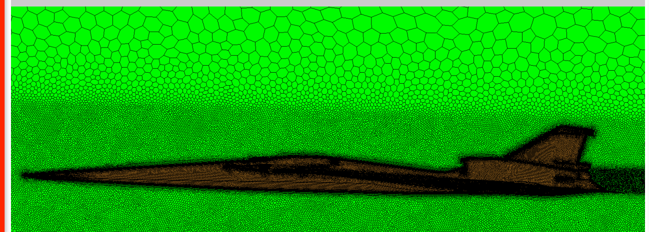
LAVA Computational Grid Paradigms

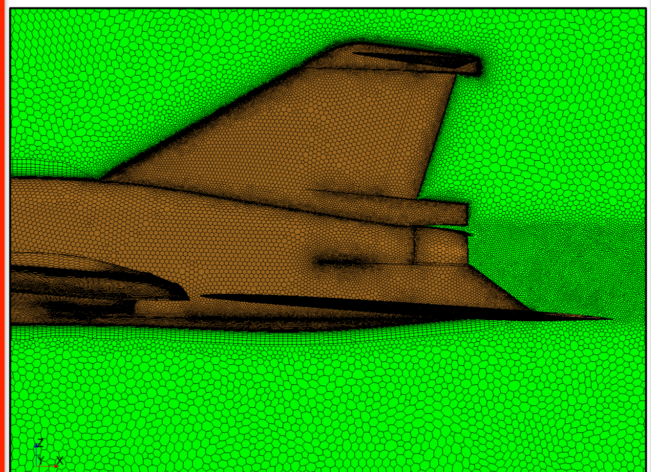
Structured Cartesian AMR



- Essentially no manual grid generation
- Highly efficient Structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods are available
- Non-body fitted -> Resolution of boundary layers inefficient

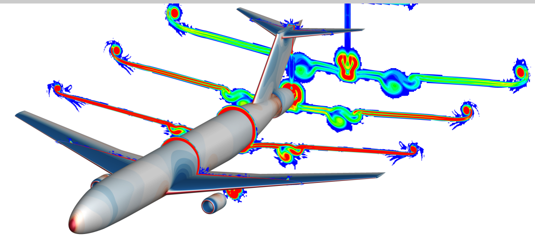
Unstructured Arbitrary Polyhedral

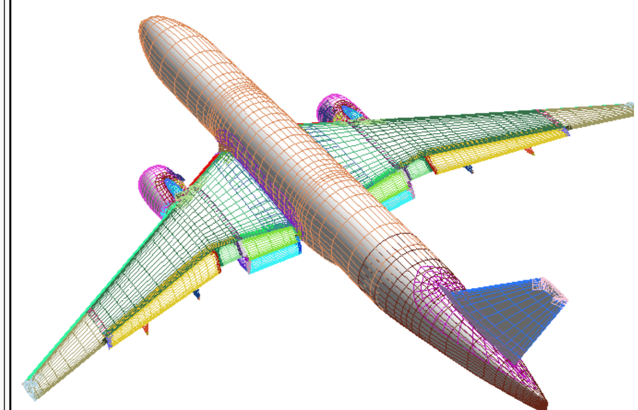




- Grid generation is partially automated
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods are yet to fully mature

Structured Curvilinear



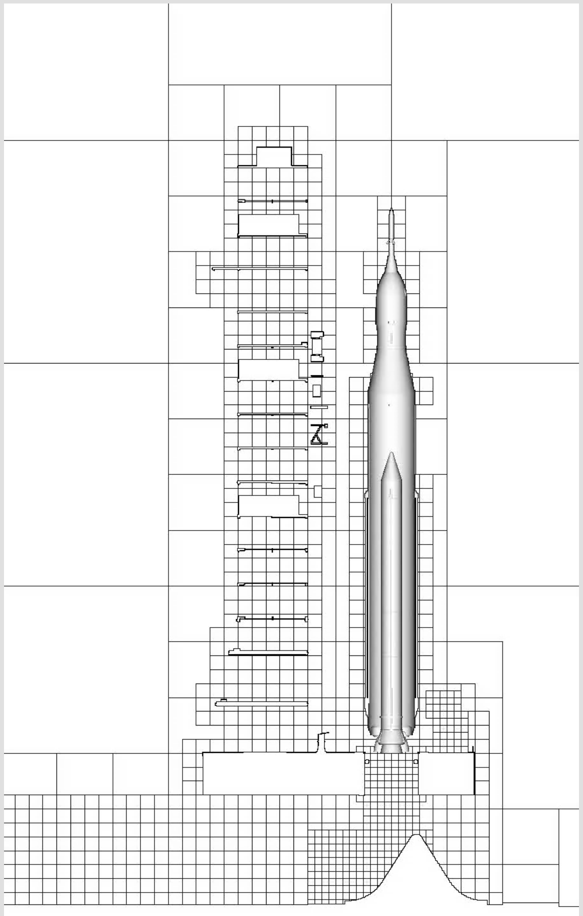


- High quality, body fitted, and overset grids
- Low computational cost
- Reliable higher order methods are available
- Grid generation is largely manual and time consuming

LAVA – Cartesian IBM, Navier-Stokes

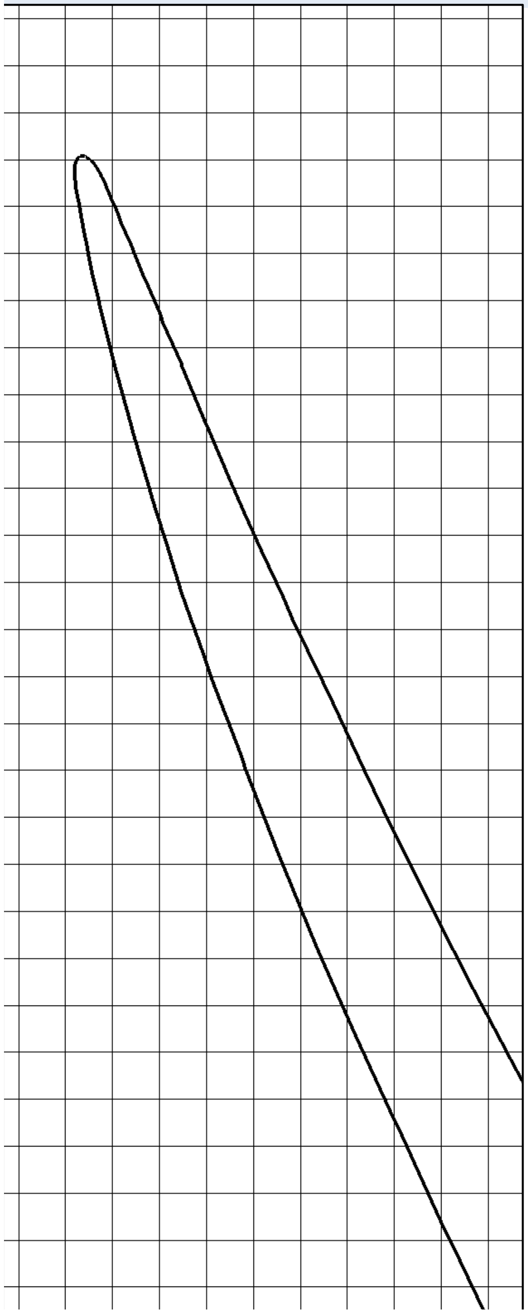
- Solving compressible Navier-Stokes equations
- Higher-order shock capturing with WENO5/6-Z
- Viscous terms in conservative form
- Explicit in time: Runge-Kutta time-integrator
- Implicit in time: via dual time-stepping
- Block-structured Cartesian with AMR
- Immersed boundary methods
- Essentially no manual grid generation
- Coarse/fine interface is $O(h^2)$
- MPI-parallel

Prescribed motion liftoff simulation for SLS ignition overpressure



Relevant refs.: Kiris et al. (Aerosp. Sci. Tech., 2016), Barad et al. (ParCFD, 2015), Brehm et al. (CAF 2015, JCP 2013 & 2015)

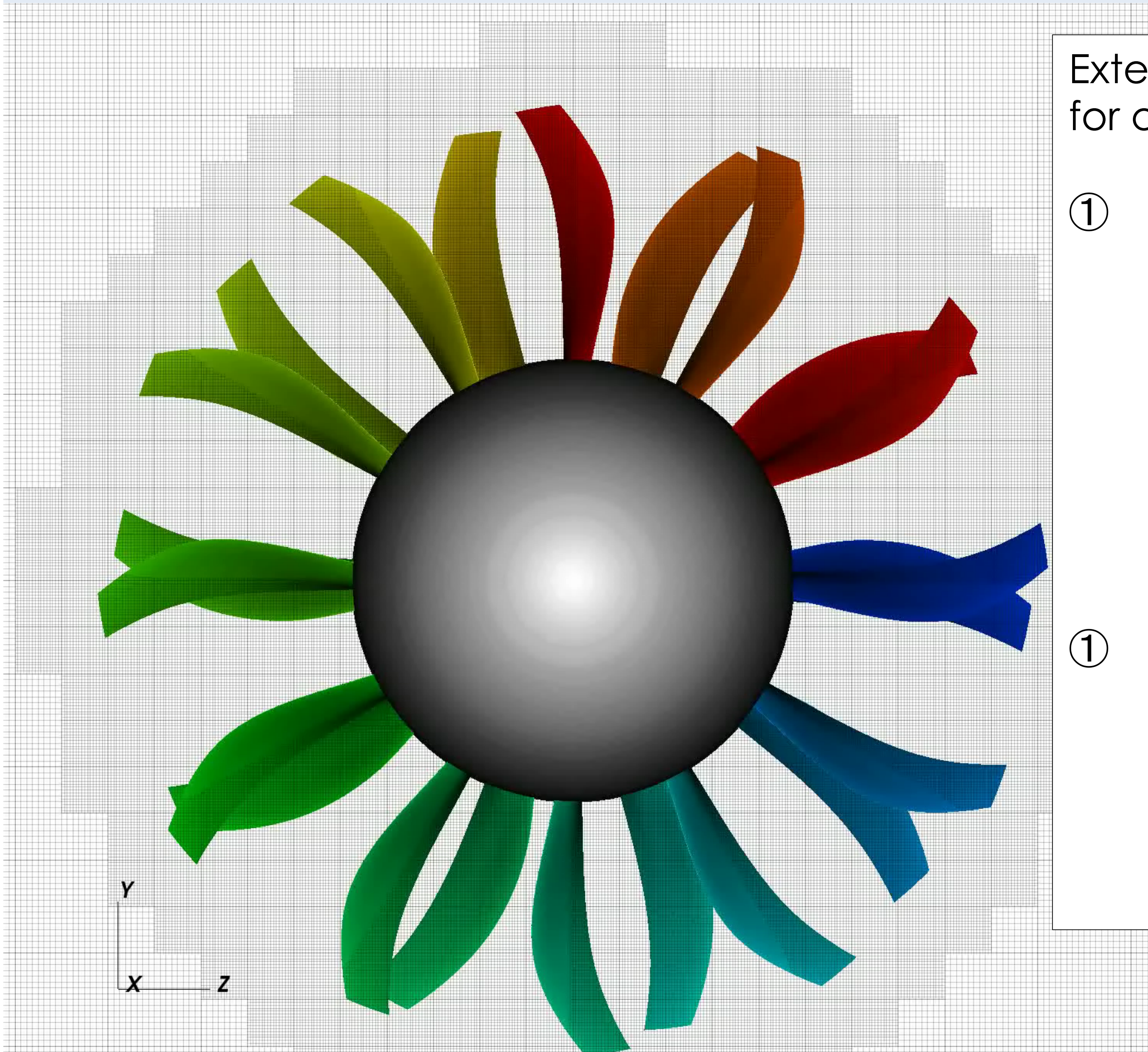
Immersed Boundary Method (IBM) Introduction



- IBMs enable automatic volume mesh generation from water tight surface triangulations
- For problems involving moving and deforming boundaries IBM provides clear advantages (for example no mesh deformation needed)
- Main disadvantage is that at high Reynolds numbers, IBMs become inefficient or require some type of wall model
- Most immersed boundary methods are only lower order accurate
- LAVA Cartesian has two different IBM methods available:

  1. Ghost cell based scheme (2010-present)
  2. Interior only, higher order accurate schemes (2015-present)

Extensions of IBM for Open Rotor



Extensions of IBM required for open rotor simulations:

① Optimizations for high-performance:
- Interior only scheme for thin geometry
- Geometry queries
- Re-computation of irregular stencils
- Many others

① Address accuracy challenges that are associated with IBM discretizations for moving geometry

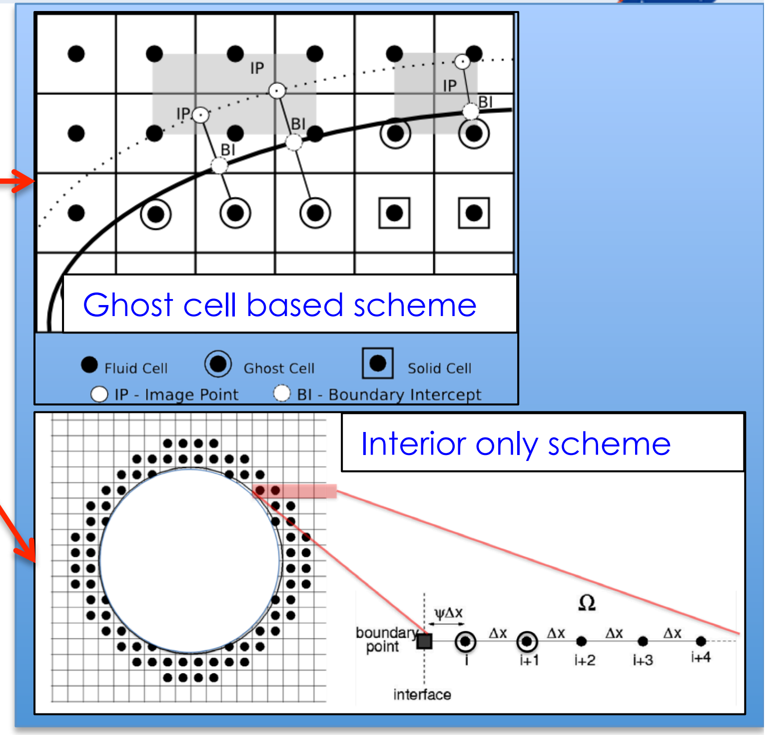
See LAVA Open Rotor Paper: AIAA 2016-0815

IBM Performance Challenge: Thin Geometry

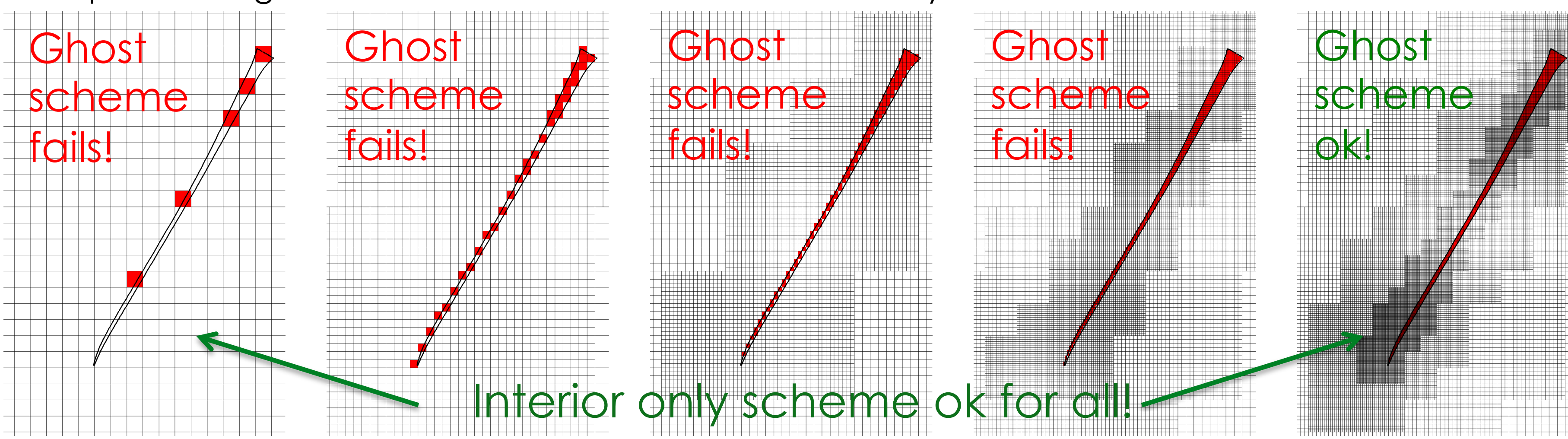
Interior only vs ghost cell based IBM:

- Ghost cell based schemes require filling cells in solid which are used by interior stencils
- Interior based schemes have stencils based only on points in fluid

For thin and/or under-resolved geometry, interior only based schemes are far superior!



Example showing Cartesian mesh refinement for a thin body:

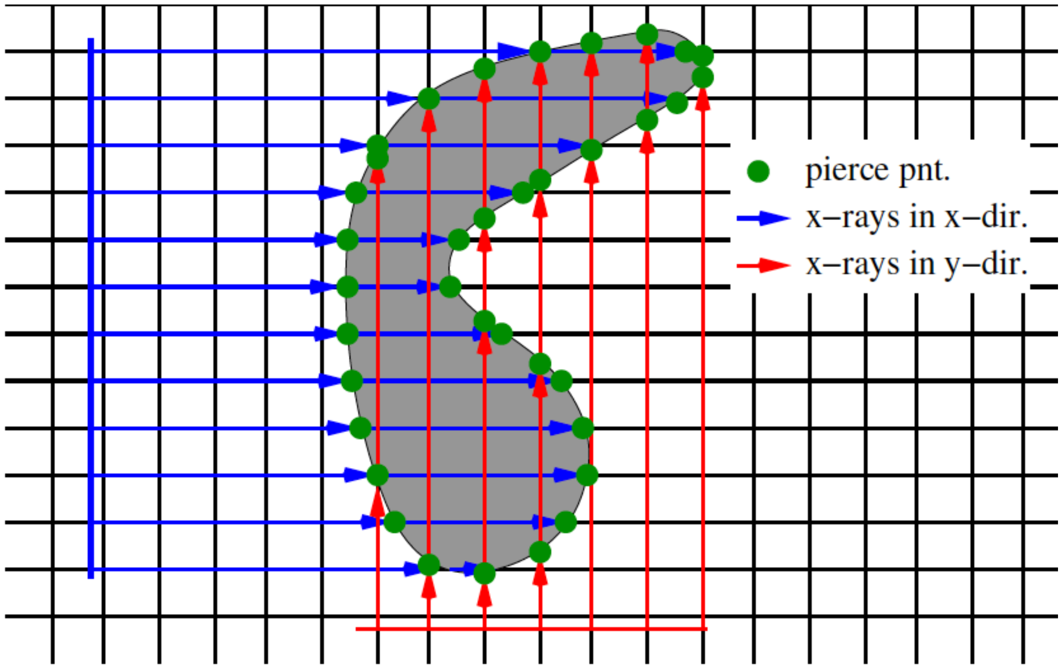


IBM Performance Challenge: Geometry Queries

- High-performance queries required for moving geometry:
  - Point inside/outside
  - Ray-surface intersection
  - Nearest point
  - Box-surface intersection

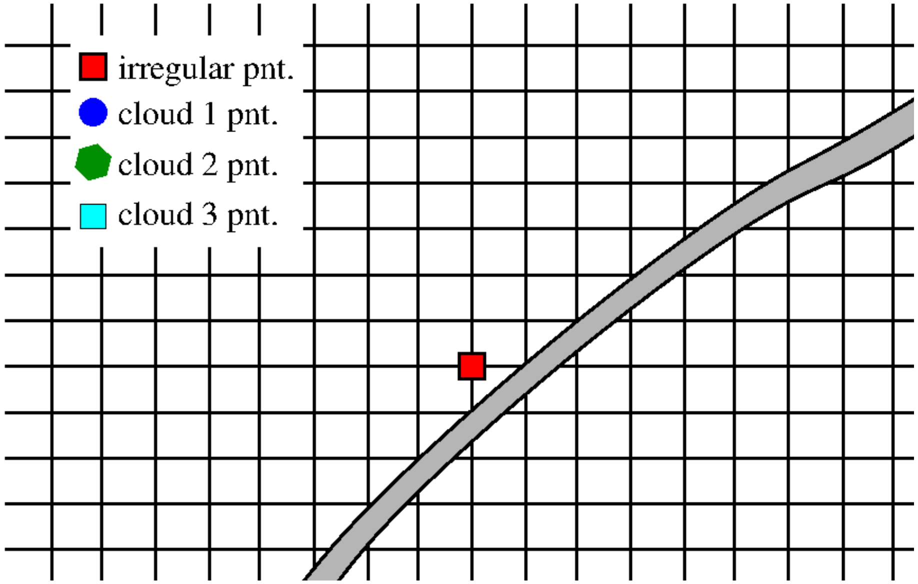
- Our approach is based on surface triangulations:
  - Exact queries, instead of (approximate) level-sets which are challenging for thin and/or moving geometry
  - Using highly optimized bounding volume hierarchy (BVH) based queries [thanks to Intel; and Tim Sandstrom]

Example ray-surface intersection queries:



IBM Accuracy Challenge: Point Cloud Selection

- Interior only IBM does not use ghosts
- Graph walking for stencil clouds: full clouds are built up from individual clouds at irregular points (reduces number of intersection tests)
- The clouds are used to maintain "leak proof" discretizations for thin geometry:
  - RHS operators
  - Surface interpolation for output
  - Etc



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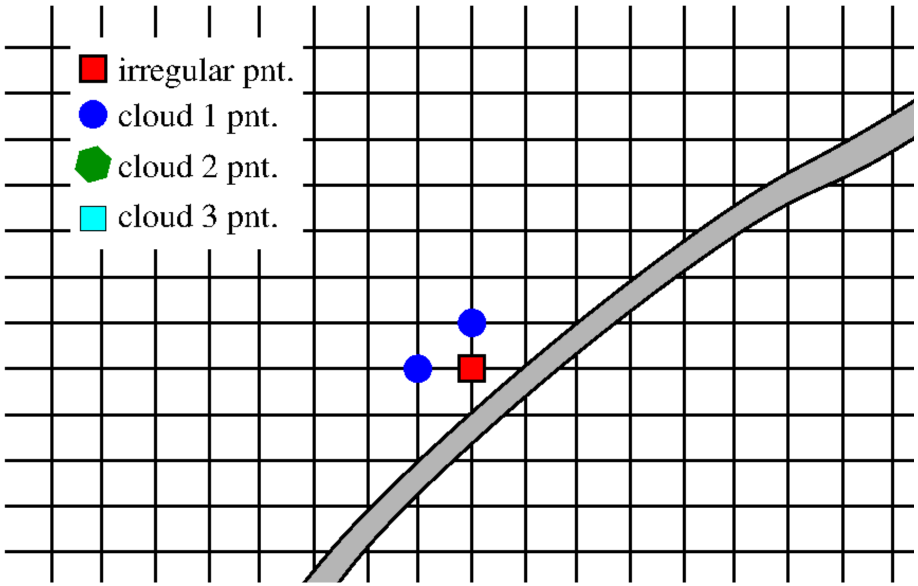

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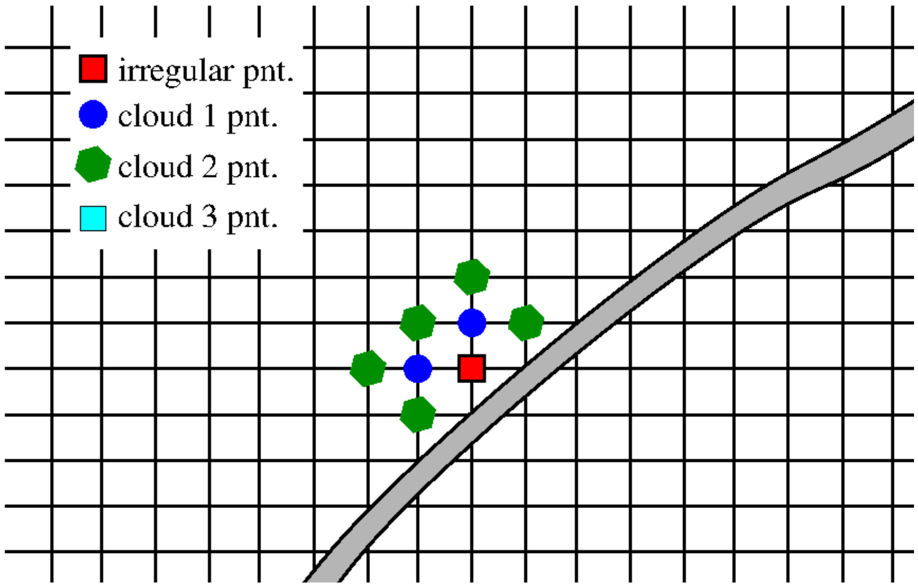

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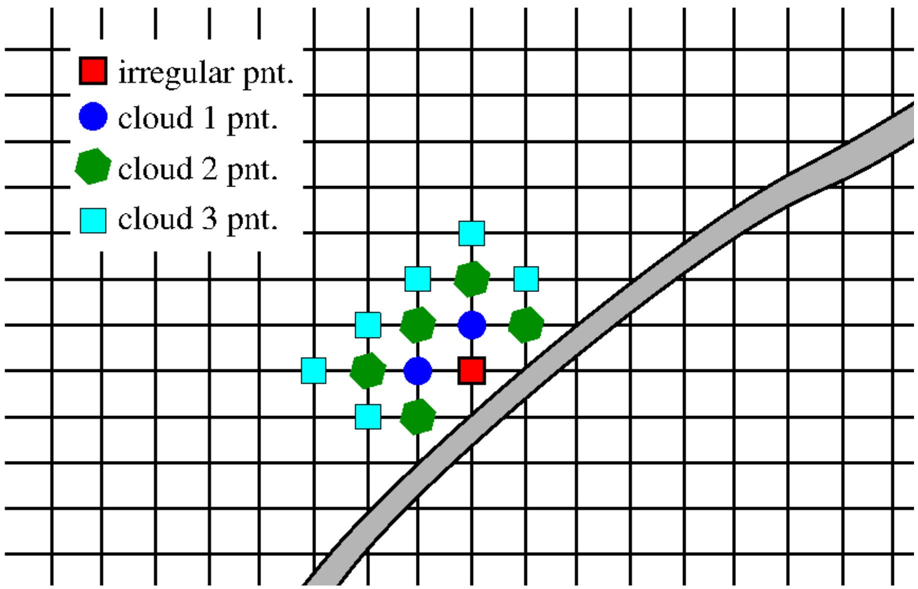
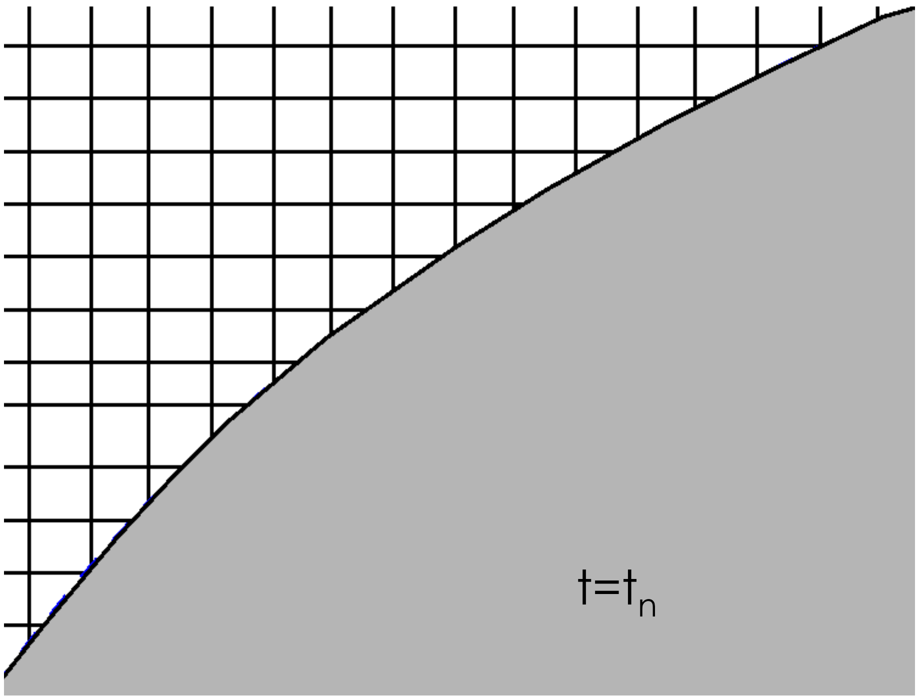


IBM Accuracy Challenge: Freshly Cleared Cells

- Invalid time history at Freshly Cleared Cells (FCC)
- Utilize neighboring information to update data in FCC (exclude other FCCs in point cloud), ie backfilling with least-squares + BC.
- More advanced approaches are being considered



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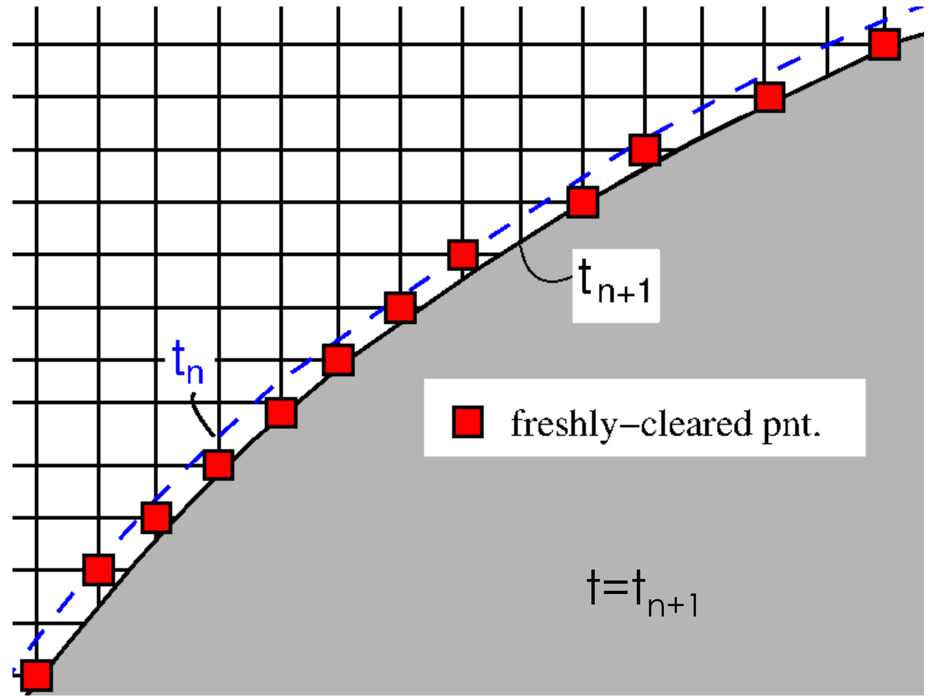
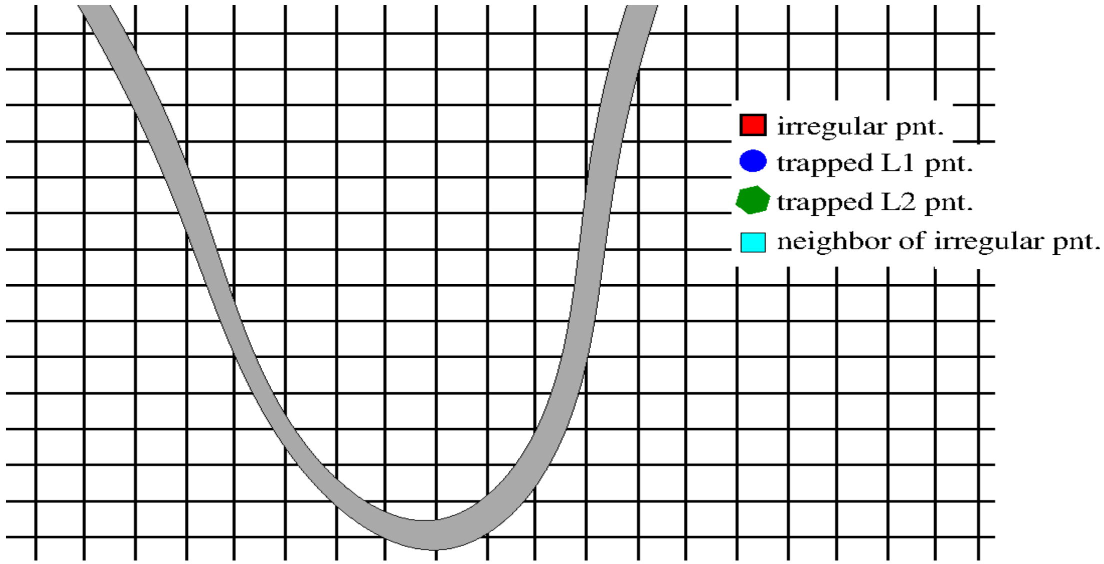


IBM Accuracy Challenge: Trapped Points

- Occur in gaps that are smaller than irregular stencil size
- Current treatment is to reduce order of accuracy in the relevant direction



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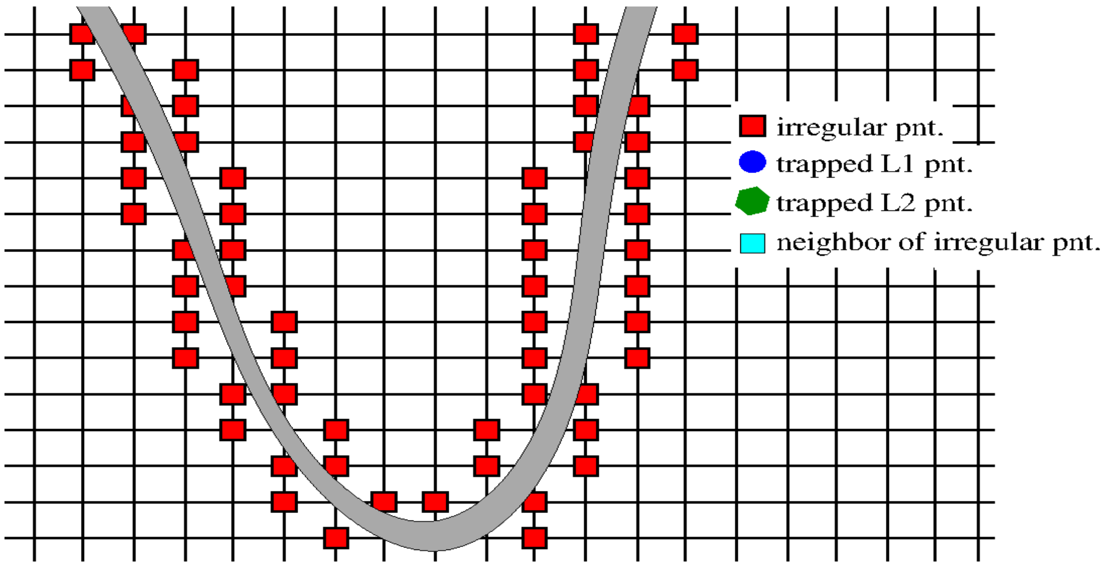

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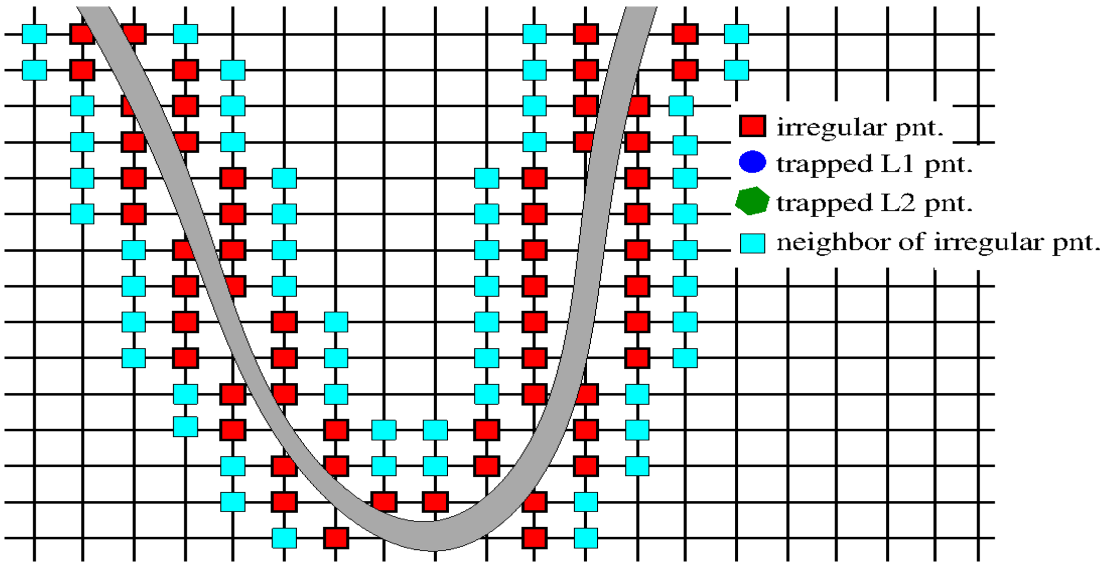

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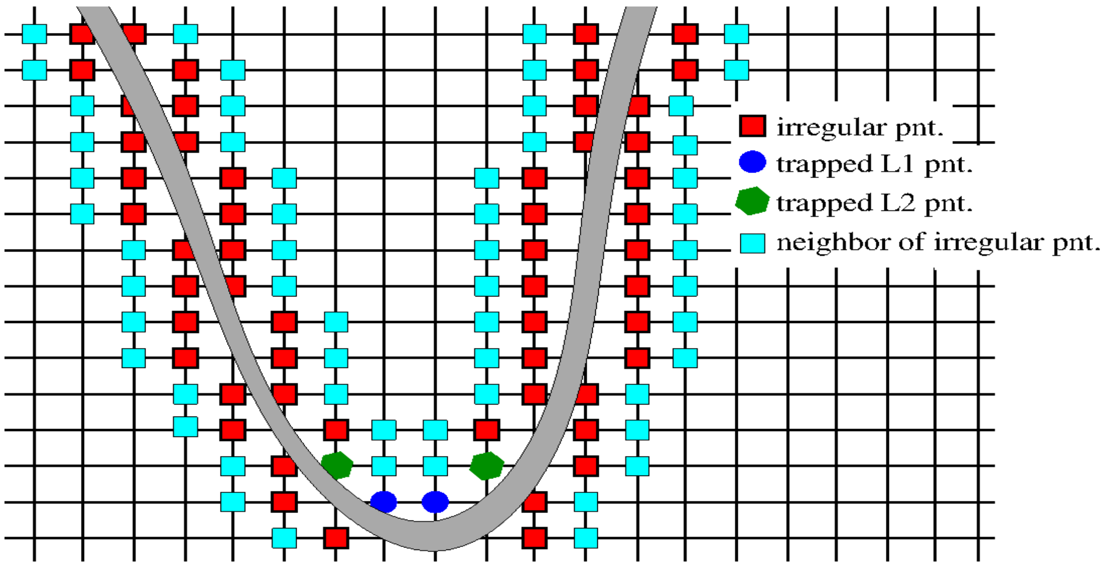

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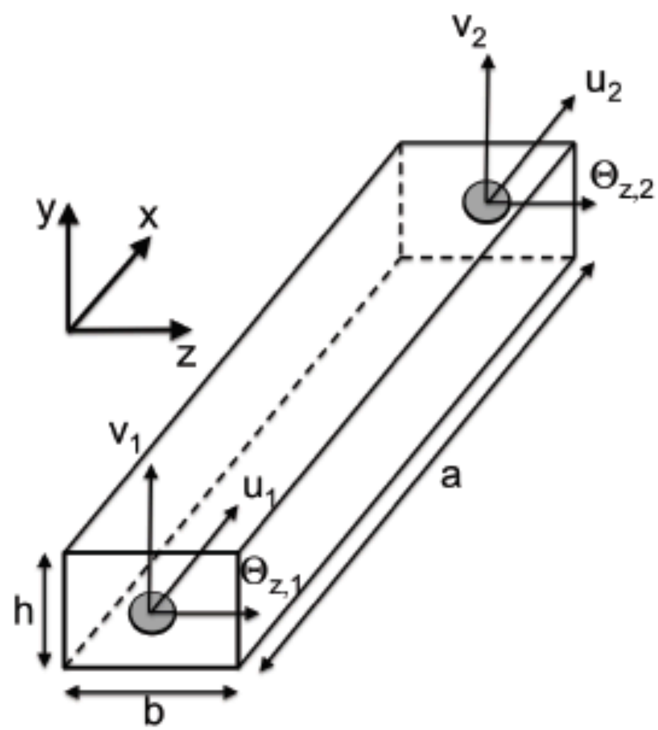
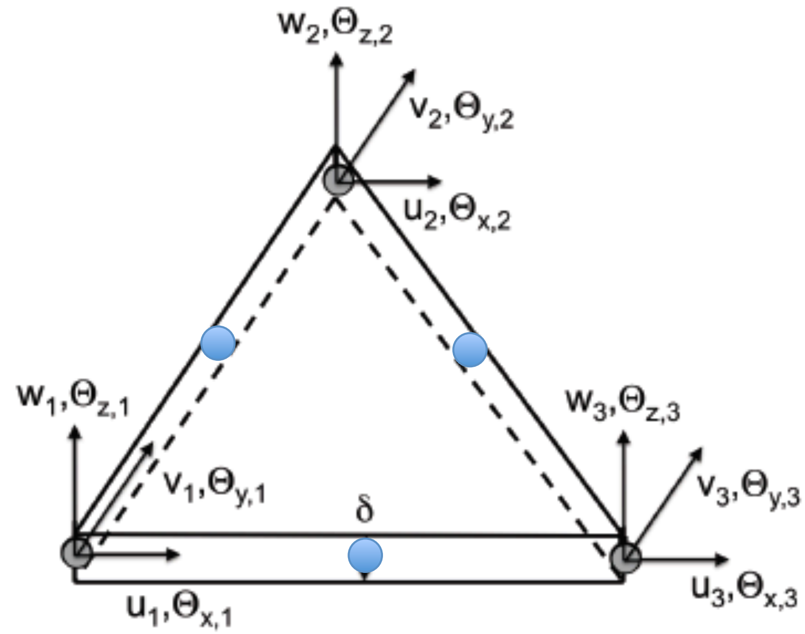
2D Beam Element



3 degrees of freedom:

- axial deformation, u
- vertical displacement, v
- rotational degree of freedom, Θ_z
- linear geometric and linear material

3D Triangular Shell Element



6 degrees of freedom:

- ❑ Membrane element
  - in-plane deformations, u and v
  - additional drilling DOF, Θ_z
- ❑ Bending element
  - out-of-plane displacement, w
  - rotational degrees of freedom, Θ_x & Θ_y
- ❑ Higher-order formulation to introduce drilling DOF, $\mathbf{K=K_b+K_h}$ (Bergan and Felippa, Comp. Meth. Appl. Mech. Eng., 1995)

Structural Solver: Time-Integration

- Global system solved for in terms of u=[u,v,w,Θ_x,Θ_y,Θ_z]:

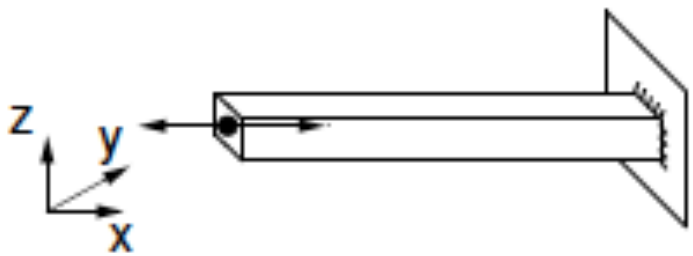
$$M\frac{d^2u}{dt^2} + C\frac{du}{dt} + Ku = f$$

- Newmark method:

$$[a_1 M + a_2 C + K]\, u_{n+1} = f_{n+1} + [a_1 M + a_2 C]\, u_n + [a_3 M - a_4 C]\, \dot{u}_n + [a_5 M - a_6 C]\, \ddot{u}_n$$
$$\ddot{u}_{n+1} = a_1 [u_{n+1} - u_n] - a_3 \dot{u}_n - a_5 \ddot{u}_n$$
$$\dot{u}_{n+1} = a_2 [u_{n+1} - u_n] + a_4 \dot{u}_n + a_6 \ddot{u}_n,$$

- Solve sparse system of equations with GMRES algorithm
- Solution on each node separately or MPI parallel
- No damping is assumed for all problems considered here (**C**=0)
- Structural eigen-mode analysis by solving: $\omega_m^2 \underline{M} v = \underline{K} v$

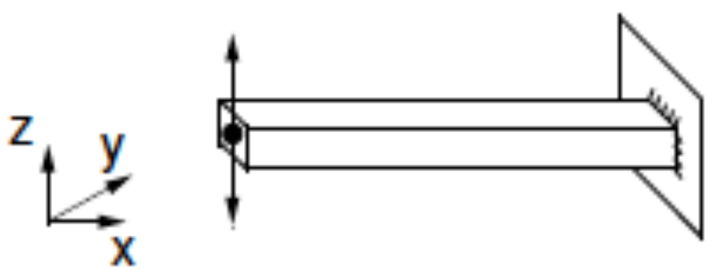
- Axial vibration test



Error convergence study for first two axial vibration modes

N_e	Error Mode 1	Error Mode 2
2	4.06×10^{-2}	9.17×10^{-1}
5	6.46×10^{-3}	1.75×10^{-1}
10	1.61×10^{-3}	4.36×10^{-2}

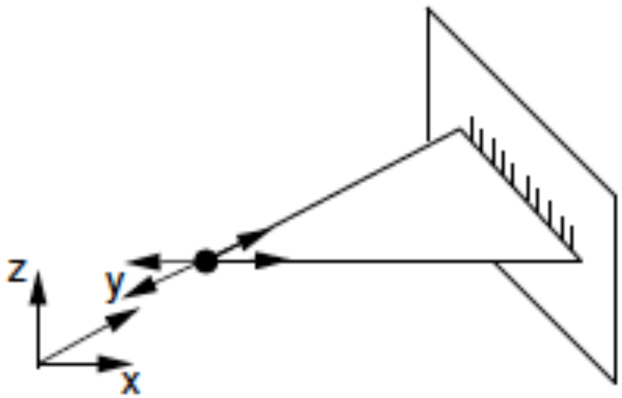
- Bending vibration test



Error convergence study for first two bending vibration modes

N_e	Error Mode 1	Error Mode 2
2	1.92×10^{-3}	1.87×10^{-1}
5	2.74×10^{-4}	1.14×10^{-2}
10	2.9×10^{-5}	1.13×10^{-3}

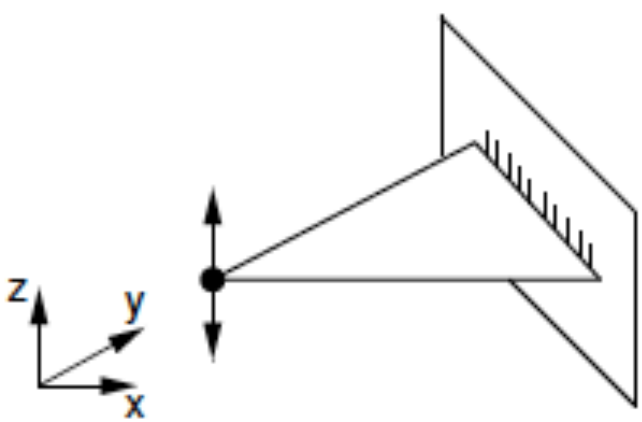
- In-plane vibration test for triangle



First five in-plane vibration modes for triangle

Mode	Analytic	FEM
1	4.973	4.952
2	26.391	27.799
3	31.944	32.051
4	62.066	71.004
5	95.832	93.452

- Bending vibration test for triangle



First five bending vibration modes for triangle

Mode	Analytic	5×5-Mesh	10×10-Mesh
1	37.5	39.283	38.047
2	161	173.55	163.91
3	243	223.23	237.48
4	392	435.25	404.12
5	592	522.73	566.54

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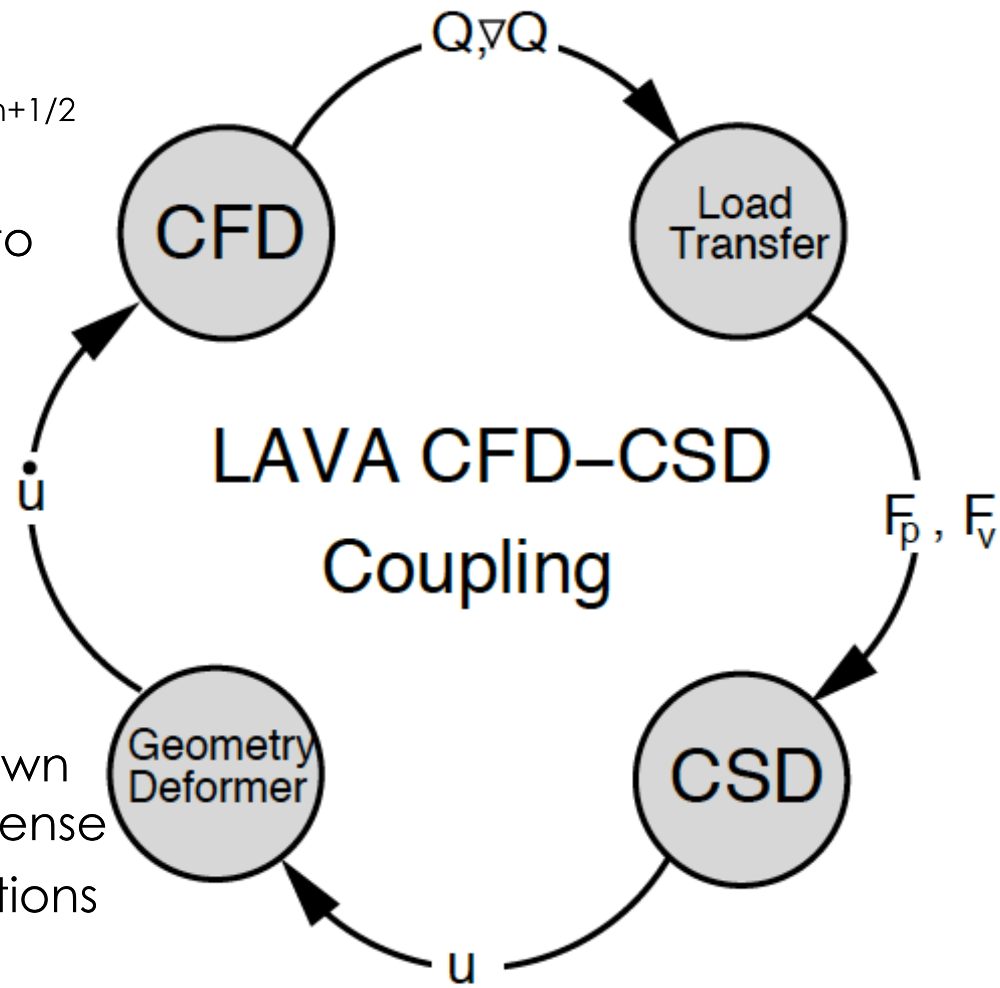
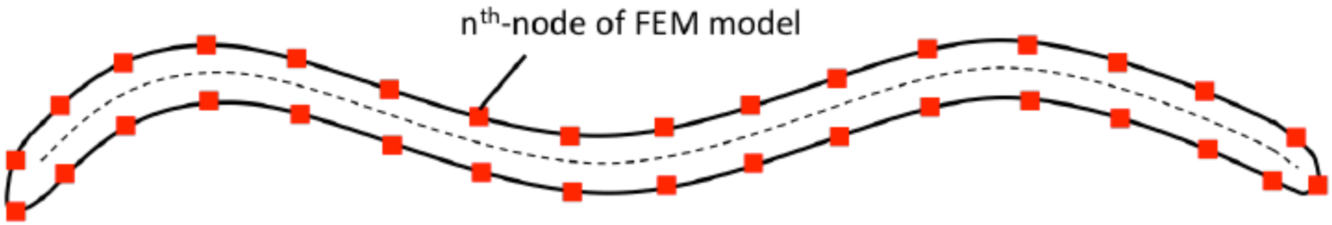
CFD-CSD Coupling Within LAVA

- CFD: Explicit (RK-4):
  - Update of two time levels t_n & $t_{n+1/2}$
  - $\Delta t_{CSD}=\Delta t_{CFD}/2$
  - Loss of 4th-order accuracy due to 2nd-order accuracy for CSD
  - CFD solver lags CSD solver
- CFD: Implicit (BDF-2):
  - Lends itself to strong coupling approach but computationally expensive
  - Loose coupling for all results shown here due to computational expense
  - Update after nonlinear subiterations
- CSD: Implicit (Newmark-2)



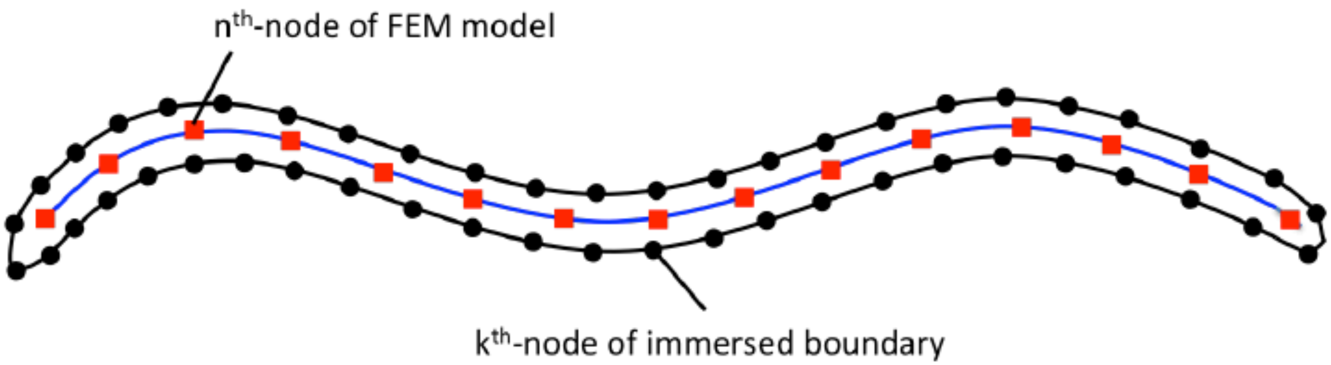
Methods for CFD-CSD Coupling

- Same geometry description for CFD and CSD:



  - No special loads and displacement transfer algorithms are necessary

- Auxilliary surface for CSD that differs from the CFD geometry



  - Conservative loads transfer from CFD to CSD

$$\sum_{n=1}^{N} \boldsymbol{F}_n^{(IB)} = \sum_{k=1}^{K} \boldsymbol{F}_k^{(FEM)}$$

  - Mapping of displacement field from CSD to CFD

$$\boldsymbol{x}_k^{(IB)} = \sum_{n=1}^{N} c_n \boldsymbol{x}_n^{(FEM)}$$

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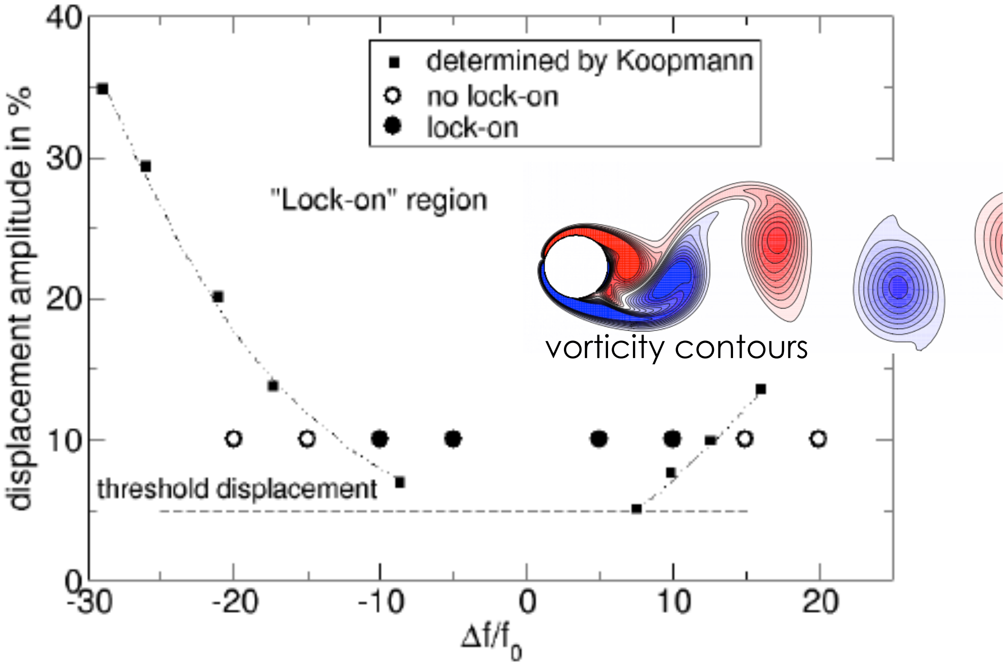
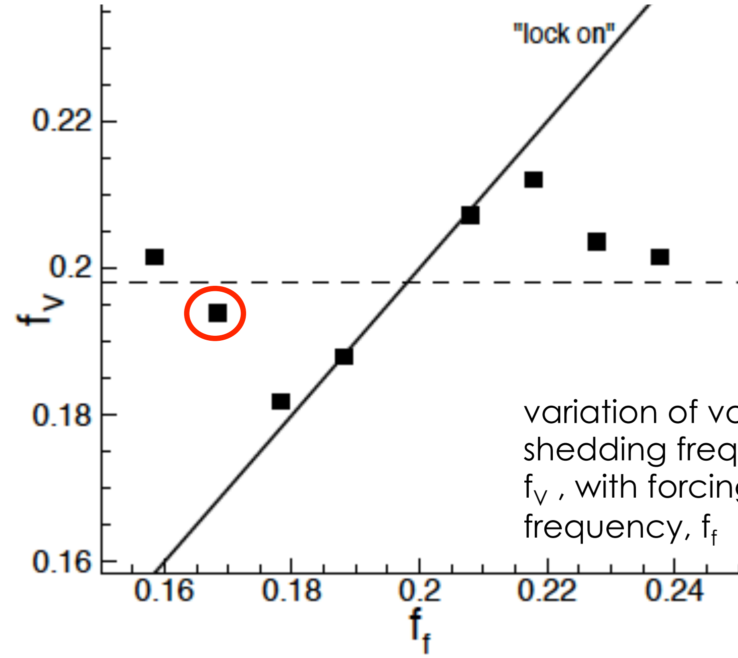
OSCILLATION CYLINDER: LOCK-ON PHENOMENON

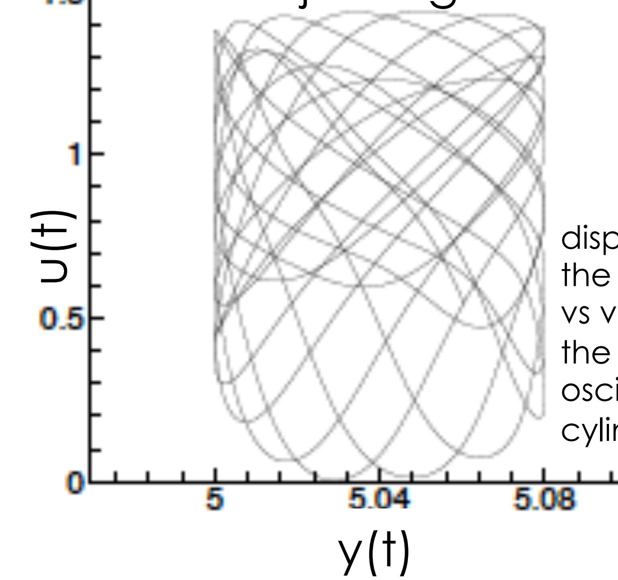




variation of vortex shedding frequency, f_V , with forcing frequency, f_f

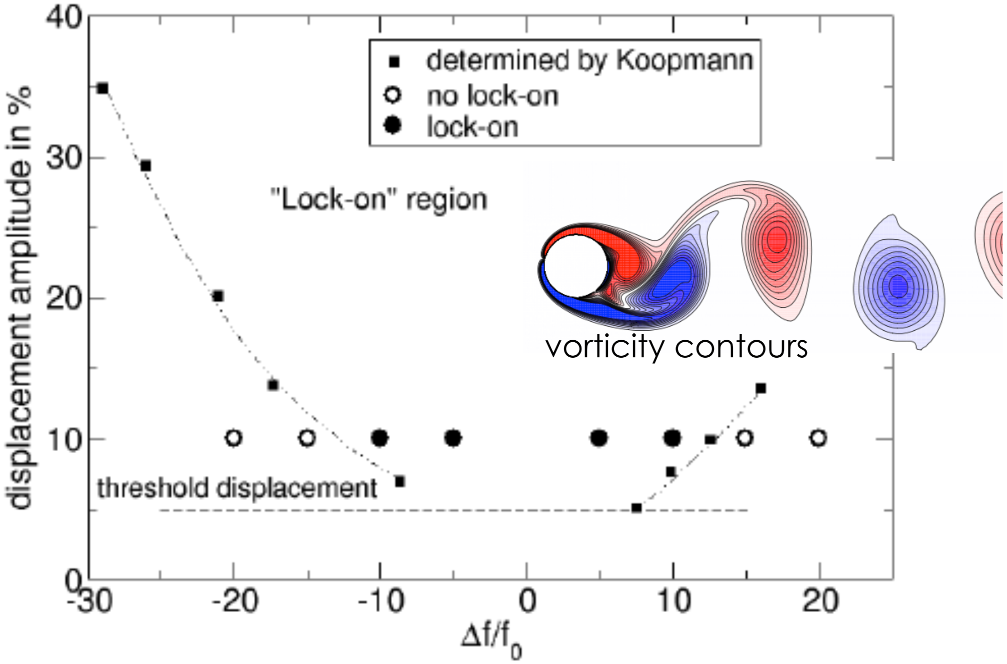
- ❑ Comparison with experiments by Koopman (JFM 1967)
- ❑ Subsonic M=0.1
- ❑ Re=200
- ❑ Natural shedding frequency $f_0 \approx 0.2$
- ❑ Reproduce lock-on phenomenon for A/D=10%
- ❑ Relevant for FSI problems (bending tower)

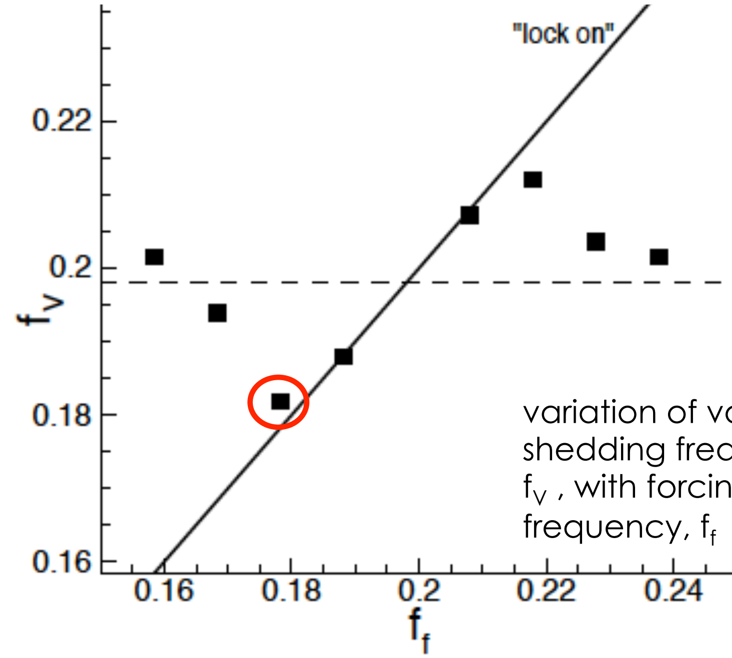
Lissajous figure



displacement of the cylinder y(t) vs velocity u(t) in the wake of the oscillating cylinder

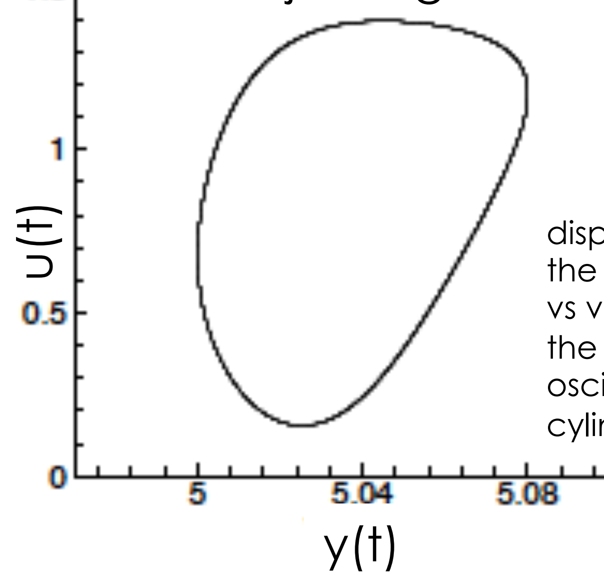
Oscillation Cylinder: Lock-On Phenomenon





variation of vortex shedding frequency, f_V , with forcing frequency, f_f

Lissajous figure

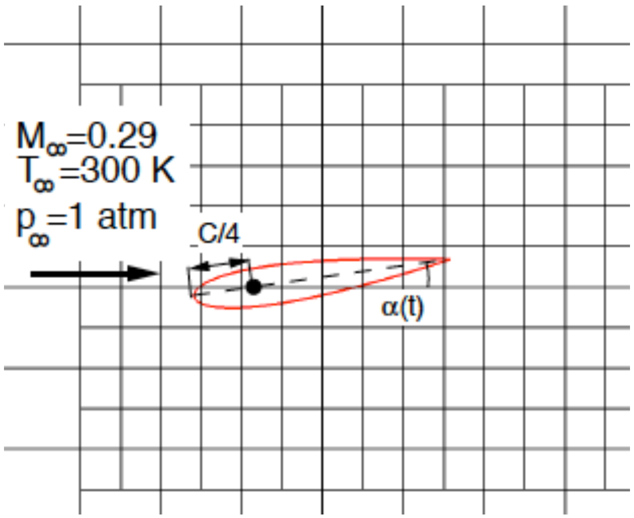


displacement of the cylinder y(t) vs velocity u(t) in the wake of the oscillating cylinder

- Comparison with experiments by Koopman (JFM 1967)
- Subsonic M=0.1
- Re=200
- Natural shedding frequency $f_0 \approx 0.2$
- Reproduce lock-on phenomenon for A/D=10%
- Relevant for FSI problems (bending tower)

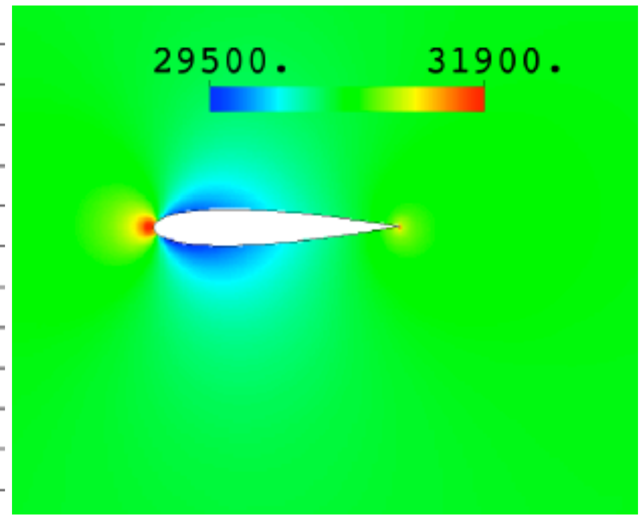
PITCHING NACA0015 AIRFOIL

Simulation Setup

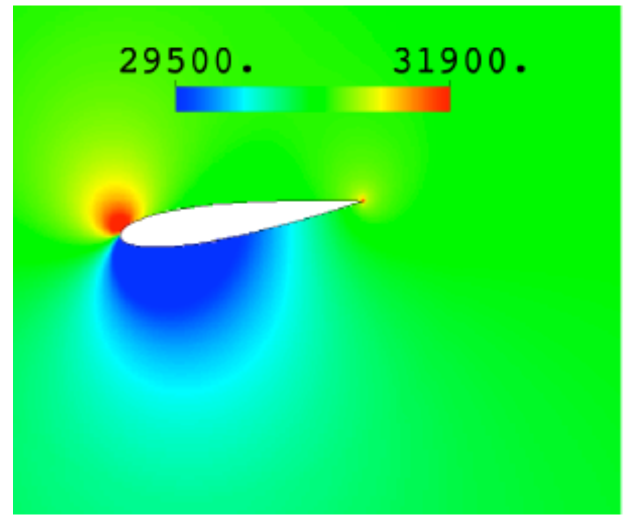


16 × 16 cells/box

Pressure (upstroke)



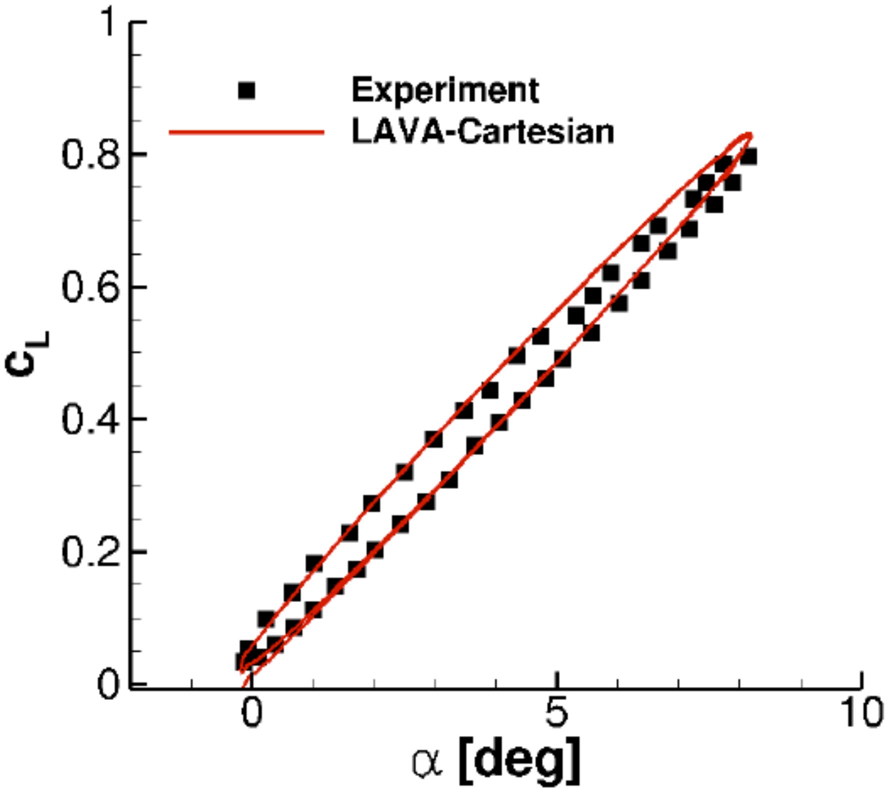
Pressure (down-stroke)



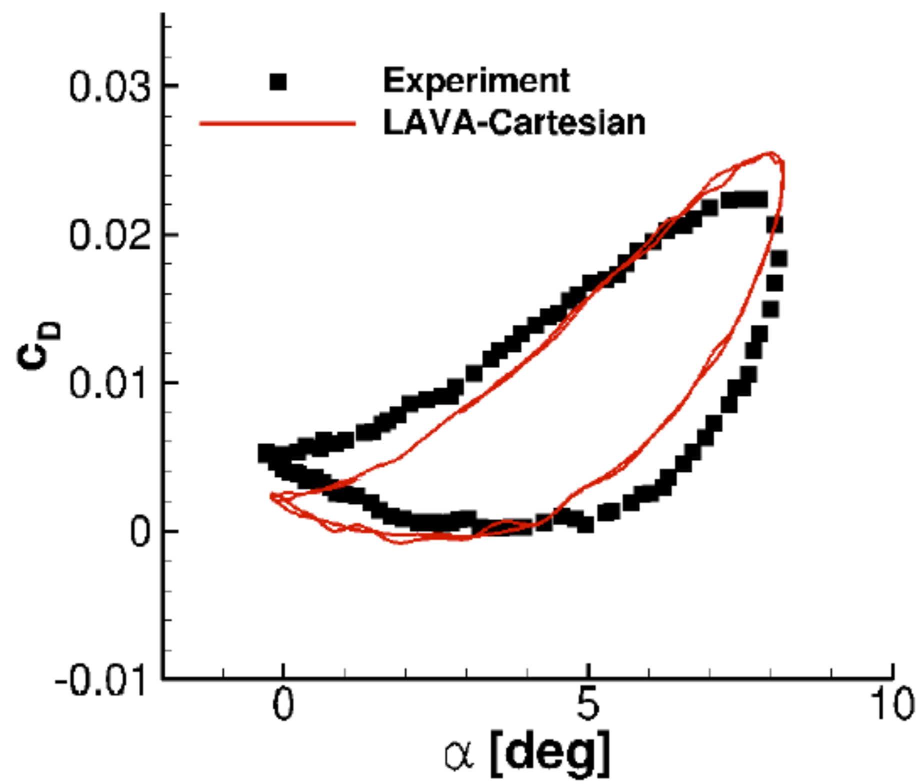
- ❑ Comparison with experiments by Piziali (NASA-TM-1994-4632, 1994)
- ❑ Consider the attached flow case
- ❑ M_∞=0.29 and Re=1.95×10^6 (wall modelled)
- ❑ AoA: $a(t)=4°+4.2° \sin(2kM_\infty t+1.5\pi)$
- ❑ Measured forces from pressure data only

PITCHING AIRFOIL

Lift Coefficient



Drag Coefficient



- ❑ Good comparison for lift coefficient
- ❑ Discrepancy in drag coefficient somewhat similar to what was observed in 2D simulations found in literature, see for example Ko and McCroskey (AIAA 1995) and Nichols and Heikkinen (AIAA 2005)

OUTLINE

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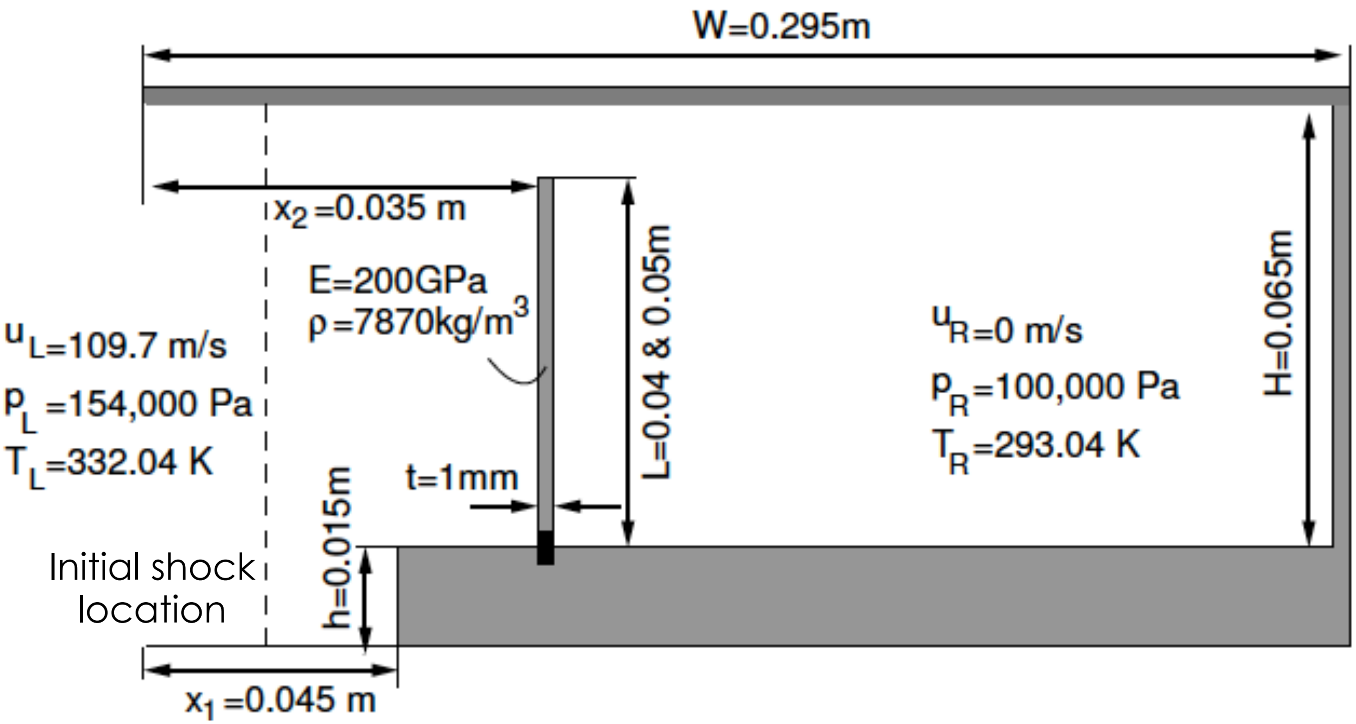
DEFORMING PANEL

Density Contours

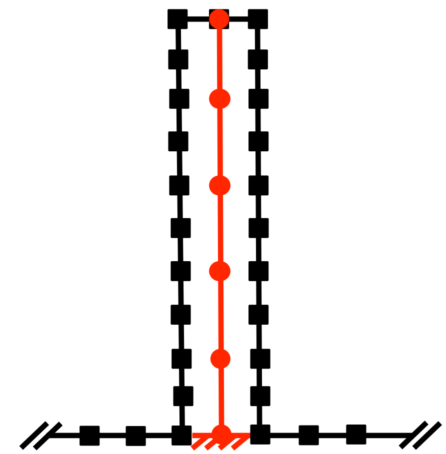
- Shock moves at M=1.2 in ambient air (assumed inviscid)
- Comparison with experiments and numerical simulations by Giordano et al. (2005)
- Objective: Predict deformation of the cantilever panel motion
- Eigenfrequency $\omega=(Et^2/\rho L^4)^{1/2}$ and maximum displacement $v_{max}=3pL^4/2Et^3$

DEFORMING PANEL

CFD Setup



CSD Setup



■ node of IB

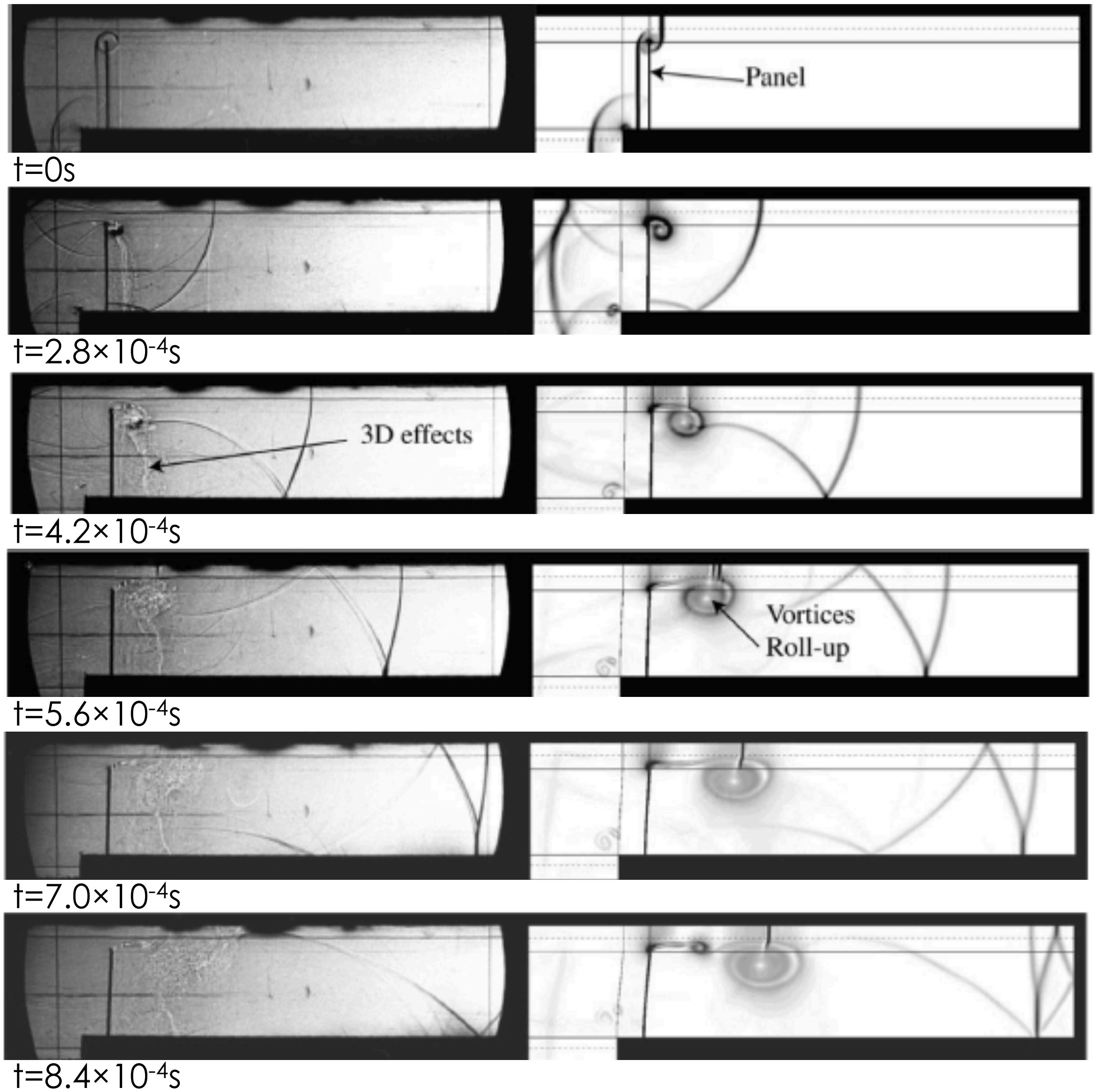
● node of FEM model

Note: not all nodes are shown in CSD setup.

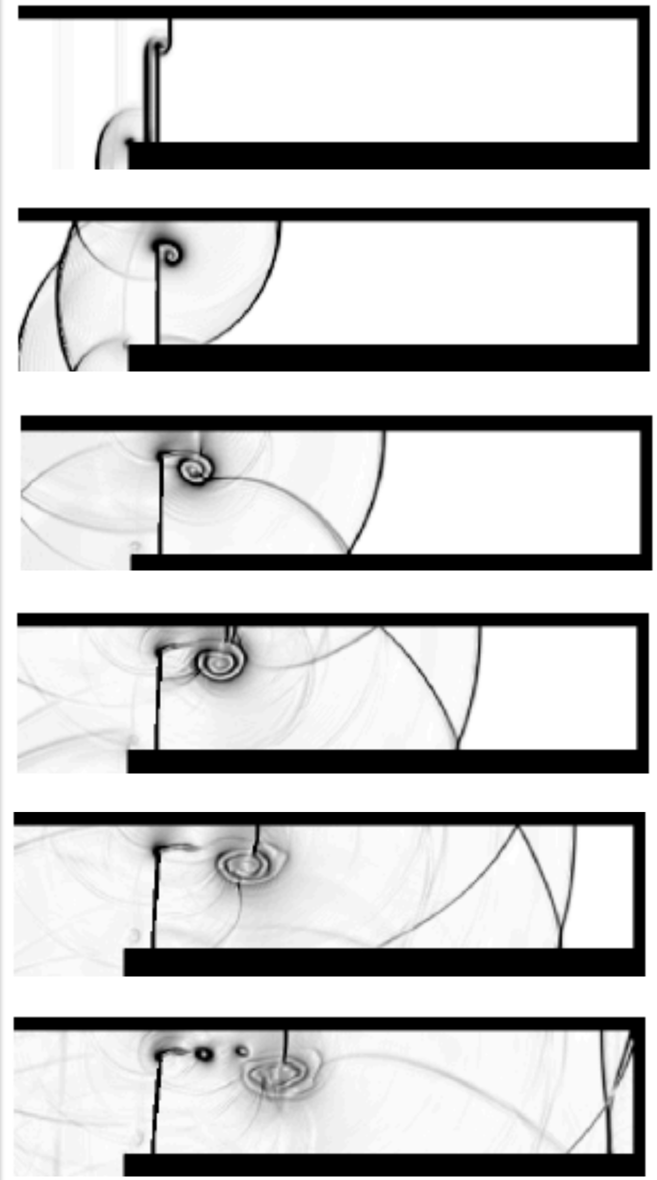
- ❑ Shock moves at M=1.2 in ambient air (assumed inviscid)
- ❑ Comparison with experiments and numerical simulations by Giordano et al. (2005)
- ❑ Objective: Predict deformation of the cantilever panel motion
- ❑ Eigenfrequency $\omega=(Et^2/\rho L^4)^{1/2}$ and maximum displacement $v_{max}=3pL^4/2Et^3$

DEFORMING PANEL: NUMERICAL SCHLIEREN

Experiment and simulation by Giordano *et al.*

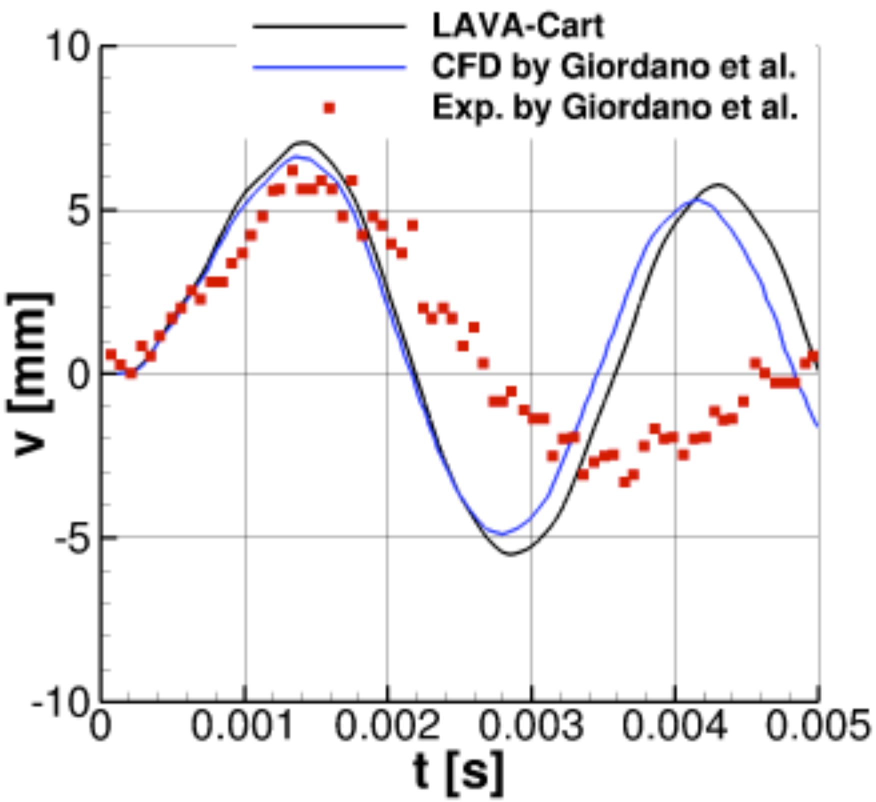


LAVA-Cartesian

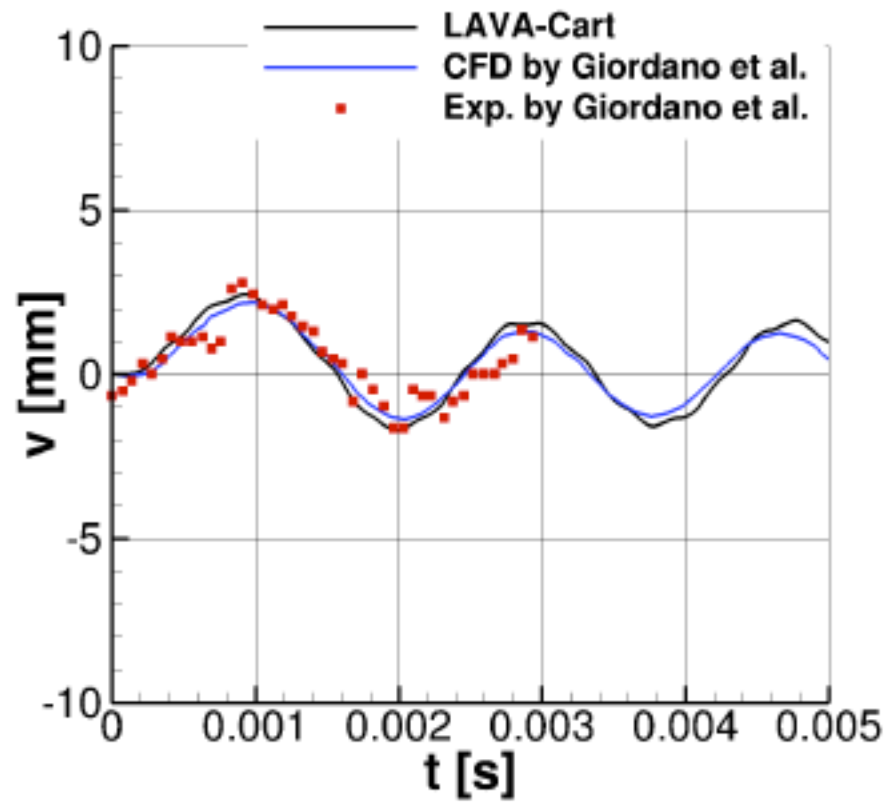


DEFORMING PANEL

Tip Deflection for L=50mm



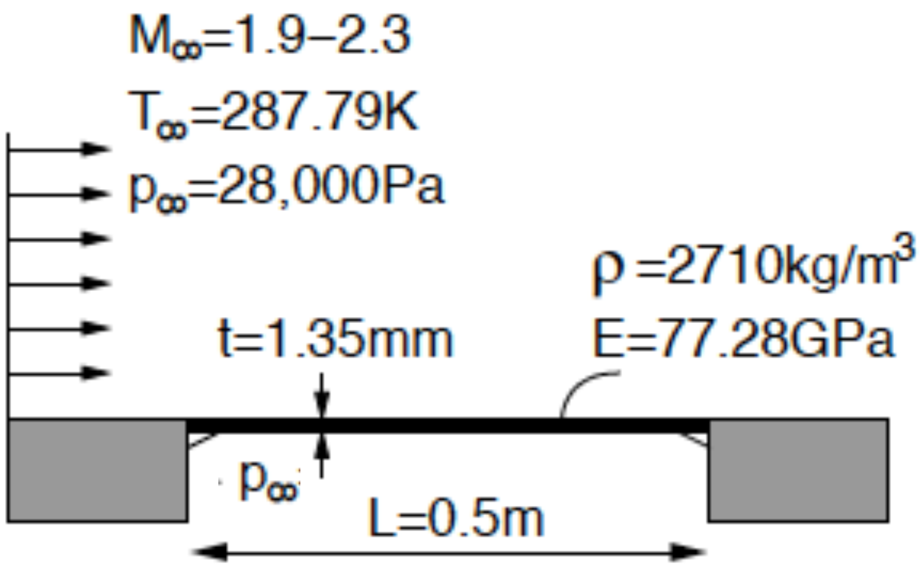
Tip Deflection for L=40mm



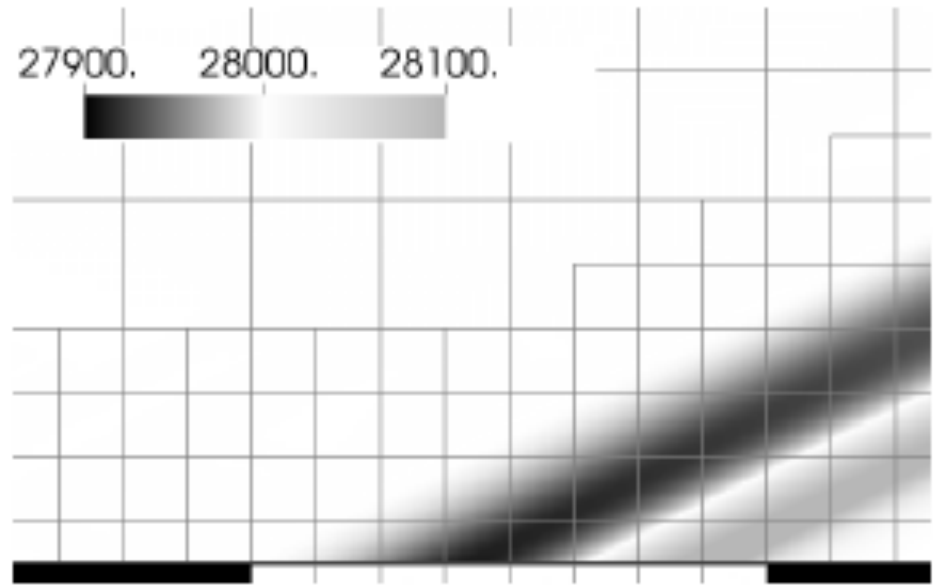
- Numerical results agree well for L=50mm but mismatch with experiments
  - Initially, damping was assumed play an important role
  - Base of panel deforms slightly
- Good agreement between experiment and simulations for shorter panel

FLUTTER ANALYSIS OF FLAT PLATE

Simulation Setup



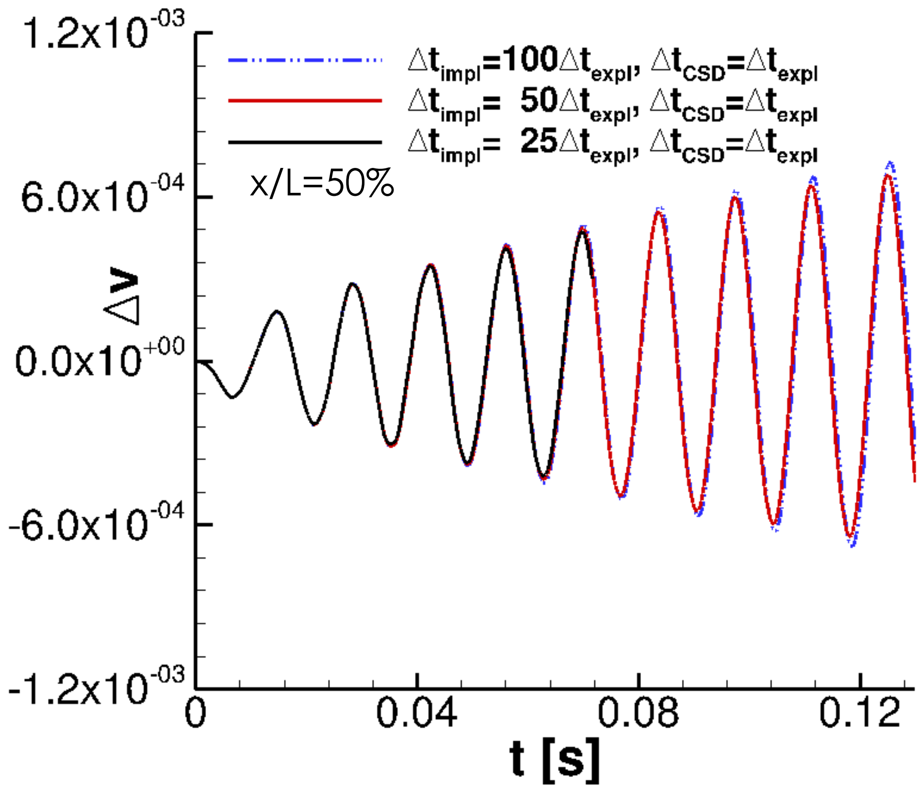
Pressure Contours

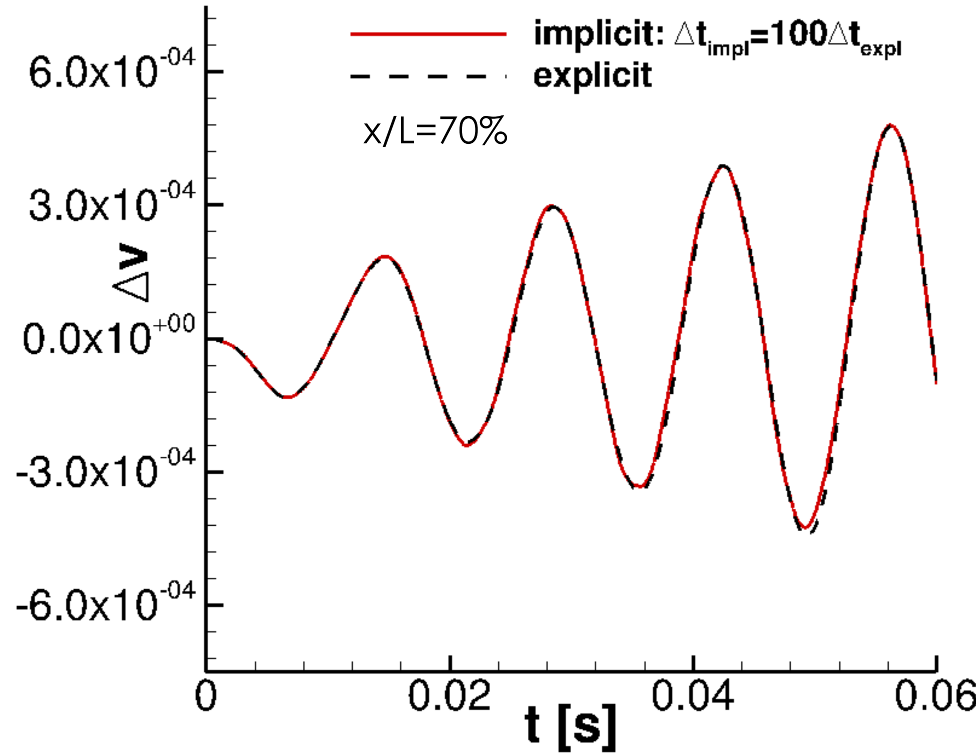


16 × 16 cells/box

- Supersonic flow passing flexible plate (assumed inviscid)
- Comparison with predictions by Dowell (1974) and simulations by Vito et al. (JCP 2-06)
- Objective: Predict onset of aeroelastic flutter
- CSD: 300 × 2D-beam elements with (u,v,Θ_z) and $(u_0,v_0,\Theta_{z,0})=(u_N,v_N,\Theta_{z,N})=0$
- CFD: AMR with $\Delta x_{min}=3.9\times10^{-3}$ and roughly overall 4×10^4 grid points (with AMR)

Explicit vs Implicit CFD Schemes

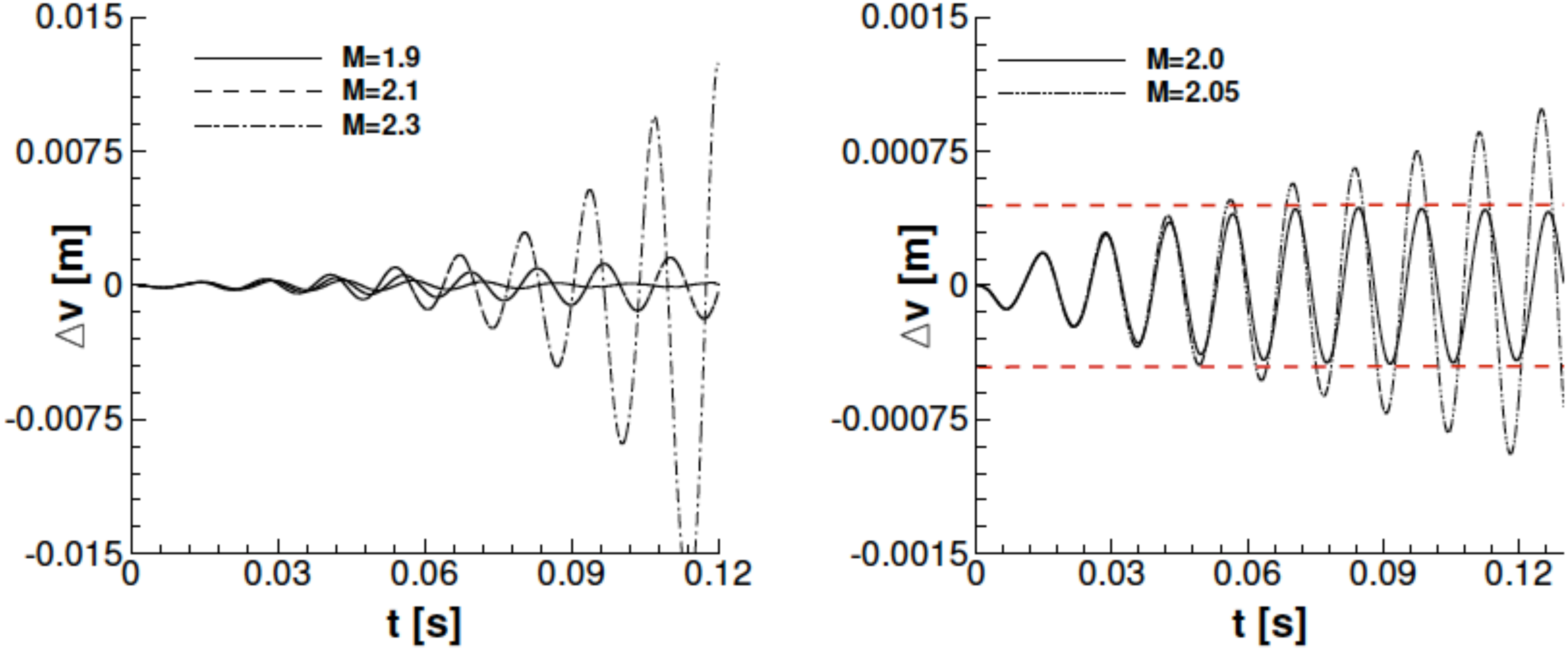




- ❑ Implicit time integration can be very beneficial for certain applications
- ❑ CFD timestep is limited by relevant temporal scales in flows and grid CFL
  - $CFL_G = v_G \Delta t / \Delta x < 1$ (here <1), do not allow open up two cells
- ❑ Decision between explicit and implicit depends on flow conditions (for each implicit step N sub-iterations are required)

FLUTTER ANALYSIS OF FLAT PLATE

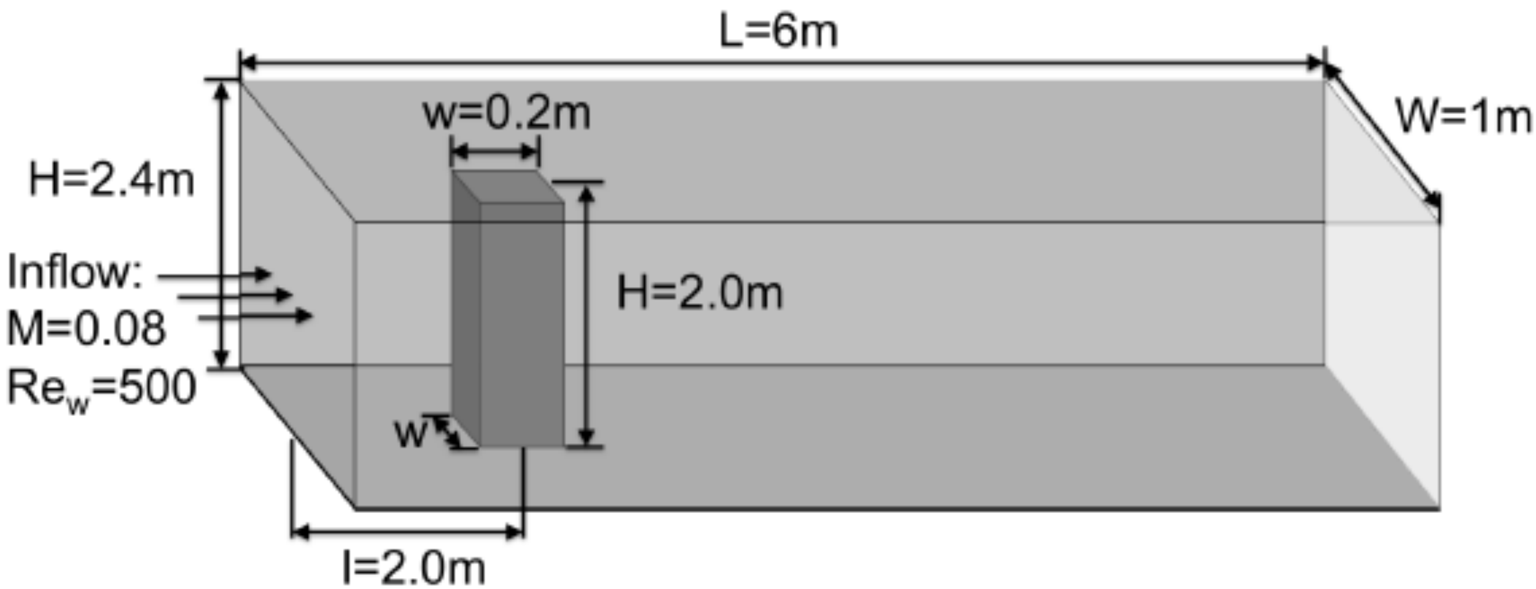
Vertical Plate Deflection at x/L=50%



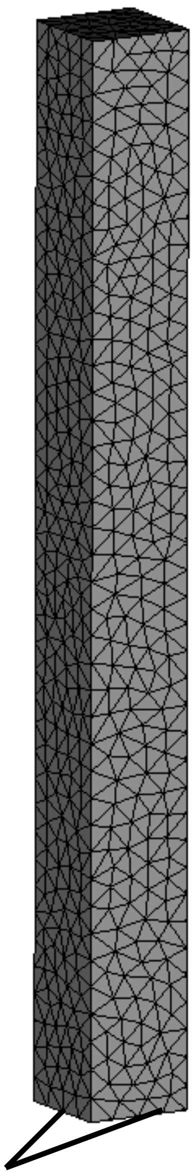
- ❑ Start up simulation with uniform load of Δp=100Pa for 0s ≤ t ≤ 0.01s
- ❑ Dowell and Vito et al. (2016) predict onset at M≈2 (here: M=2.00-2.05)
- ❑ Solutions are grid converged (temporally and spatially)

3D BENDING TOWER

CFD Simulation Setup

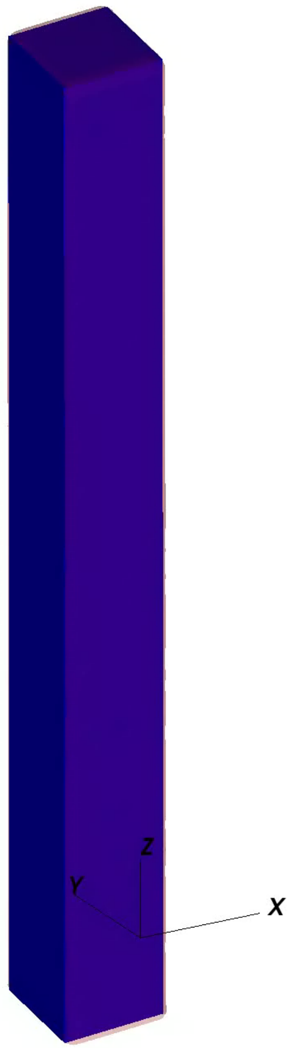


CSD Surface Triangulation



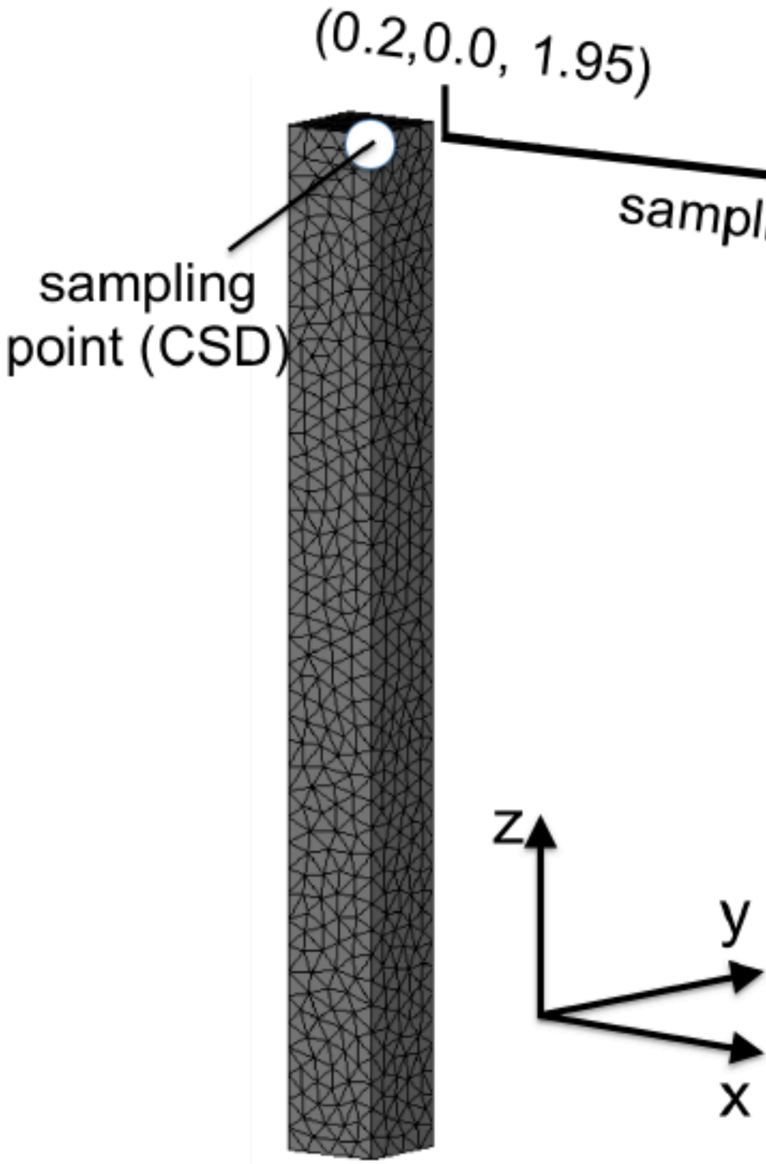
- Subsonic (M=0.08) channel flow past flexible tower
- <u>Objective:</u> simulation of full 3D CFD-CSD coupling
- CSD setup: 2×10^3 Triangles (reminder: all linear)
- CFD setup: $\Delta x_{min}=9\times10^{-3}$ leads to 2×10^6 grid points

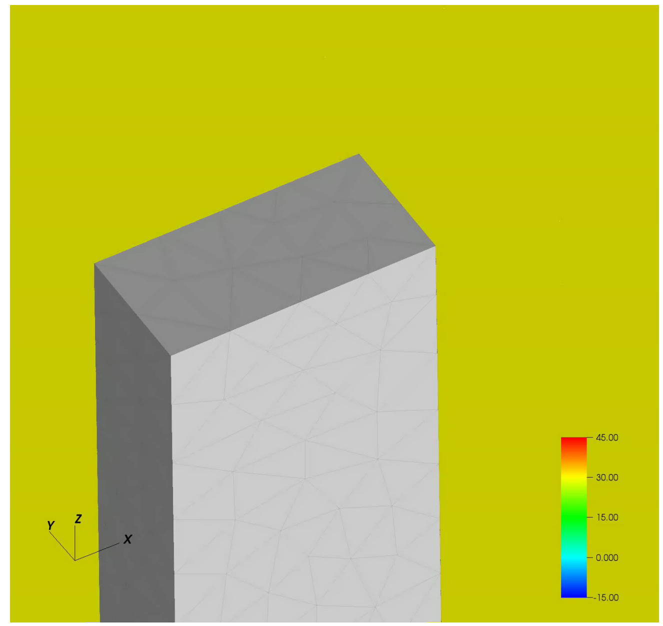
3D BENDING TOWER: FLOW VIZ



Contours of vorticity magnitude, $|\omega|=200s^{-1}$

SAMPLING

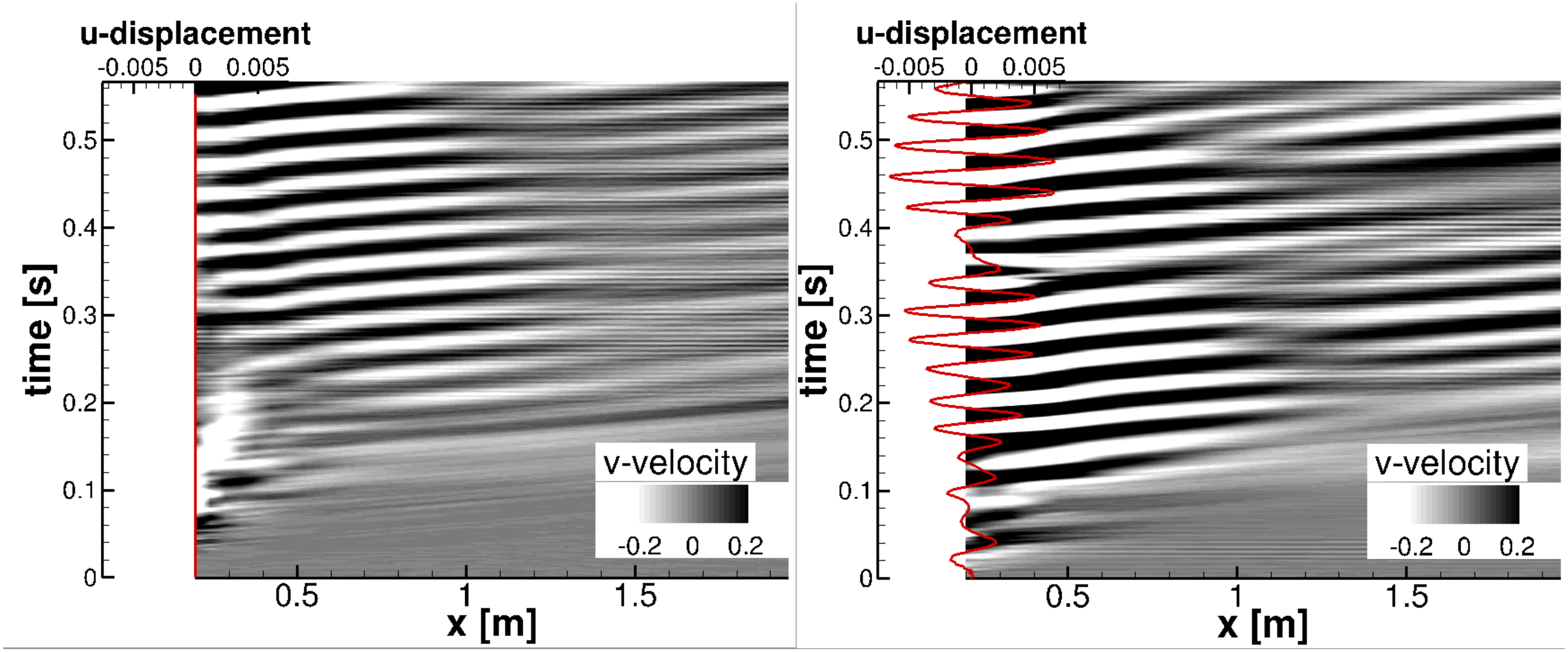




- record structural deformation of tower and unsteady flow field in the wake of the tower

SAMPLING

Static Tower Flexible Tower



- Synchronization of flow field and tower motion (lock-on)
- Fluctuation amplitudes seemed to be enhanced
- At t≈0.35, flow field and tower motion get out-of-sync
- Re-synchronization after brief intermittent event

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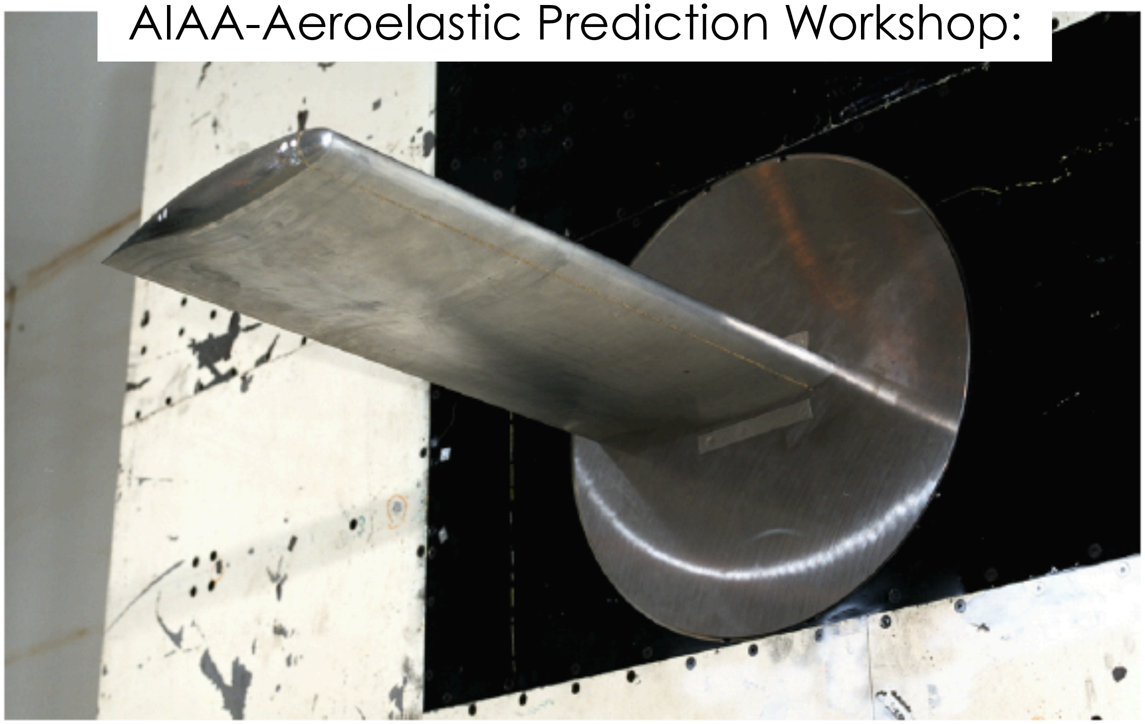
Experimental Setup for
AIAA-Aeroelastic Prediction Workshop:

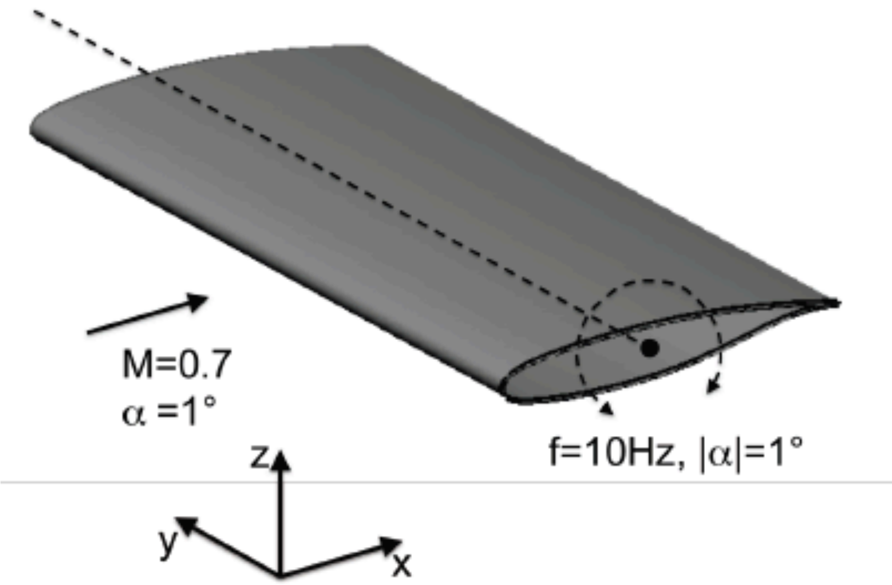


- Details about the workshop and analysis of participations in Schuster et al. (AIAA-2013) and Heeg at al. (AIAA-2016)
- LAVA solvers are applied to some of the test problems from the workshop
- Curvilinear results (Housman SciTech 2017)
- Test problems put together with increasing complexity

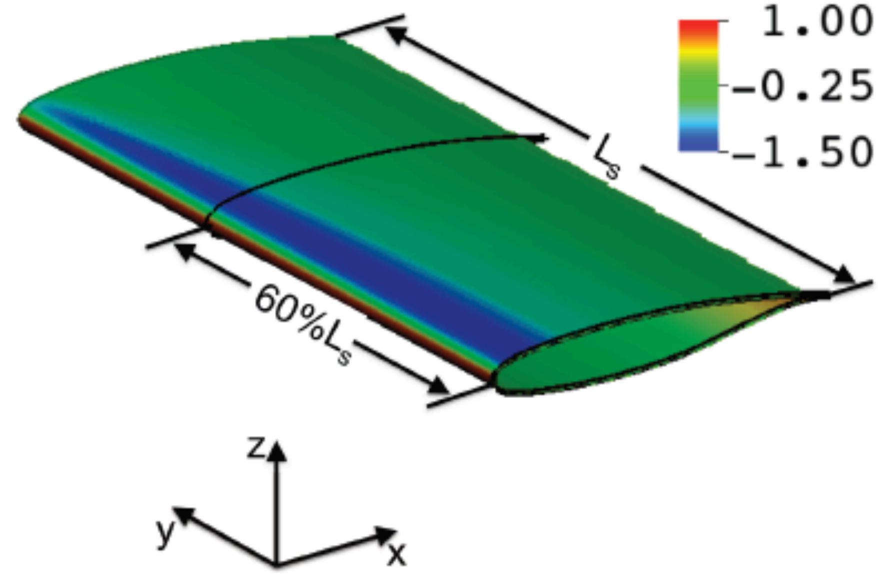
- Category 1: Flow past a stiff wing ➔ excellent agreement among participants
- Category 2: Forced oscillation with and without separation ➔ reliable prediction of unsteady separation is still a huge problem
- Category 3: Coupled fluid structure interaction ➔ various challenges were revealed, e.g., time-step convergence, nonlinearities in the flow field, separation, understanding of flow physics, etc.

AIAA-AEPW: PITCHING WING – CASE 1B

Simulation Setup



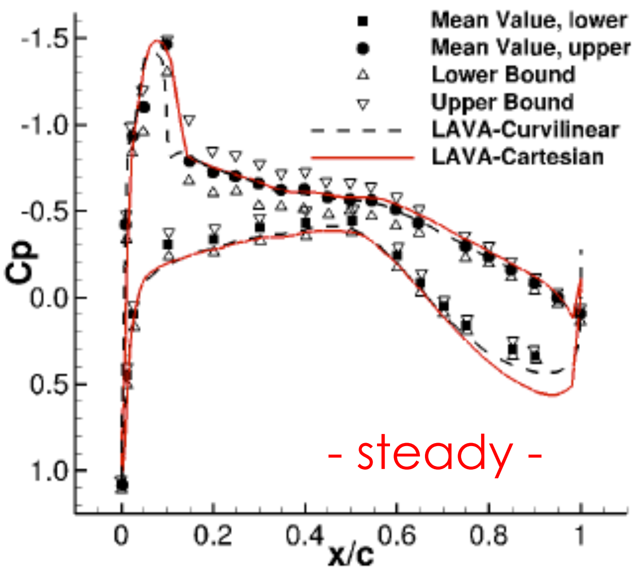
Instantaneous Pressure Contours



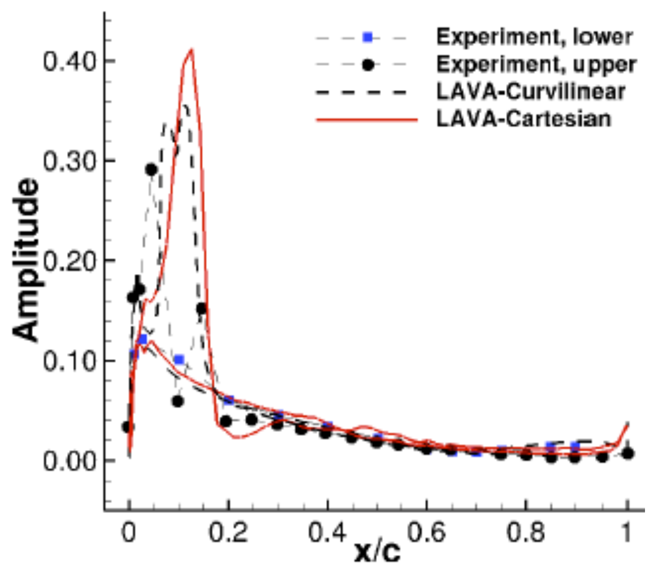
- Comparison with pitching wing experiment in NASA Langley's TDT wind tunnel by Piatak and Cleckner (J. Aircraft 2003)
- M=0.7 and Re=4.56×10^6
- AoA: a(t)=3°+1° sin(2πft+1.5π), with α_m=3°, Δα=1°, and f=10Hz
- Two meshes (coarse/medium: 15/30×10^6 cells)

AIAA-AEPW: PITCHING WING

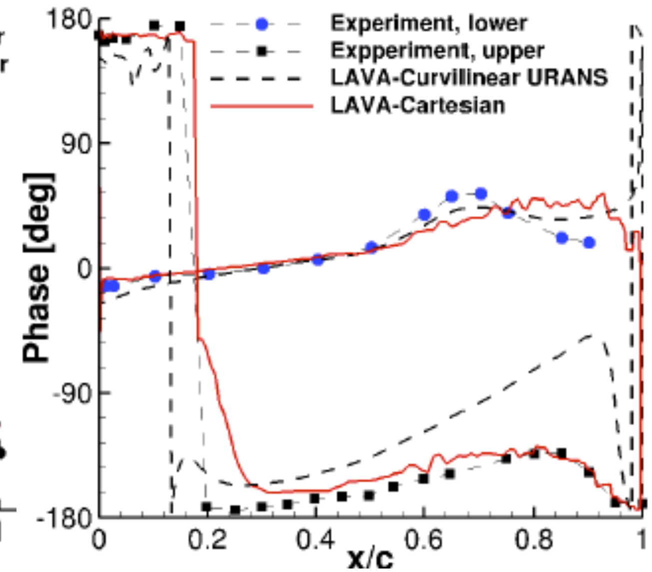
Pressure Coefficient



Pressure Amplitude



Phase

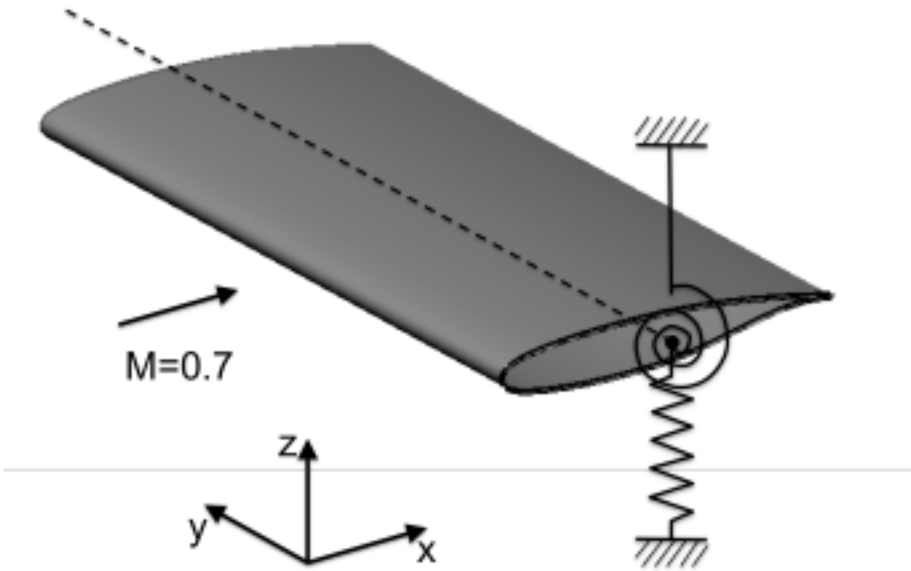


- Comparison with experiments and LAVA-Curvilinear
- Good agreement for steady case
- LAVA results are within the scatter of the computational results of the workshop
- Low amplitudes at x/c≈0.1 are assumed to be due to malfunctioning sensor
  - LAVA-Curvilinear displays small dip at x/c≈0.1 (not grid converged)

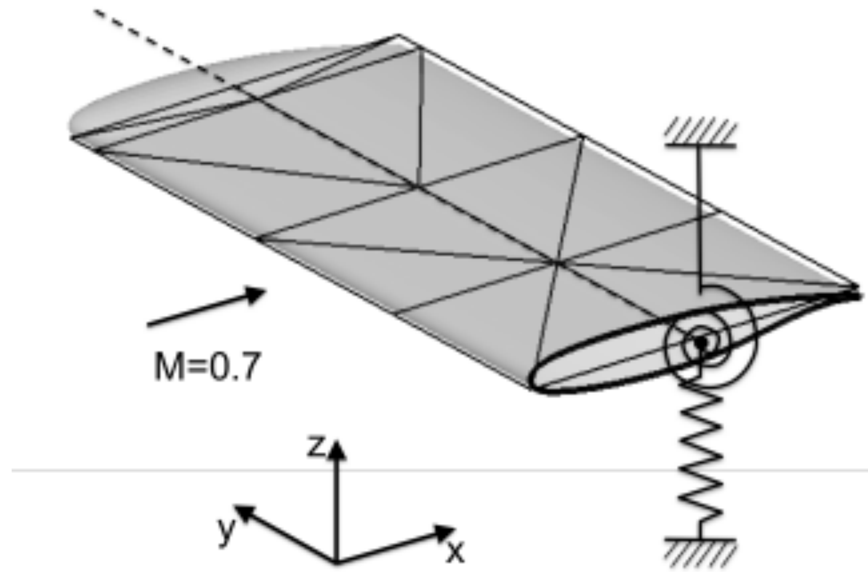
AIAA-AEPW: FLUTTER ANALYSIS OF 3D WING

Simulation Setup

Two-Degree Structural Model



Centerplane FEM Model

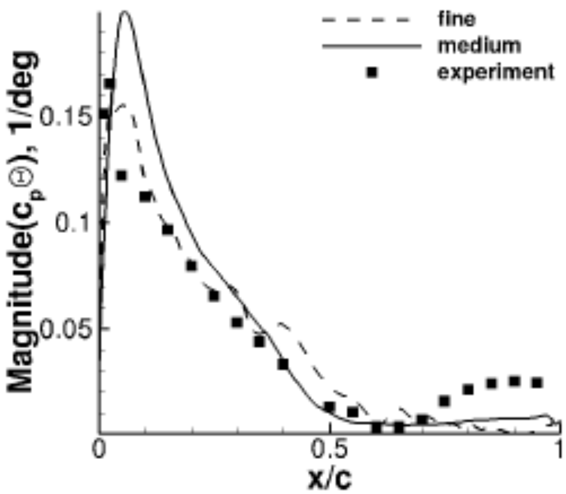


- Case 2QCe: Same setup as oscillating wing Case 1b but elastic response
- Objective: Predict flutter frequency and unsteady pressure distribution
- CSD setup: Allow plunging and pitching motion (f_{plunge}=3.33Hz and f_{pitch}=5.2Hz)
- CFD setup: Δx_{min}=1.8/3.6×10^{-3} leads to 15/30×10^{6} grid points
- Predicted flutter frequency: 4.14/4.16Hz (CFD) and 4.3Hz (Exp.)

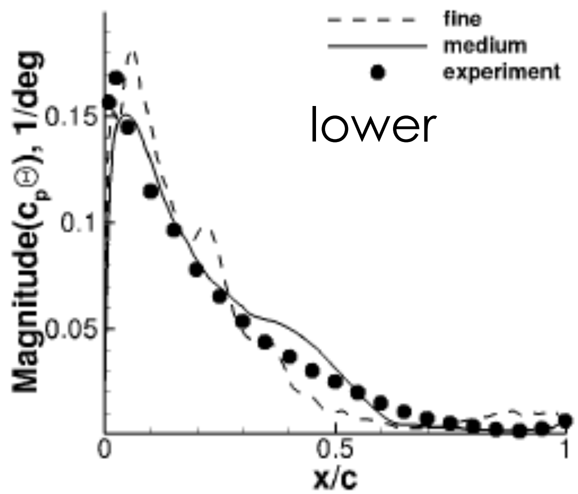
AIAA-AEPW: FLUTTER ANALYSIS OF 3D WING

Extraction at 60% chord

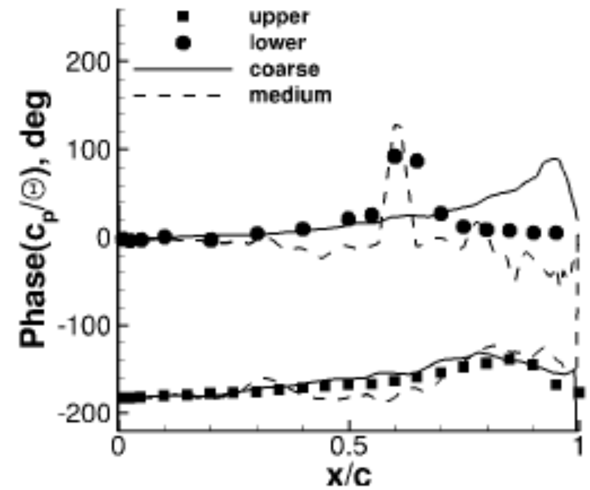
C_p on upper surface



C_p on lower surface

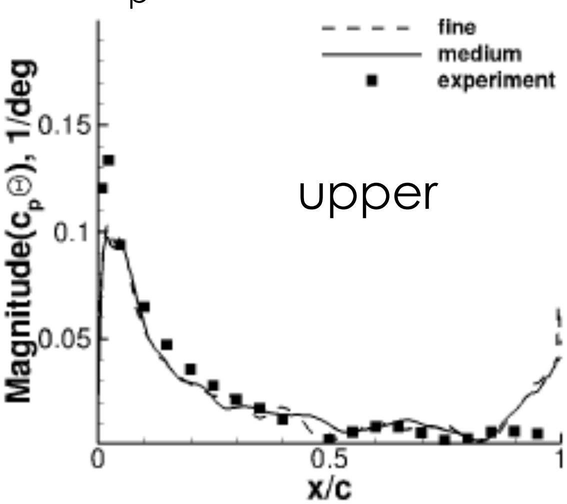


Phase distribution

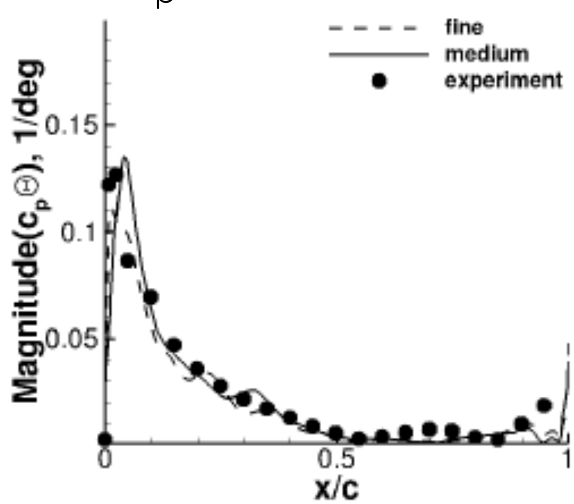


Extraction at 95% chord

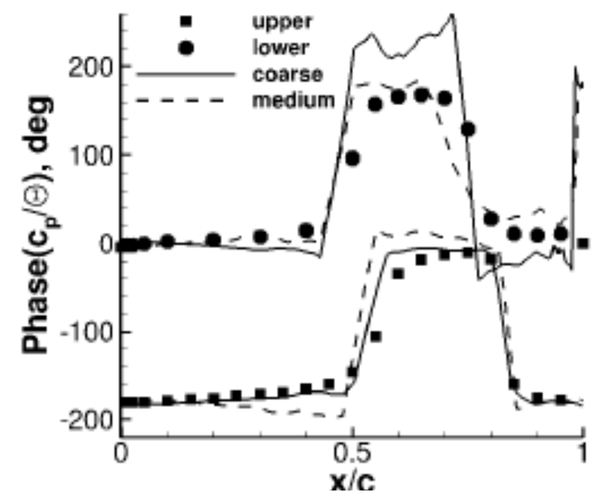
C_p on upper surface



C_p on lower surface



Phase distribution



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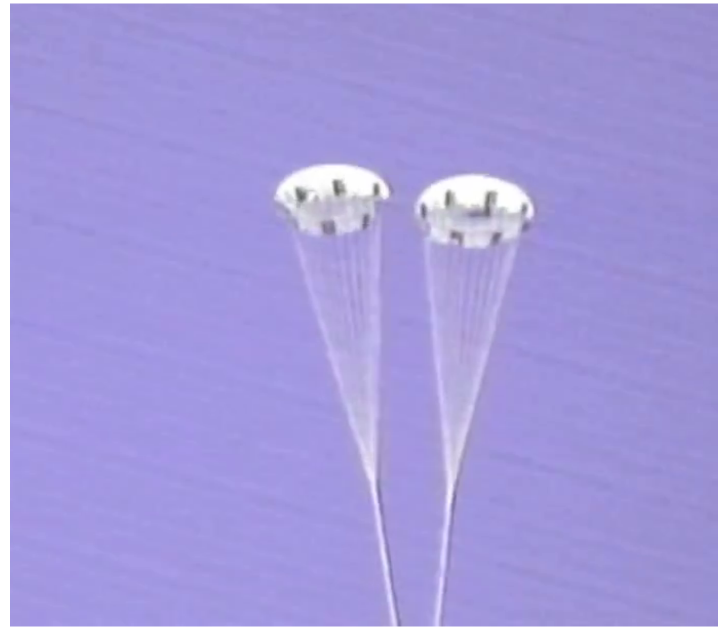
SUMMARY & FUTURE WORK

Summary:

- LAVA's recently developed FSI capabilities were presented and validated
- Structural solver was validated in standalone mode
- Infrastructure to allow full FSI coupling was put into place
- Different coupling approaches were demonstrated
- Good agreement with experimental results for lock-on phenomenon, flutter prediction, and AePW test cases

Orion Parachute Testing,
Yuma, Arizona (Feb. 2013)



Rigid Parachute LAVA Simulation

Future Work:

- Implement advanced structural models (geometric and material nonlinearities)
- Improve computational expense
- Improved wall modeling

Acknowledgments

- This work was supported by the NASA Advanced Air Transport Technology (AATT) project under the Advanced Air Vehicles Program (AAVP)

- Jeff Housman of NASA Ames Research Center for many fruitful discussions and for the LAVA Curvilinear results

- Tim Sandstrom (optimized ray-tracing kernels, and particle visualizations) of NASA Ames Research Center

- Aeroelastic prediction workshop (AePW2) group

- Computer time provided by NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center