Fluid-Structure Interaction Modeling of High-Aspect Ratio Nuclear Fuel Plates using COMSOL

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Background

- A limited number of experiments have been dedicated to the effects of coolant flow upon flat, curved, and/or involute fuel-plates used in reactors like the High Flux Isotope Reactor (HFIR)

- Fluid-Structure Interaction (FSI) simulations have recently become feasible due to advances in computer hardware and software.
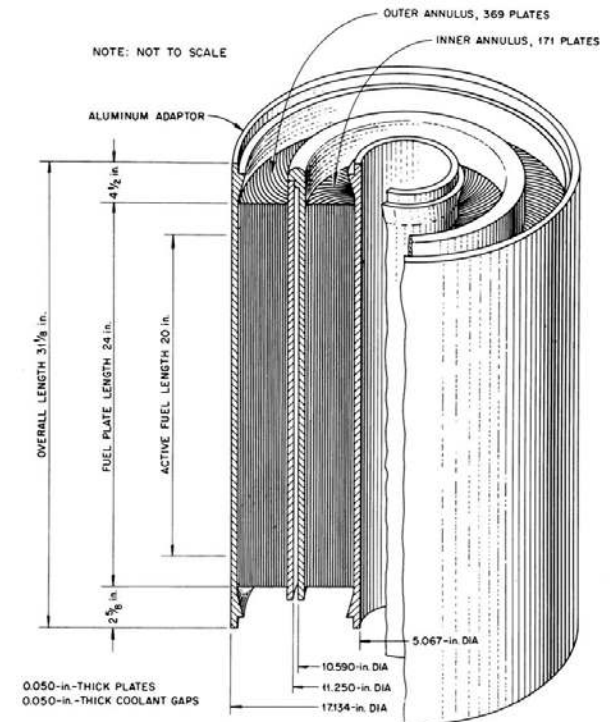
Background Cont.

- The Miller Critical Velocity, M_C, is an analytical model for the maximum inlet velocity allowed before catastrophic failure of parallel fuel plates

- $M_C = \left[\dfrac{15 \cdot E \cdot t_p^3 \cdot t_w}{\rho \cdot W^4 (1-\nu)^2}\right]^{1/2}$

- Modern FSI analysis tools can be compared against M_C to evaluate stability and fluctuation thresholds.

COMSOL Analysis

- COMSOL's ability to perform multiphysics computations makes it a good candidate for the FSI analysis of HFIR's fuel plates.

- COMSOL allows the user to manually add fluid dynamics and structural mechanics physics, or more conveniently, use a built in FSI module.

- Additional physics that COMSOL supports may also be added to the model; hence, a complete HFIR model will include FSI along with other physics.

Flat Plate Analysis

- The majority of the FSI analysis at ORNL has been focused on deflection of parallel, flat fuel plates similar to research reactors. Work has also started on curved and involute plates.

- For COMSOL validation, results have been compared to experimental results by Smissaert (1968), Marcum (2010), Kennedy (2012), and Liu (2011)

G. E. Smissaert, "Static and Dynamic Hydroelastic Instabilities in MTR-type Fuel Elements: Part I. Introduction and Experimental Investigation," *Nuclear Engineering and Design,* vol. 7, pp. 535-546, 1968.

W. Marcum, "Computational Fluid Dynamics Study of the Flow and Pressure Differentials Surrounding the Generic Test Plate Assembly: Ideal Boundary Conditions OSU-HMFTF-991000-CALC-001," Dept of Nuclear Engineering and Radiation Health Physics, Oregon State University, 2011.

J. C. Kennedy, C. J. Jesse, R. W. Slater and G. L. Solbrekken, "Fluid-Structure Interaction Modeling and Experimental Benchmarking," Colombia, MO, 2012.

L. Liu, D. Lu, Y. Li, P. Zhang and F. Niu, "Large-amplitude and Narrow-band Vibration Phenomenon of a Foursquare Fix-supported Flexible Plate in a Rigid Narrow Channel," *Nuclear Engineering and Design,* vol. 241, pp. 2874-2880, 2011.

Flat Plate Analysis
Kennedy Case: Description

- Kennedy performed single plate experiments, utilizing two plate thicknesses

- The experiments used a clear, plastic channel to allow deflection measurements using a laser

- Numerical analysis of the setup was also performed

- Plate Statistics
  - 32 and 40 mils thick
  - 4.342 in wide
  - 25.5 in long
 - 80 and 100 mils channel thickness
  - 1 plate

Flat Plate Analysis
Kennedy Case: Analysis

- Solutions were obtained over the entire range of experimental inlet velocities (up to 9 m/s) using the fully coupled stationary solver and had approximately 2.25 million degrees of freedom.

- Utilization of pseudo time-stepping and CFL constraint allowed stable solutions for the entire velocity range with no inconsistent artificial dissipation.

- Combined with one-way coupling as an initial-condition generator, both leading edge deflections and additional mode shapes were captured.

- The experimental data was extracted by hand from Kennedy's report using an open source program called Engage

- The majority of the computational runs were completed within 3 hours on a single-node, dual-processor, 12-core machine with 96 GB ram.

Flat Plate Analysis
Kennedy Case: Results
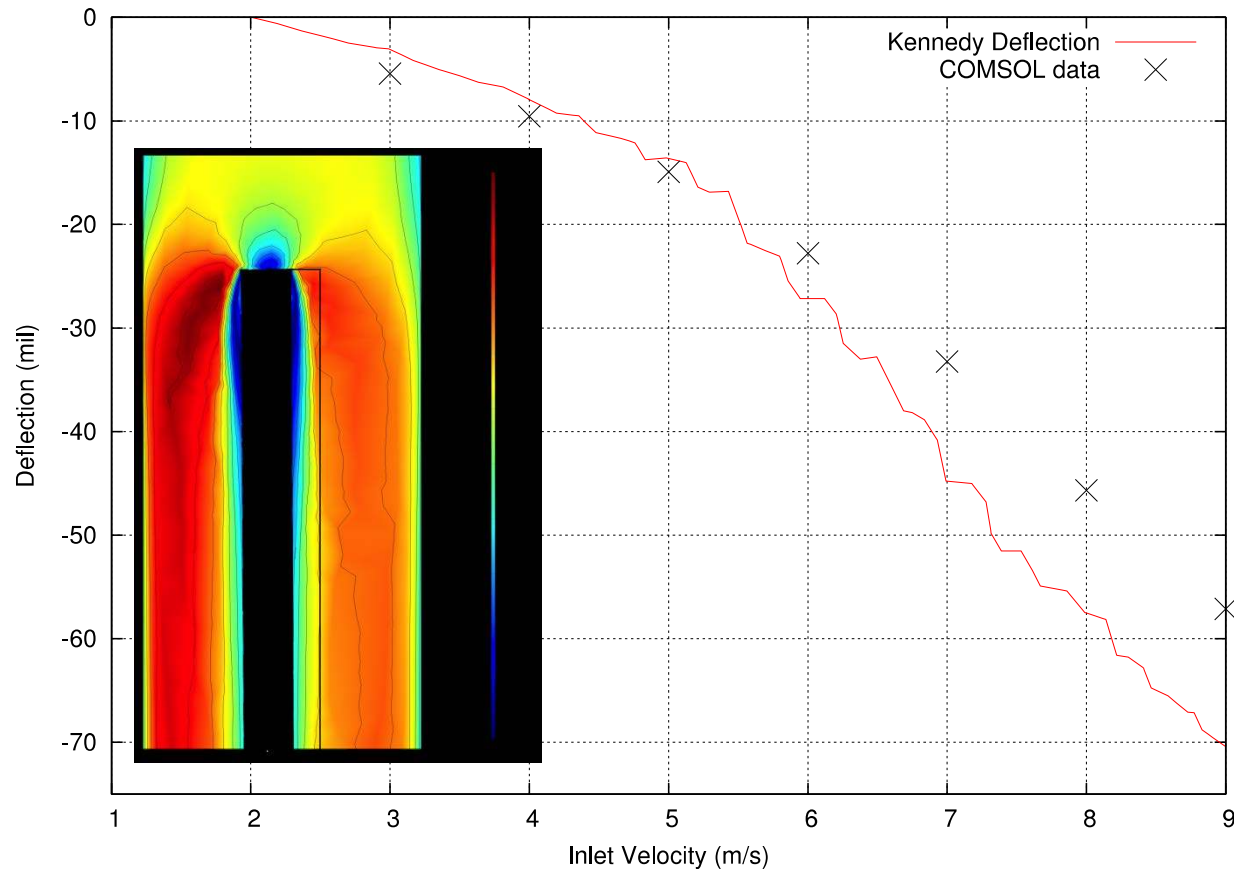
Results for Run 1 from Kennedy's report with a plate thickness of 40 mils.
There is no leading or trailing edge comb.

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Conclusion

- Experimental results play a major part in validating a code such as COMSOL for nuclear-related safety analysis.

- COMSOL has shown, through careful setup of the model and solving techniques, that it will perform the simulations needed to evaluate the fuel plates at HFIR.

- Calculation of both static and dynamic deflections for the curved HFIR plates will provide valuable insight into the high-speed flow performance of the HFIR core.

Questions

Extra Slides

ORNL/UTK FSI Benchmarking to Date

Cylinder in cross-flow: initial feasibility

- Tests both the CFD solver and FSI capabilities

- Experimental and numerical results are widely available for comparison

- Moving cylinder and stationary cylinder with moving, flexible tail

Flat Plate experiments: ongoing validation

- Smissaert – Multiplate experiment

- Marcum – Experiment and numerical results

- Kennedy – Experiment and numerical results

- Liu – Experimental results of dynamic plate deflection

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Cylinder in Cross-flow

- A predicted shedding frequency can be observed from a cylinder in cross-flow using the Strouhal number, $St = \dfrac{fD}{U}$

- For Reynolds numbers between 100 and 10^5 $St \approx 0.20$. Values outside of this range can be found in literature (White)

- This vortex shedding is a good test for a CFD solver and allows the testing of various FSI phenomena

F. M. White, Viscous Fluid Flow, Third Edition, New York: McGraw-Hill, 2005.

Cylinder in Cross-flow Cont.

Cylinder with tail case

- Cylinder is stationary

- A flexible tail, attached to the back of the cylinder, is allowed to move based upon the shedding of the cylinder

- Large deflections are observed that demonstrate the robustness of the moving mesh solver of COMSOL

- This work was proposed by Turek *et al.* as a good test of FSI capabilities

S. Turek and J. Hron, "Proposal for Numerical Benchmarking of Fluid-Structure Interaction between an Elastic Object and Laminar Incompressible Flow," Institute for Applied Mathematics and Numerics, University of Dortmund, Dortmund, Germany, 2004.

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Cylinder in Cross-flow Results: Cylinder with Tail

All three test cases have been run and the parameters for each case are presented below:

Parameter	FSI1	FSI2	FSI3
$\varrho^s \left[10^3 \frac{kg}{m^3}\right]$, density of tail	1	10	1
ν^s, Poisson's ratio of tail	0.4	0.4	0.4
$\mu^s \left[10^6 \frac{kg}{ms^2}\right]$, shear modulus of tail	0.5	0.5	2.0
$\varrho^f \left[10^3 \frac{kg}{m^3}\right]$, density of fluid	1	1	1
$\nu^f \left[10^{-3} \frac{m^2}{s}\right]$, kinematic viscosity of fluid	0.2	1	2
$\overline{U}$, average inlet velocity	0.2	1	2
Reynolds number	20	100	200

Cylinder in Cross-flow Results: Cylinder with Tail

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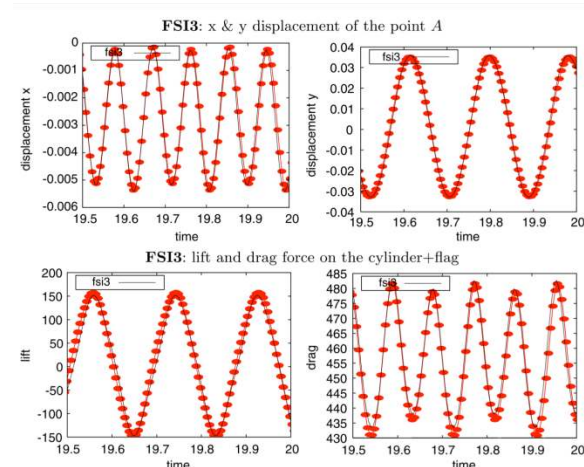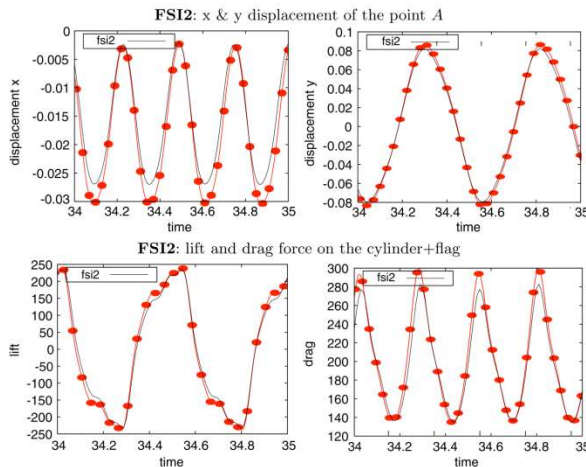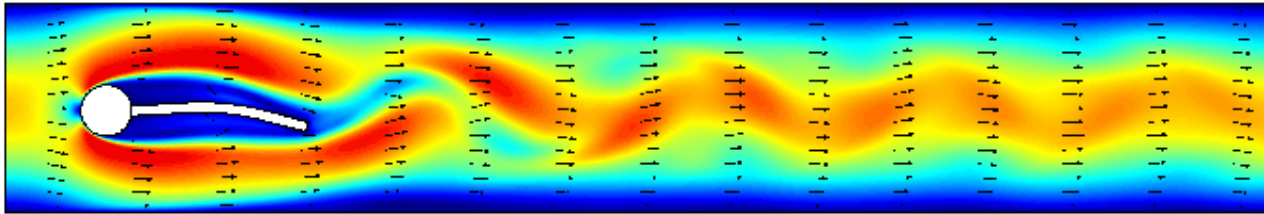
Cylinder in Cross-flow

Moving cylinder case

- Cylinder is allowed to move based upon the lift created by the shedding vortices (free displacement)

- Cylinder is moved at a specified displacement and frequency (prescribed displacement)
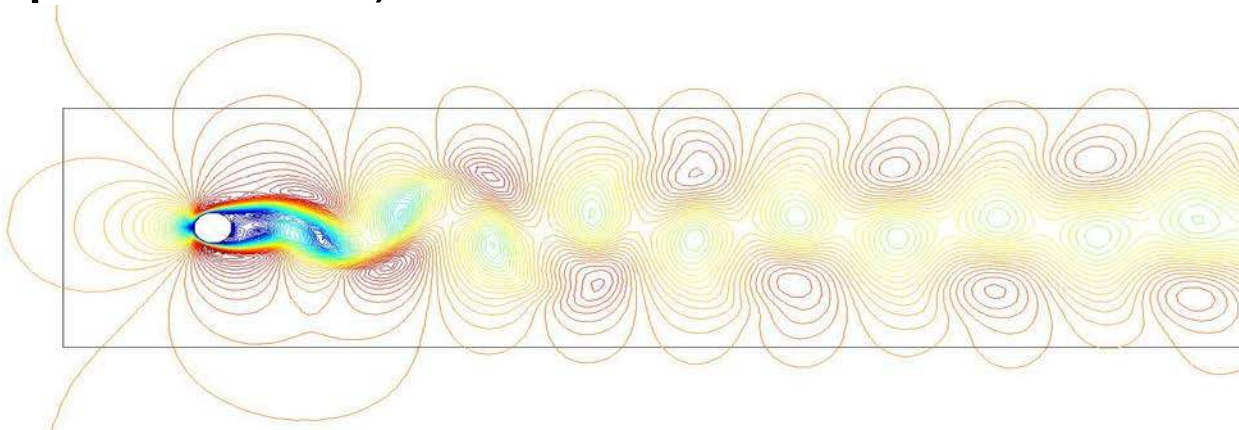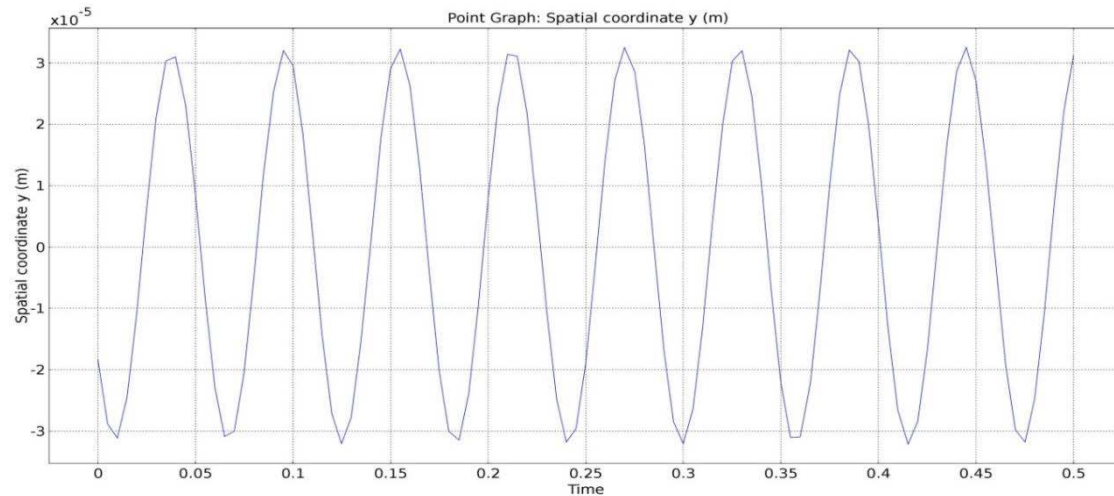
Cylinder in Cross-flow Results: Free Displacement

Solved two different ways

- In 2D using the CFD solver combined with the ODE solver to simulate the cylinder response as a mass-spring-damper system:

- In 3D using the FSI module with all physics already implemented

Reynolds number of 100 with a predicted shedding frequency of 16.5 Hz. The cylinder should move at the same frequency.

Cylinder in Cross-flow Results: Free Displacement 2D

Results for the limit cycle of cylinder displacement for the 2D case. The cylinder should be moving at approximately 16 Hz.


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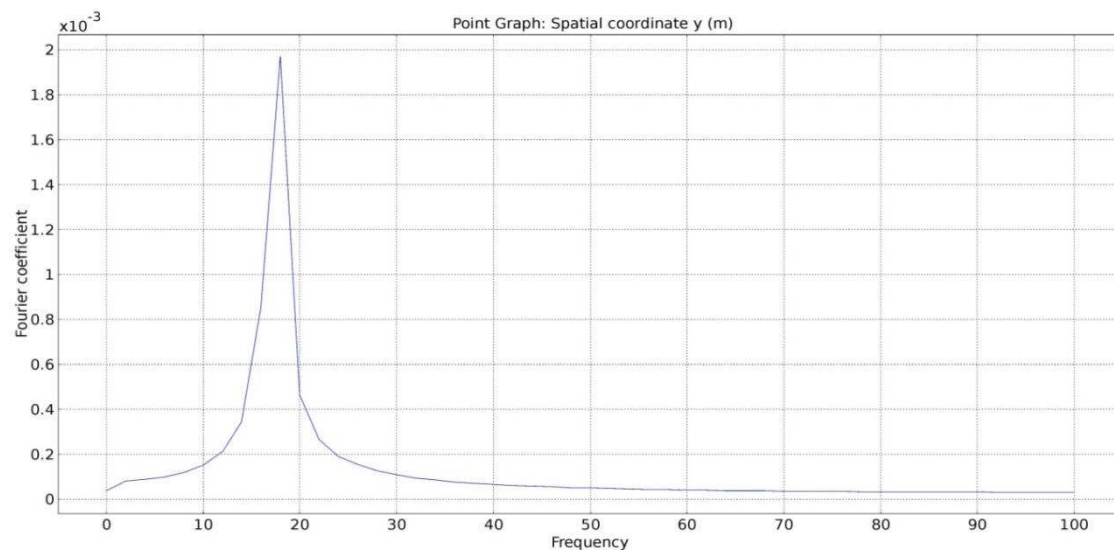
Cylinder in Cross-flow Results: Free Displacement 3D
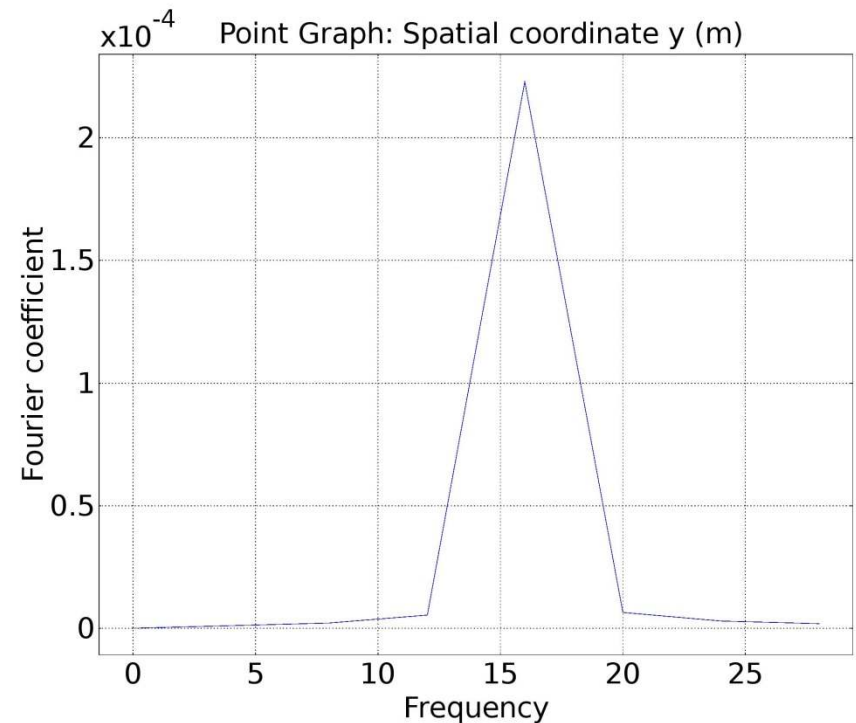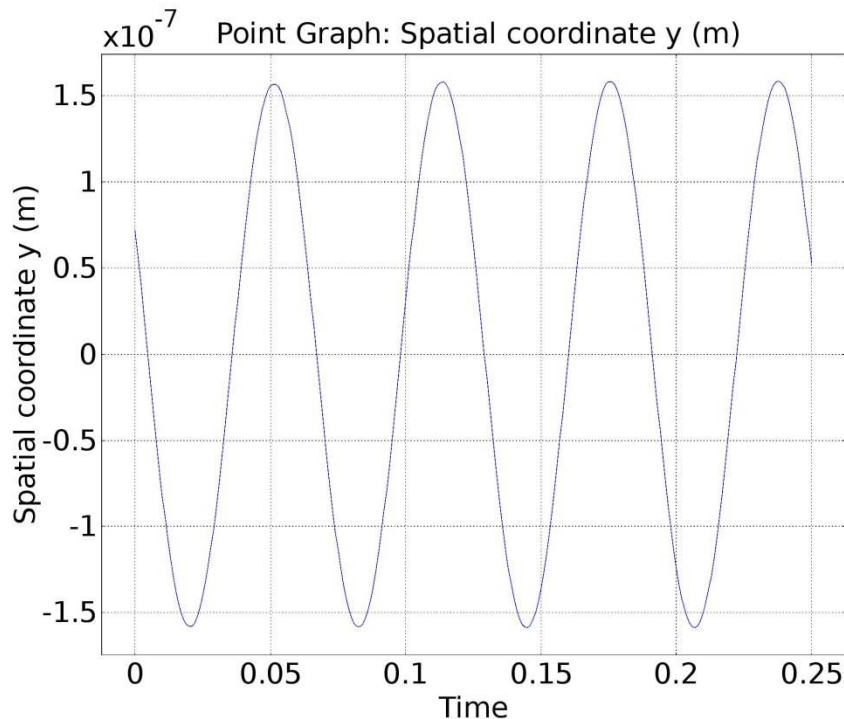
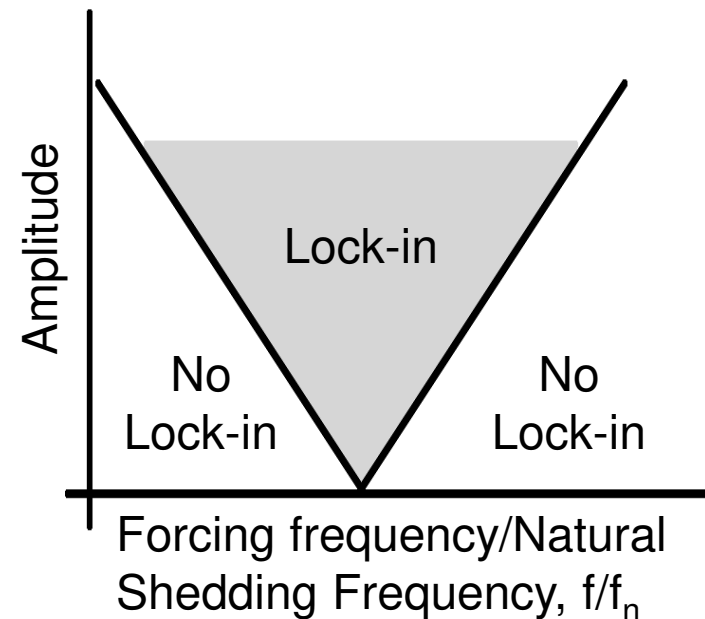The 3D results follow quite nicely with the 2D results.

A Note on Meshing

The quality of the mesh is very important to the results of the final solution. This was seen with the 2D cylinder in cross-flow as the cylinder began to drift up as it vibrated and did not oscillate about the cylinder's original position. It was discovered that the free mesh created was not symmetrical and caused an unexpected and unphysical result. This problem was alleviated by creating a uniform mesh.
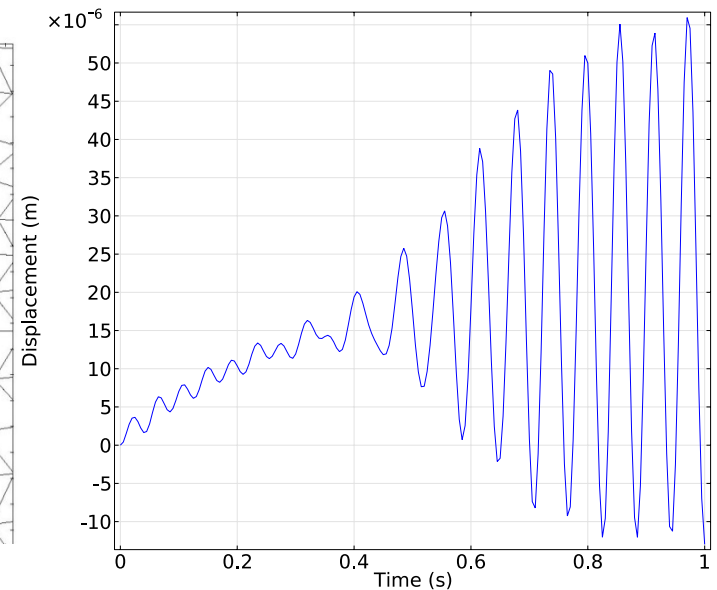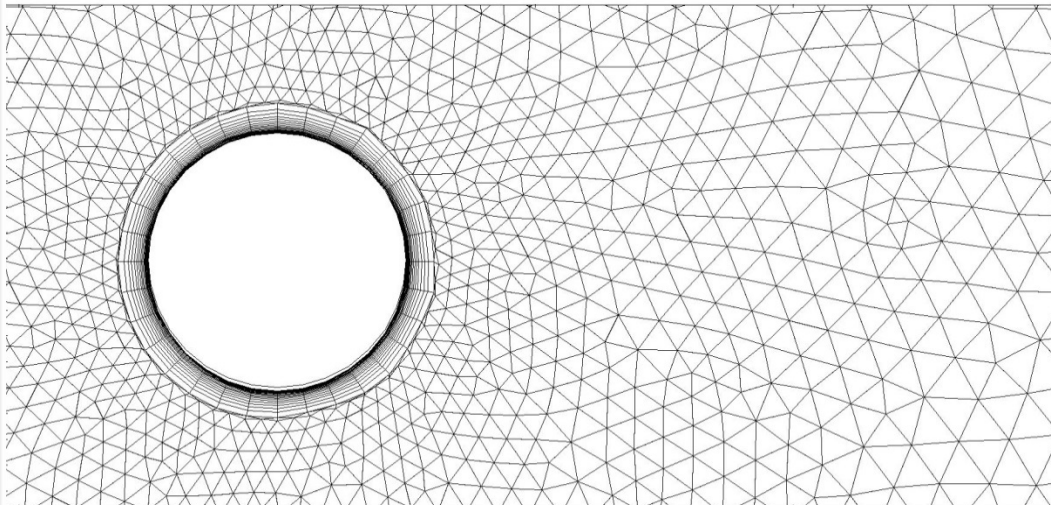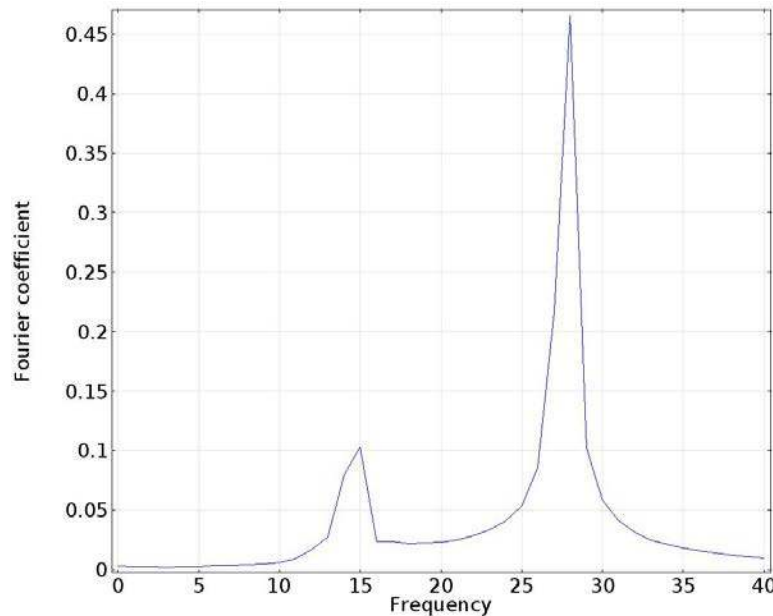
# Cylinder in Cross-flow Results: Prescribed Displacement

- Solved using the 2D FSI solver

- Depending on the amplitude and vibrational frequency, shedding will occur at the same frequency as the vibration (lock-in) or at the cylinder's natural shedding frequency (no lock-in) (Spiker)

Forcing frequency/Natural Shedding Frequency, f/f_n

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M. A. Spiker, "Development of an Efficient Design Method for Non-synchronous Vibrations", PhD Dissertation at Duke:2008.

Cylinder in Cross-flow Results: Prescribed Displacement

No lock-in case
Forcing frequency: 28 Hz
Shedding frequency: 15 Hz
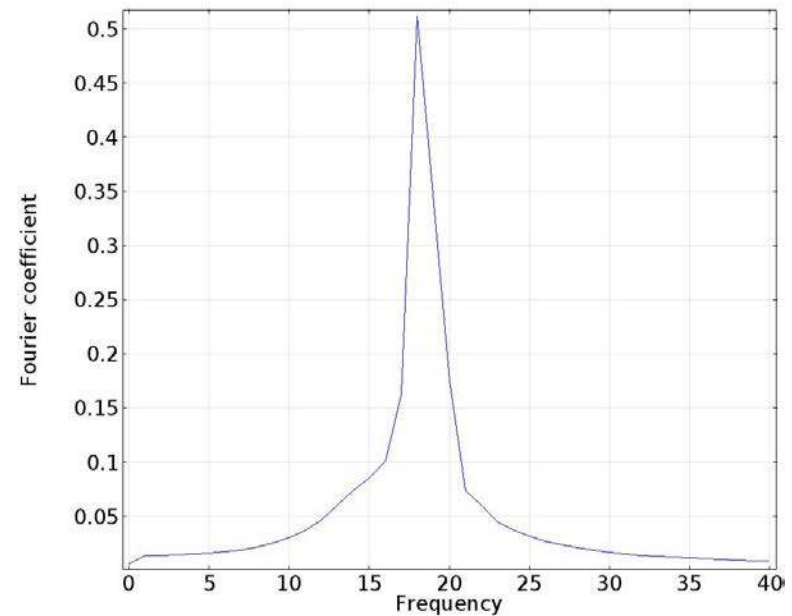
Lock-in case
Forcing frequency: 18 Hz
Shedding frequency: 18 Hz

Flat Plate Analysis: Smissaert Case

- Performed in 1968 at Penn State
- Utilized strain gages along the length of the plate to measure deflection
- Results for both static and dynamic deflection
- Plate Statistics
  - 58 mils thick
  - 4.5 in wide
  - 45 in long
  - 253 mils channel thickness
  - 5 Plates

Flat Plate Analysis
Smissaert Case: Results

Matched leading edge deflection
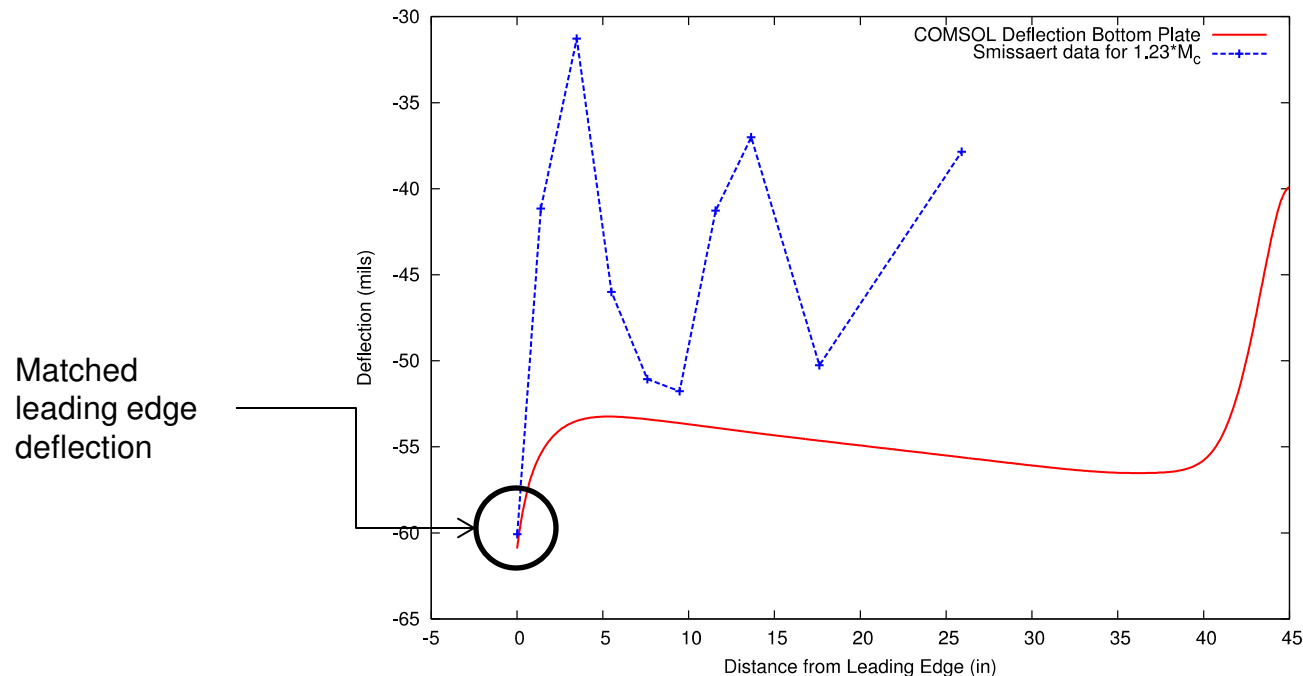
Using the stationary solver of COMSOL, the leading edge deflection was captured. This run was performed for two plates with periodic boundary conditions and was completed in approximately 2 hours on a 12 core machine. The transient solver captures more mode shapes but does not produce the maximum leading edge deflections.

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Flat Plate Analysis
Marcum Case

- Marcum performed a series of numerical simulations for the experiments to be performed at Oregon State

- The simulations only solved the Navier-Stokes equations and did not utilize FSI

- As data becomes available from OSU, the FSI results from COMSOL will be compared

- Plate Statistics
    - 50 mils thick
    - 4 in wide
    - 24 in long
    - Variable channel thickness
    - 7 plates

    - velocity = 14 m/s
    - exit pressure = 464.7 psig
    - pressure drop ≈ 55 psi
   - Reynolds Number = 1.4e5

Flat Plate Analysis
Marcum Case: Results
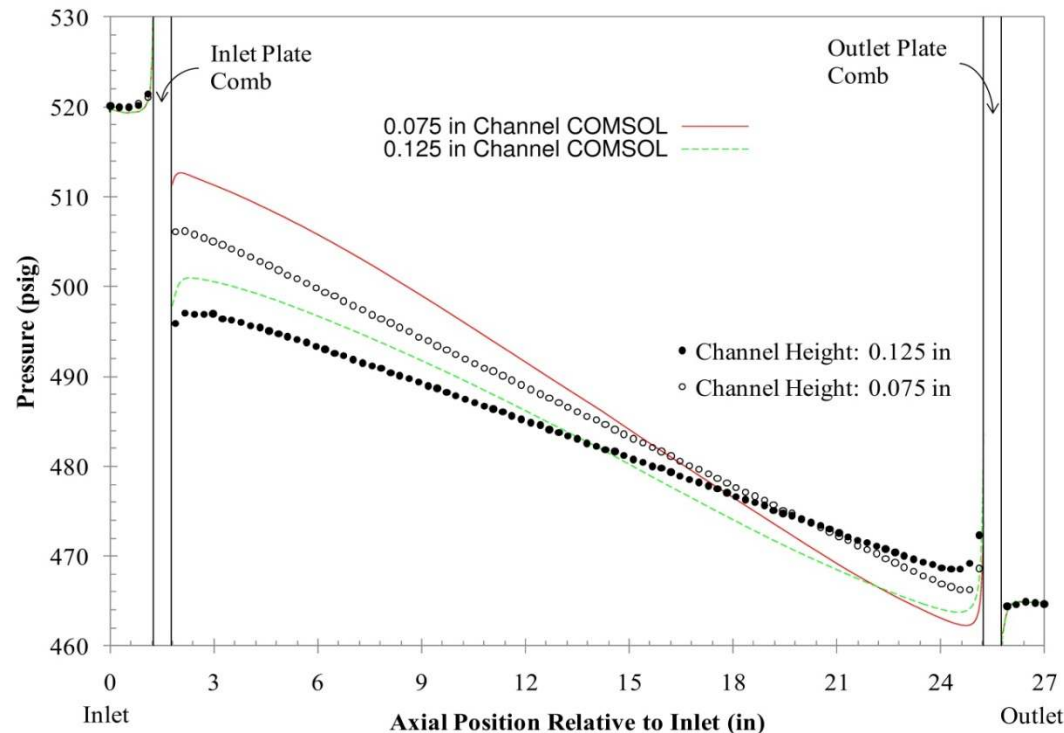
Comparison of the two plate case performed by Marcum using Star-CCM+.
In order to obtain a converged solution in COMSOL, it was necessary to
add artificial dissipation and this may explain the inconsistencies in the
pressure profiles. It was unclear whether Star-CCM+ included any
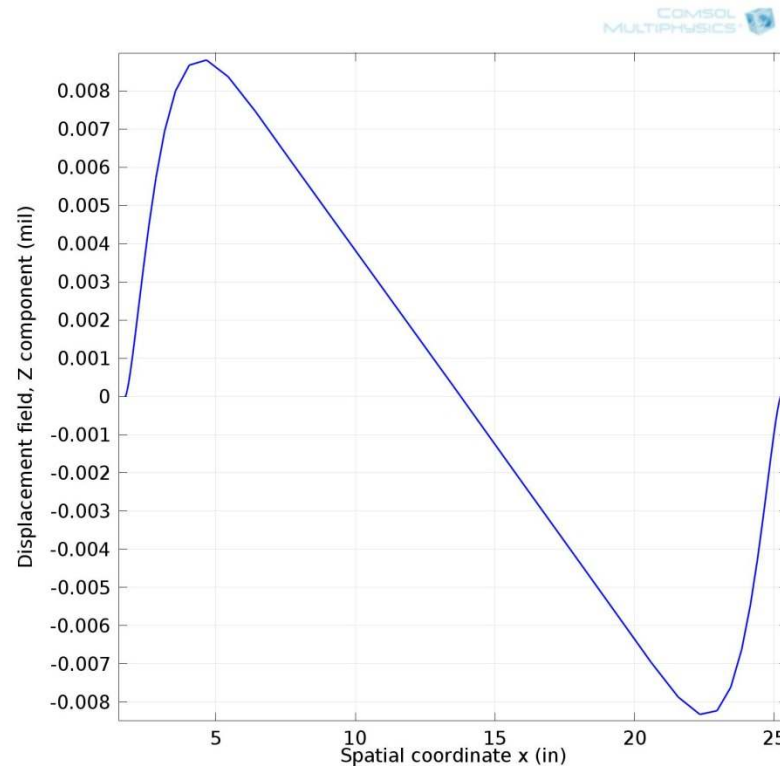dissipation.

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Flat Plate Analysis
Marcum Case: Results
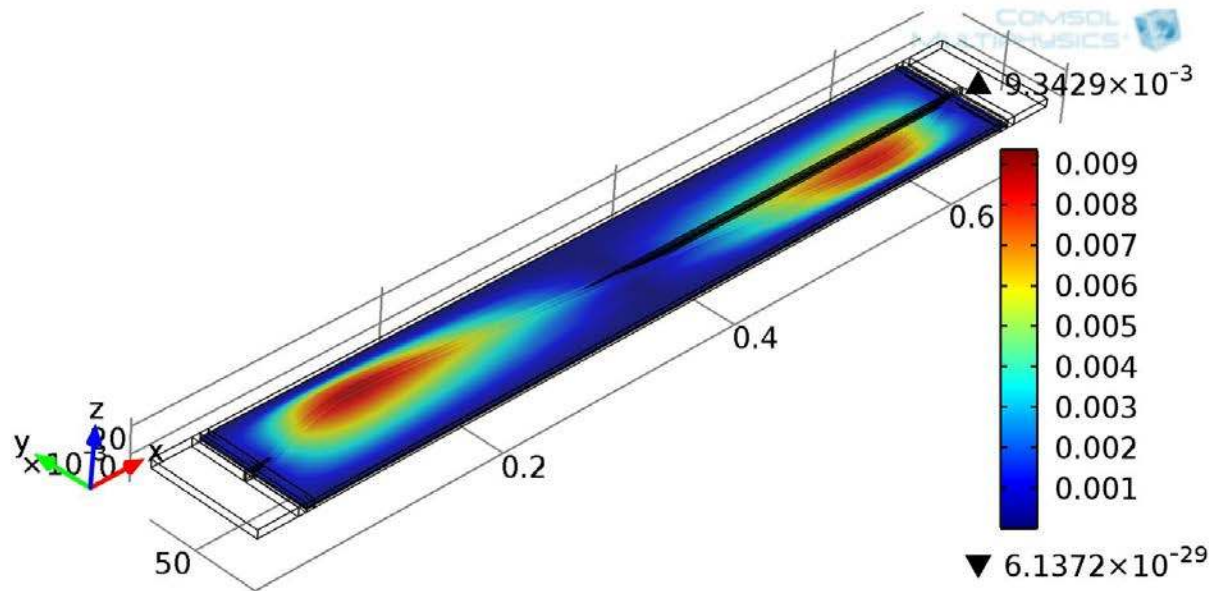
Preliminary 3D FSI results for the single plate, two channel case.
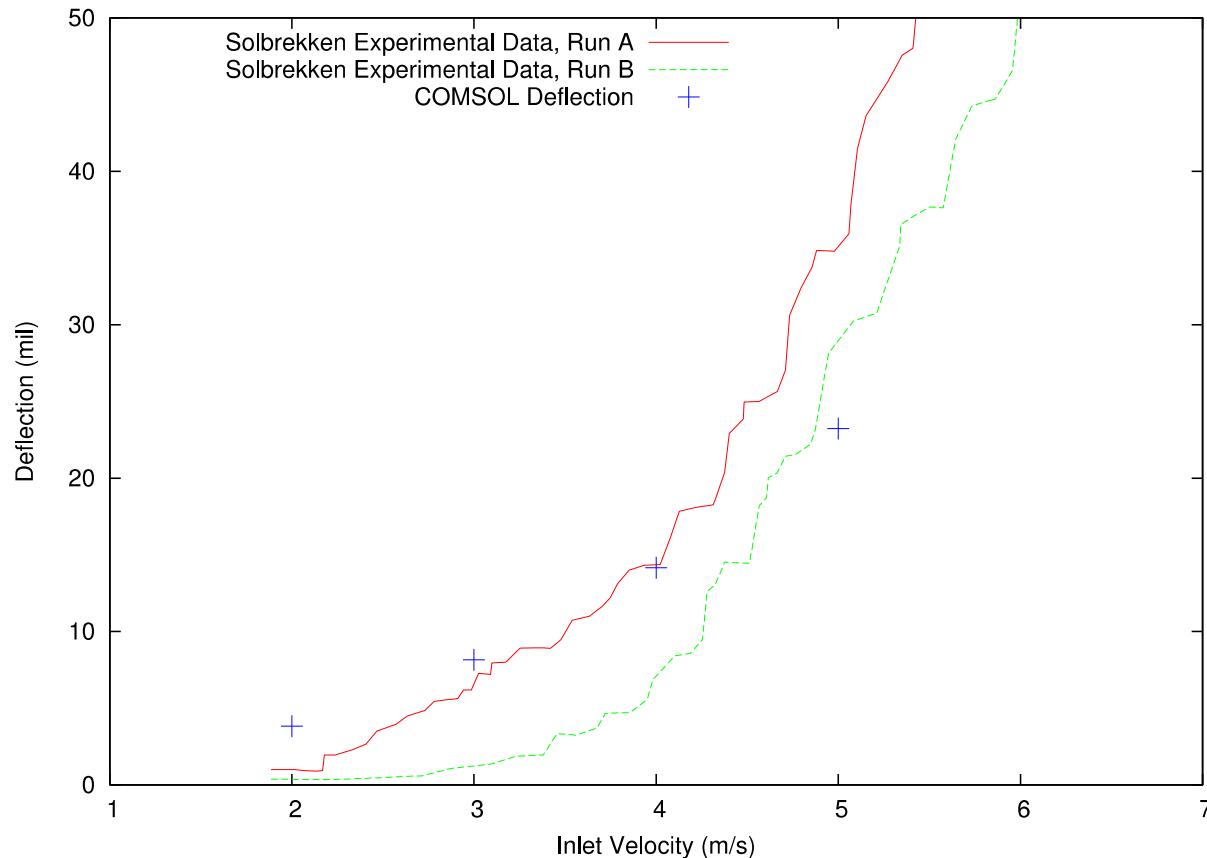
Flat Plate Analysis
Marcum Case: Results

Preliminary results of the deflection along the center line of the plate for the single plate, two channel case.
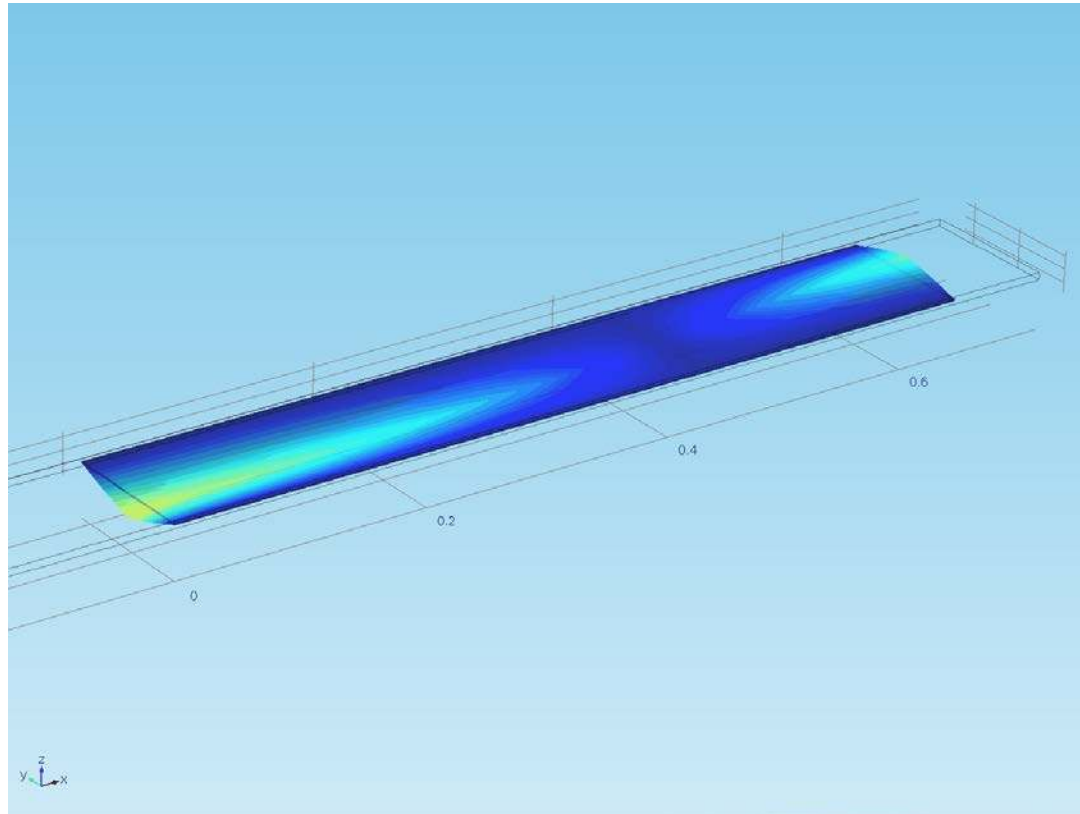
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Flat Plate Analysis
Kennedy Case: Results

Results for Run 4 from Kennedy's report with a plate thickness of 32 mils.
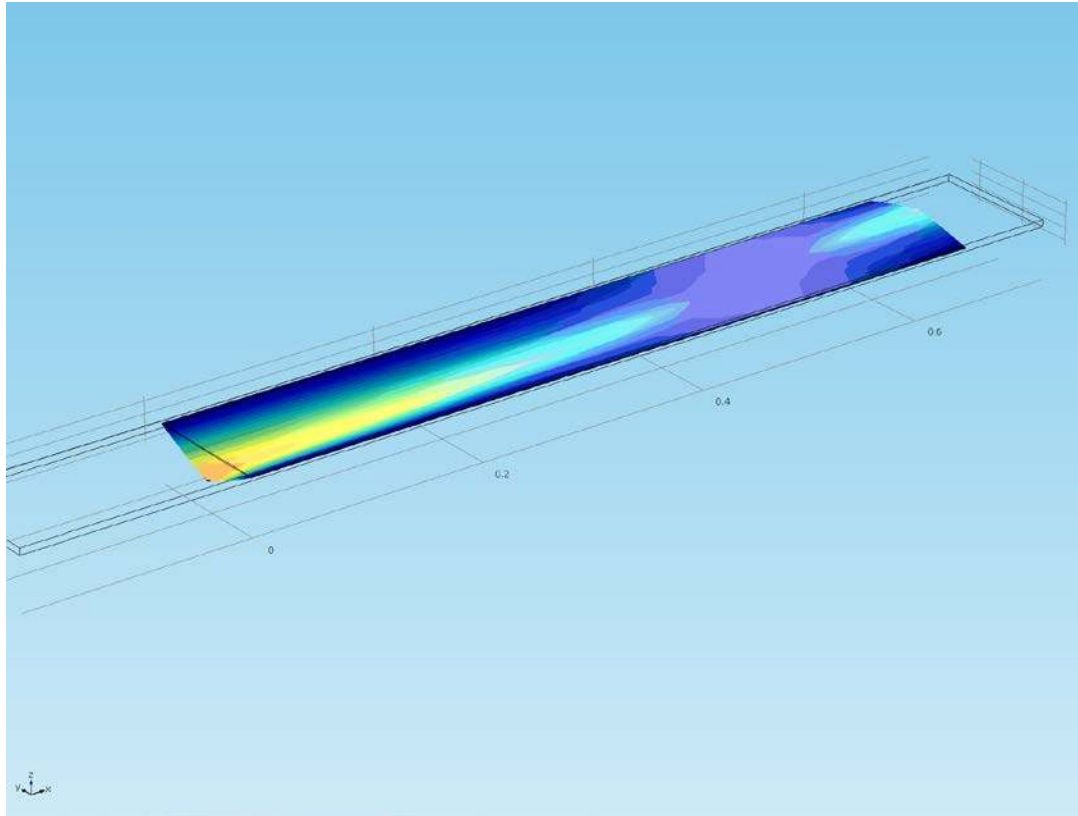There is no leading or trailing edge comb.

Flat Plate Analysis
Kennedy Case: Unstable Results

Unstable results for 7 m/s inlet velocity.

Flat Plate Analysis
Kennedy Case: Unstable Results

Stable results for 7 m/s inlet velocity.

Flat Plate Analysis
Liu Case

- Liu *et al.* performed an experimental test to examine self-induced dynamic deflection of flat plates

- The experiments used a clear, plastic channel to allow deflection measurements using a laser

- The plates are not held fixed along the entire length of the channel, only at the four corners of the plate.

- Plate Statistics
  - 1 mm, 39.4 mils thick
  - 80mm, 3.15 in wide
  - 850mm, 33.5 in long
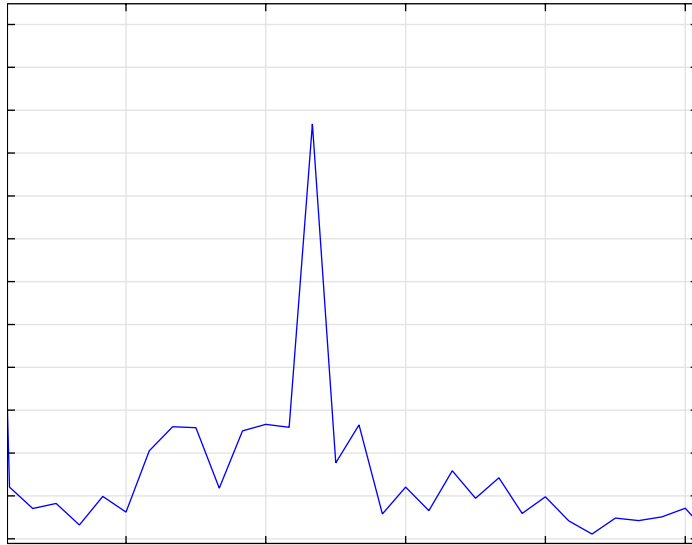 - 11mm, 433 mils channel thickness
  - 1 plate

Flat Plate Analysis
Liu Case: Results
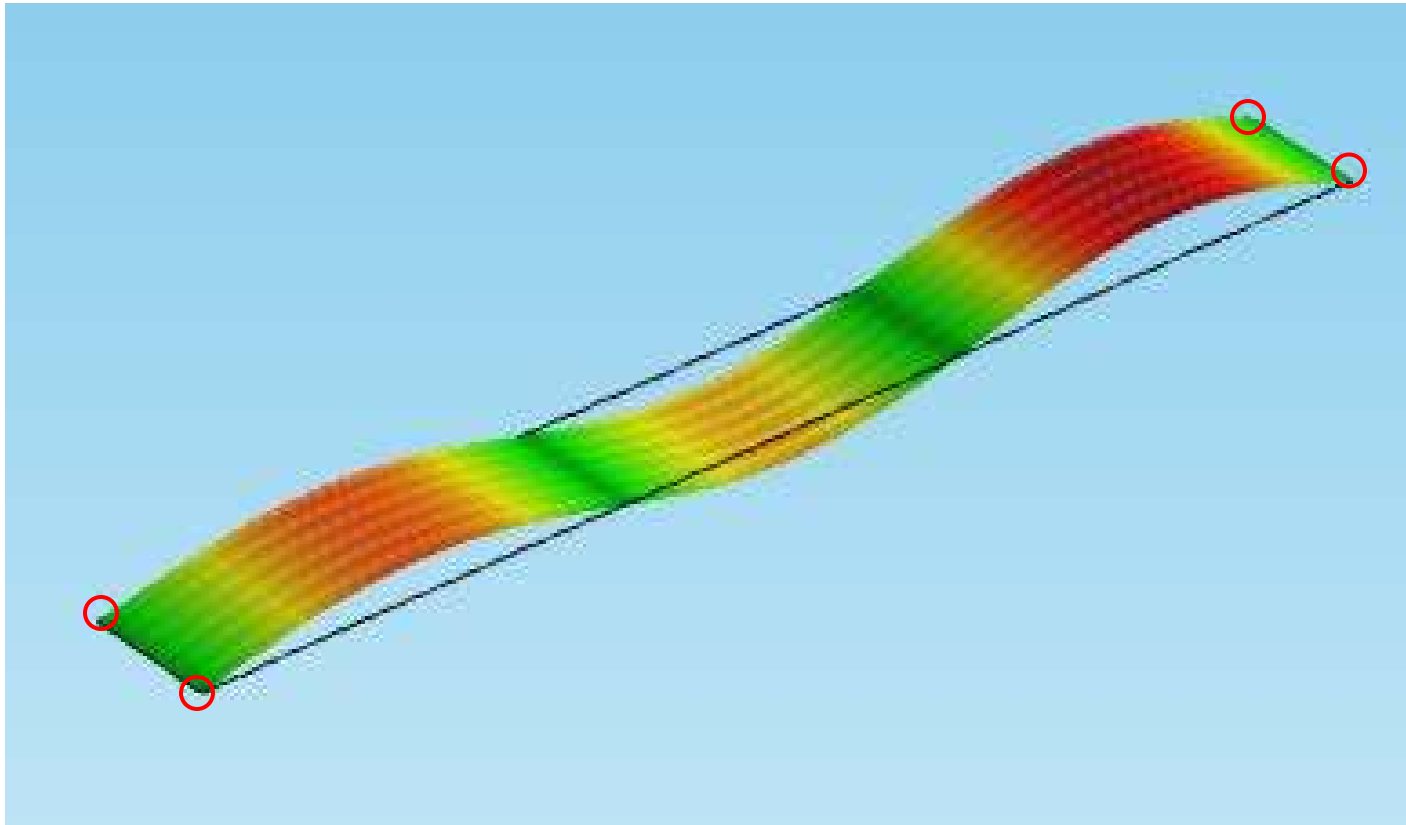
Snap shot of the dynamic deflection of the plate. The red circles indicate the fixed corners of the plate.

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Flat Plate Analysis
Liu Case: Results

Fast Fourier Transform of the periodic deflection of the flat plate solution from COMSOL.

For an inlet velocity of 1.19 m/s, the flat plate vibrated at 0.27 Hz in the experiment. Using the fully coupled FSI solver in COMSOL, a self-induced dynamic deflection was obtained. Studies of the effects of time-step size, mesh size, and channel size are being conducted in order to establish a better solution.

Flat Plate Analysis
Liu Case: Results

- The velocities involved in this experiment are much lower than those seen in the HFIR.

- The deflections are much larger than those that would be seen in the HFIR.

- If COMSOL can match this data, it should bound the difficulty envelope we expect to see in our analysis.

- This time dependent problem has already helped to establish better simulation techniques for the transient solver.