Computational Modeling of the HyMAX Experiment in Support of a New Aeroelastic Experimental Design

07/22/25

Harry Xu and Earl Dowell

Duke University, Department of Mechanical Engineering and Material Science

Duke | AEROELASTICITY

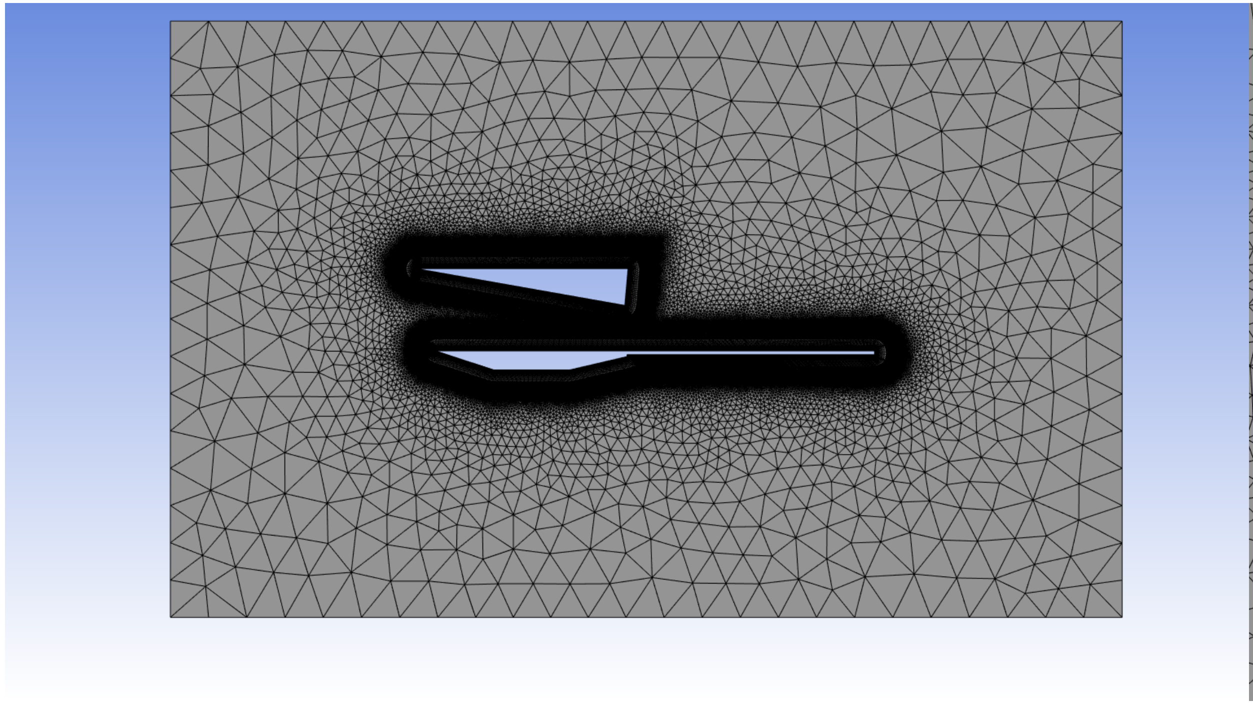
Background

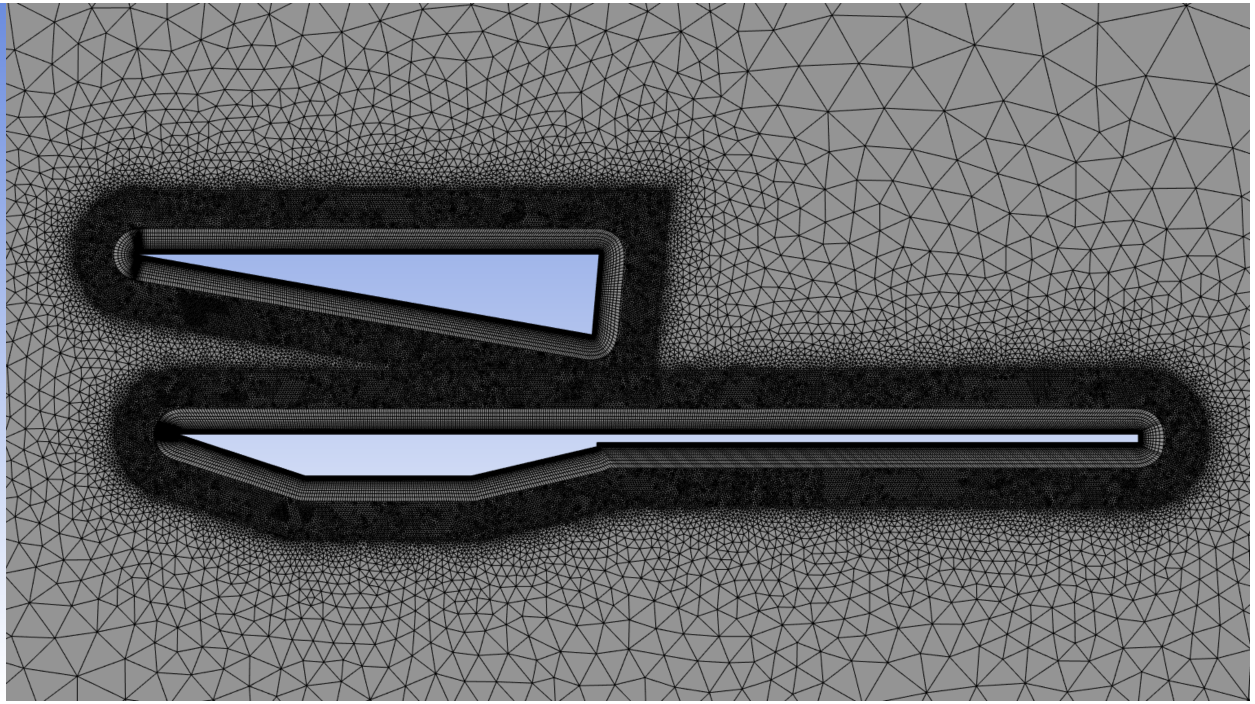
- One of two test cases for the High-Speed Working Group
- A hypersonic cantilevered plate experiment performed by University of New South Wales (UNSW) Canberra at The University of Southern Queensland (TUSQ) Ludwieg tube
  - A flexible cantilevered plate attached to a stand
    - L = 130 mm, h = 2mm, b = 80 mm
  - Optional shock generator above the setup
    - 2 primary cases – 2 degrees and 10 degrees
    - Optional – Oscillating wedge (5 degrees ± 3 degrees)
  - Test Conditions (freestream values)
    - M = 5.8
    - T = 75 K
    - P = 755 Pa
    - Re = 7.1e6 /m

- Solver used was FUN3D v14.2
  - 2D Mode, Riemann (farfield) BC on the edges of the domain, symmetry BC on the spanwise boundaries, no-slip walls
  - Turbulence Model: SA-neg with Reynolds Stress Model (QCR2000) and Rotation and Compressibility corrections
  - ALDFSS flux construction, Venkatakrishnan limiter
  - Optimized second-order backward differencing in time
  - Δt = 1e-3 (5.76e-6 s)
  - Referenced off prior study by Bartels[1]
- Utilized built-in aeroelastic modal solver
  - Two step process
    - Obtain a steady state solution with no motion
    - Restart from steady flow field with motion enabled and zero applied structural damping

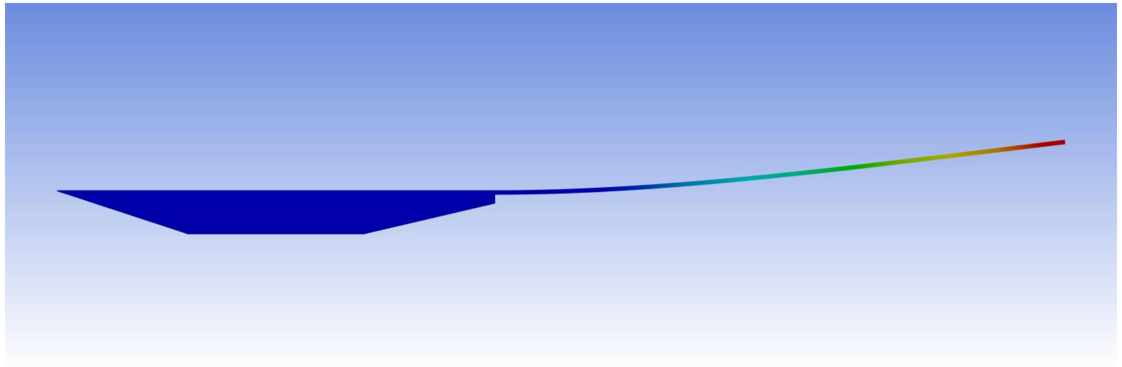
[1]Bartels, R., "NASA Langley Research Center Contributions to the 3rd AePW High-Speed Working Group – HyMAX Computational Aeroelastic Predictions," AIAA SciTech, 2023, https://ntrs.nasa.gov/api/citations/20230000286/downloads/LaRC_HyMAX_presentation_1-21-2023.2.pdf

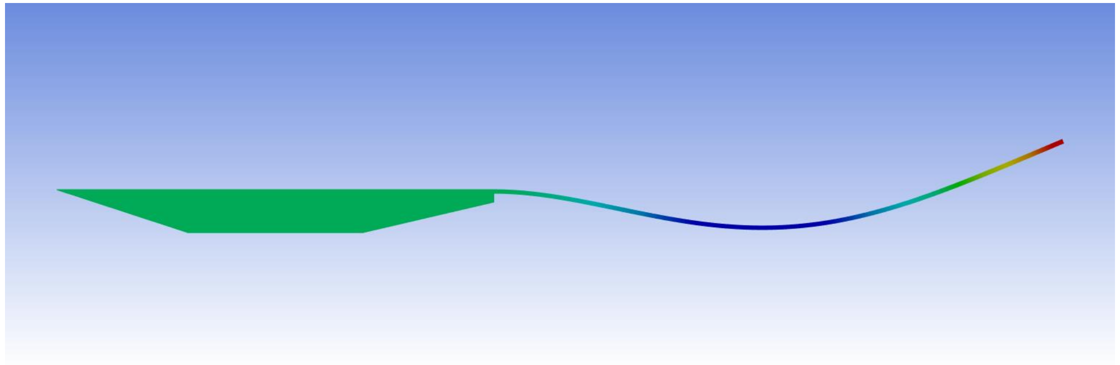
- Unstructured mesh with inflation layer
  - Coarse mesh in the farfield
  - Two areas of refinement – around the shock generator and test section
  - Inflation layer with Δz = 3e-6 m the on the shock generator and test section
    - y+ < 1 along the plate





- Only two structural modes used in the simulations



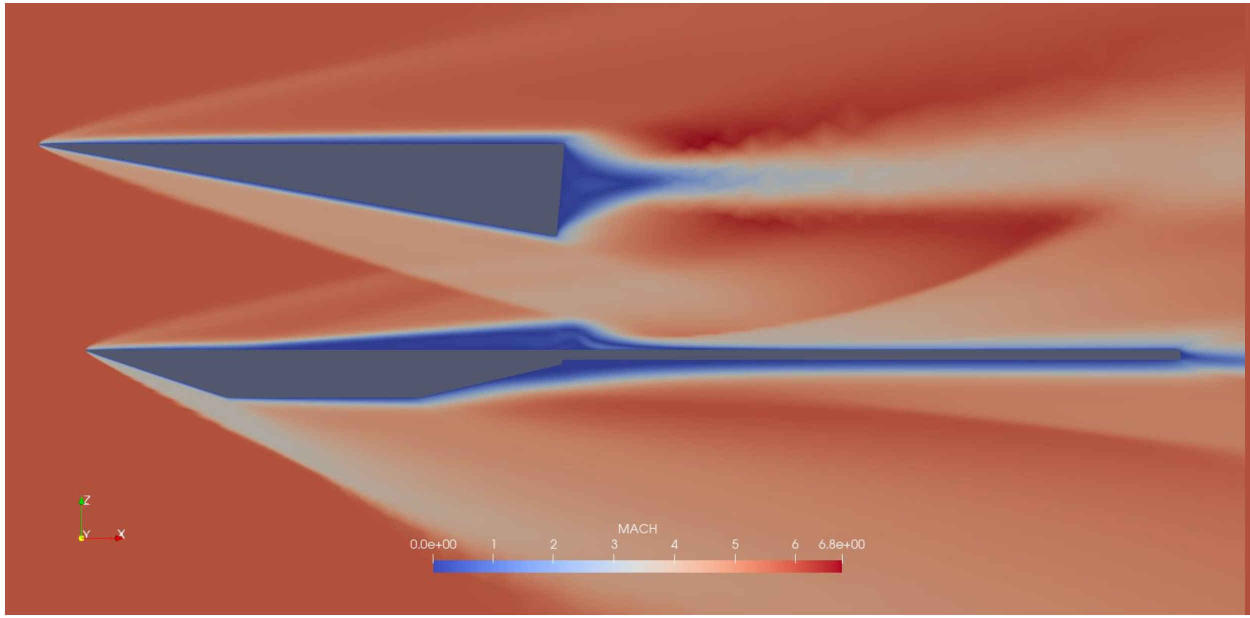


- Fixture and plate included, with fixed boundaries conditions applied to the fixture
- Material properties from the 2019 paper[2]
  - E = 52.7 GPa, r = 2670 kg/m^3, η = 0.33
- Ansys Mechanical used to obtain mode shapes and frequencies
  - 1st mode - 84.723 Hz, 2nd mode - 530.41 Hz
  - From the paper, 1st mode – 83 Hz

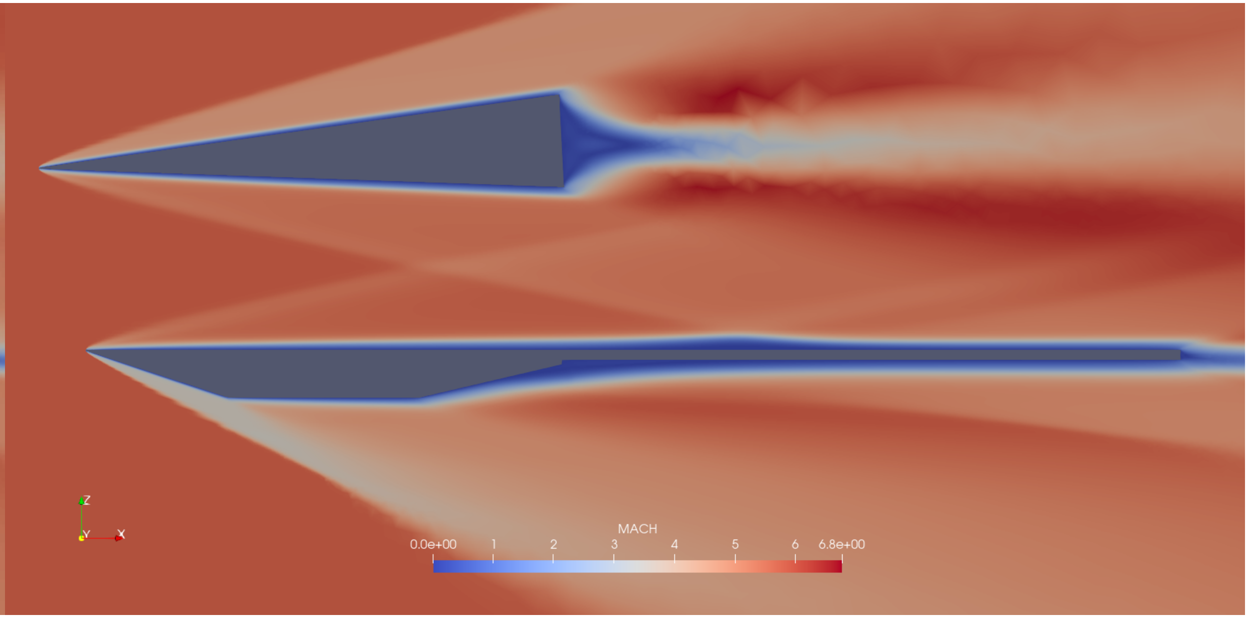
[2]Currao, G., Neely, A., Kennell, C., Gai, S., and Buttsworth, D., "Hypersonic Fluid–Structure Interaction on a Cantilevered Plate with Shock Impingement," *AIAA Journal*, Vol. 57, No. 11, 2019, pp. 4819-4834. https://doi.org/10.2514/1.J058375

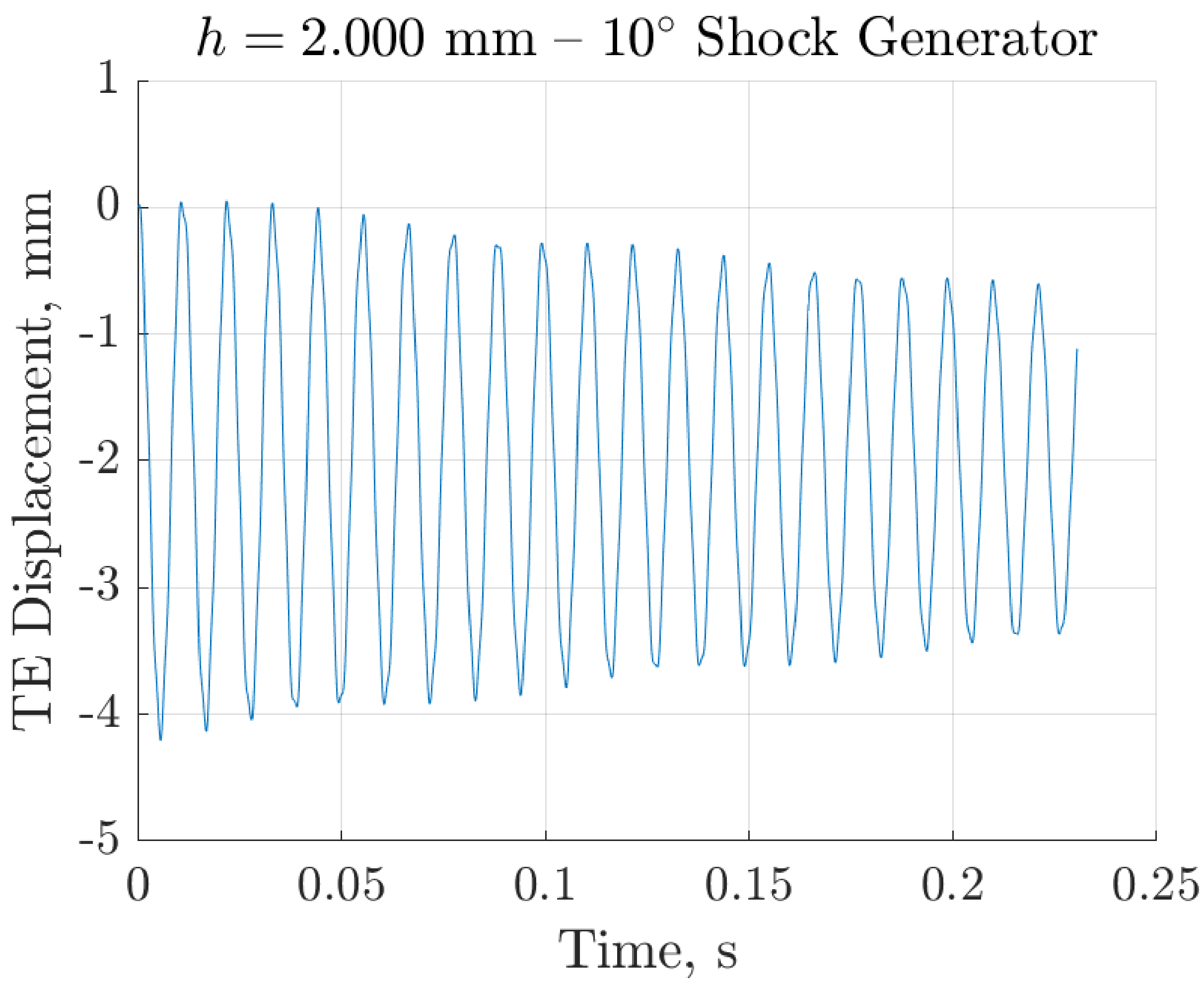
Mach Contours

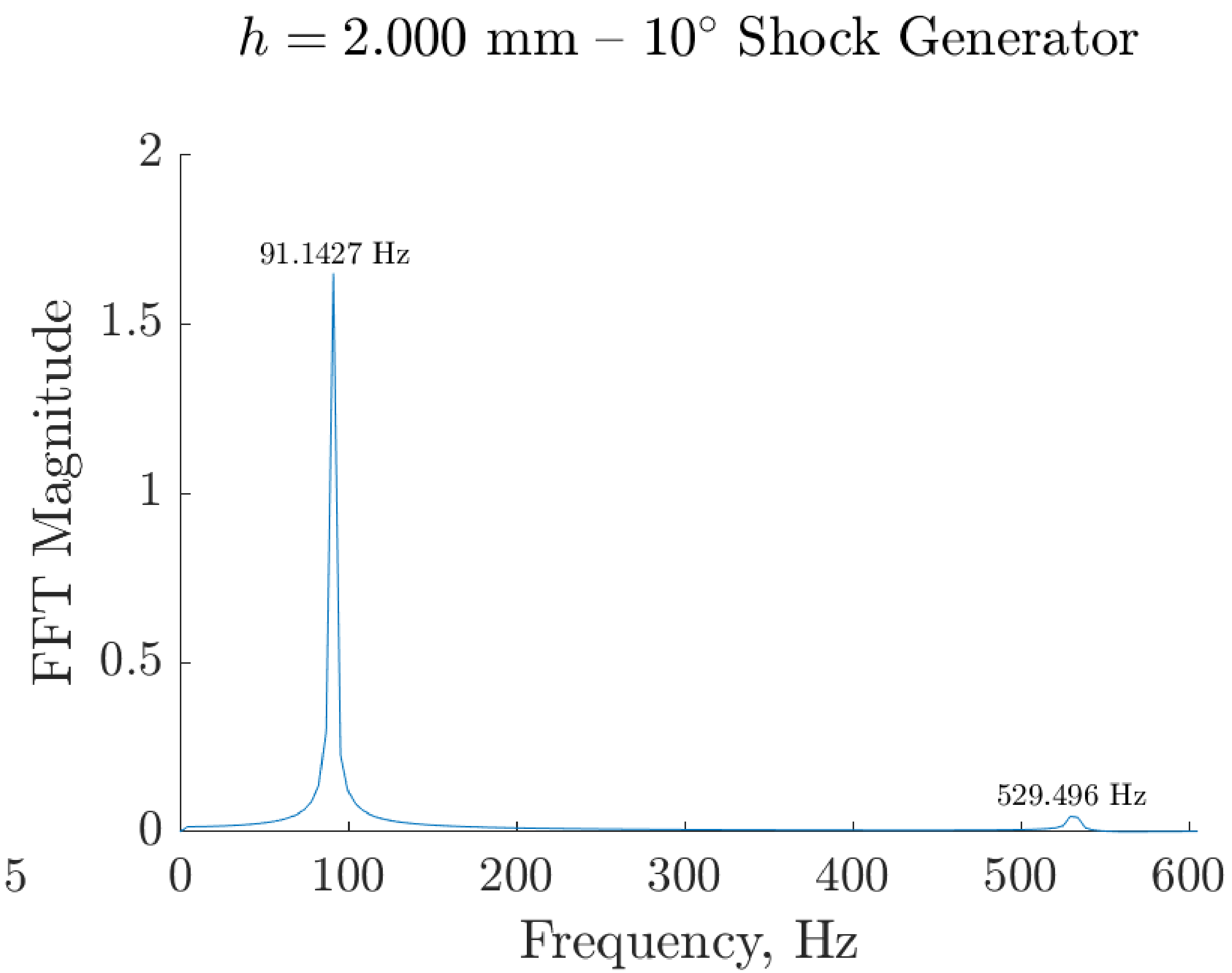
10° Wedge



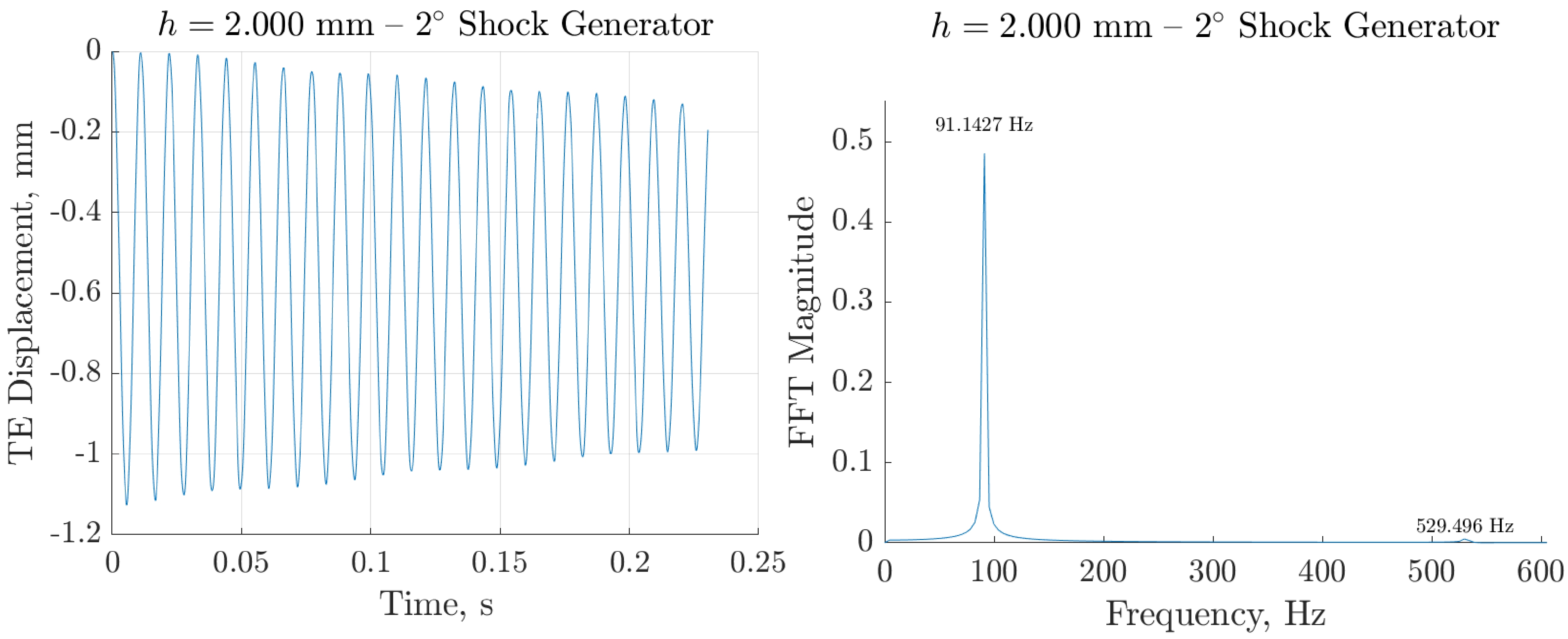
2° Wedge



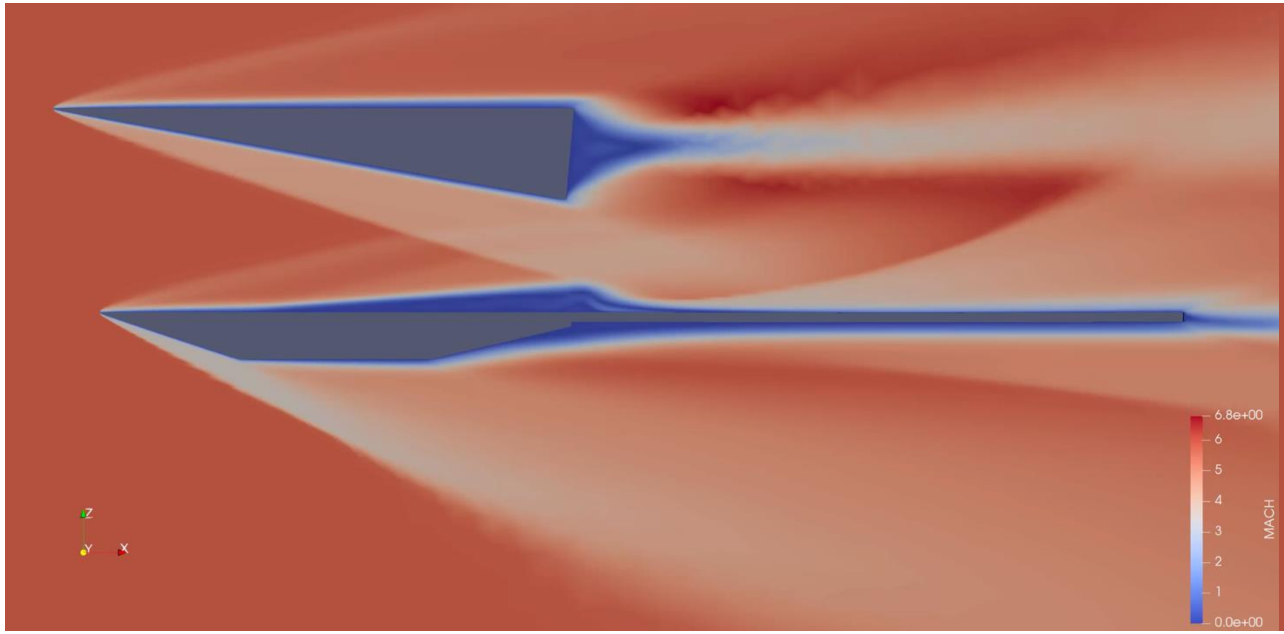




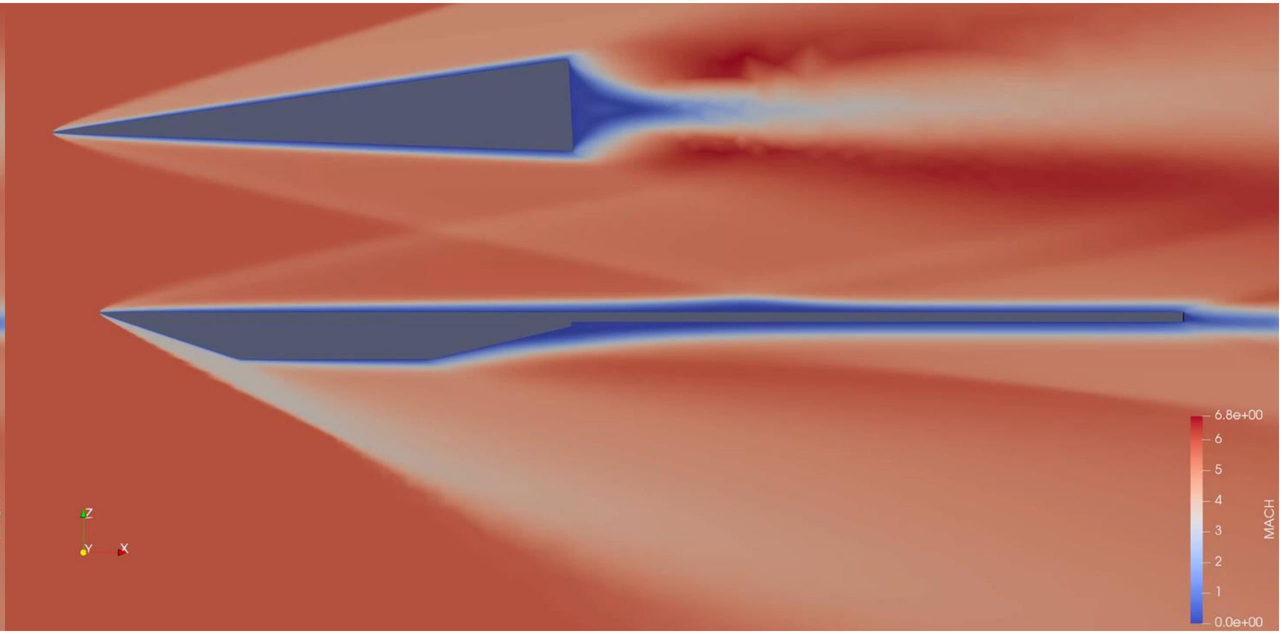
Duke | AEROELASTICITY

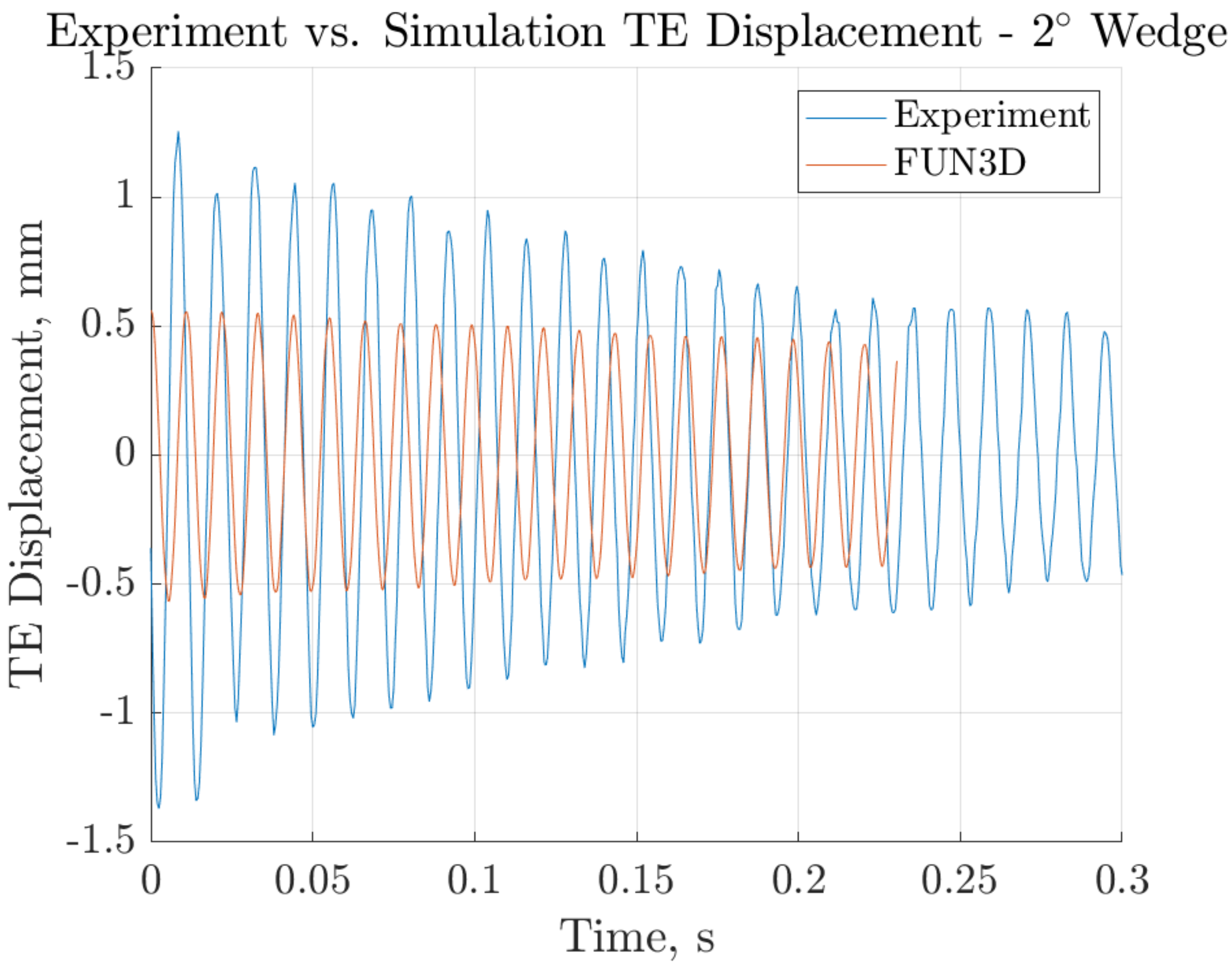

$h = 2.000$ mm – 2° Shock Generator
TE Displacement, mm
Time, s
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
0
0.05
0.1
0.15
0.2
0.25
$h = 2.000$ mm – 2° Shock Generator
FFT Magnitude
Frequency, Hz
91.1427 Hz
529.496 Hz
0
0.1
0.2
0.3
0.4
0.5
0
100
200
300
400
500
600

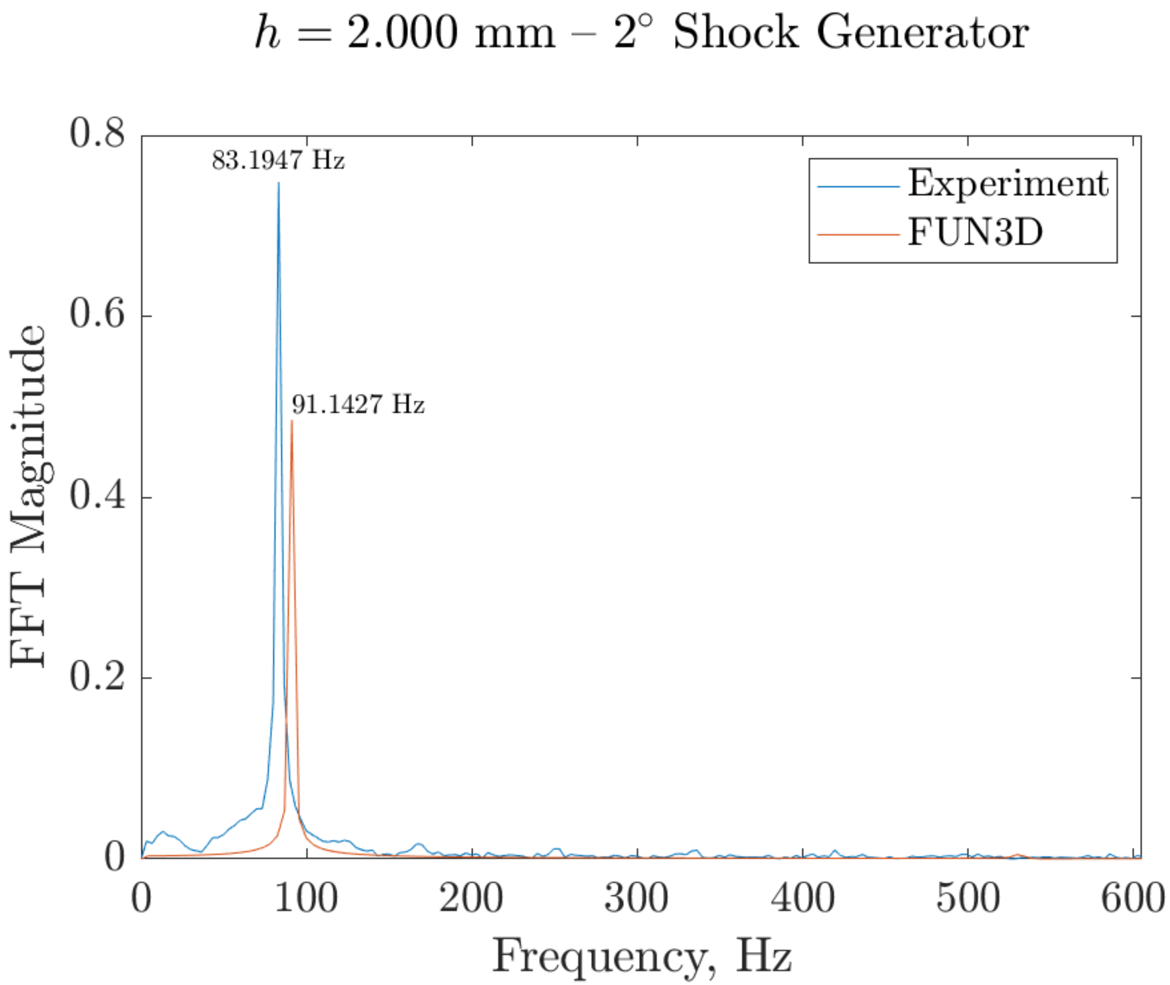
10° Wedge



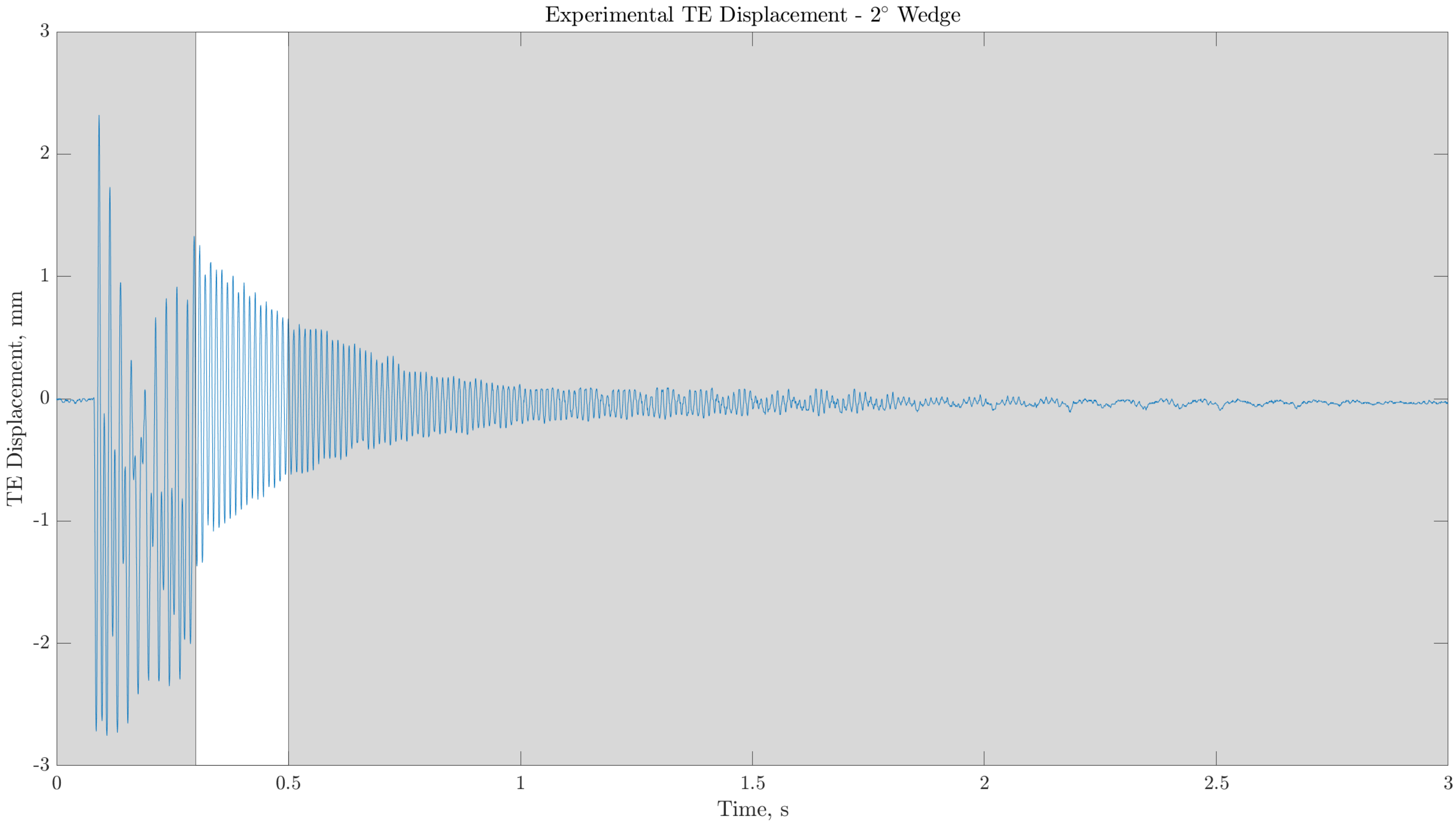
2° Wedge







Duke | AEROELASTICITY



Duke | AEROELASTICITY

- Predicting flutter boundary through an analytical parameter
  - Strong sensitivity to aerodynamic to structural compliance ratio, shown by McHugh et al.[3]

$$\Lambda = \frac{\rho U^2 L^3}{MD}$$

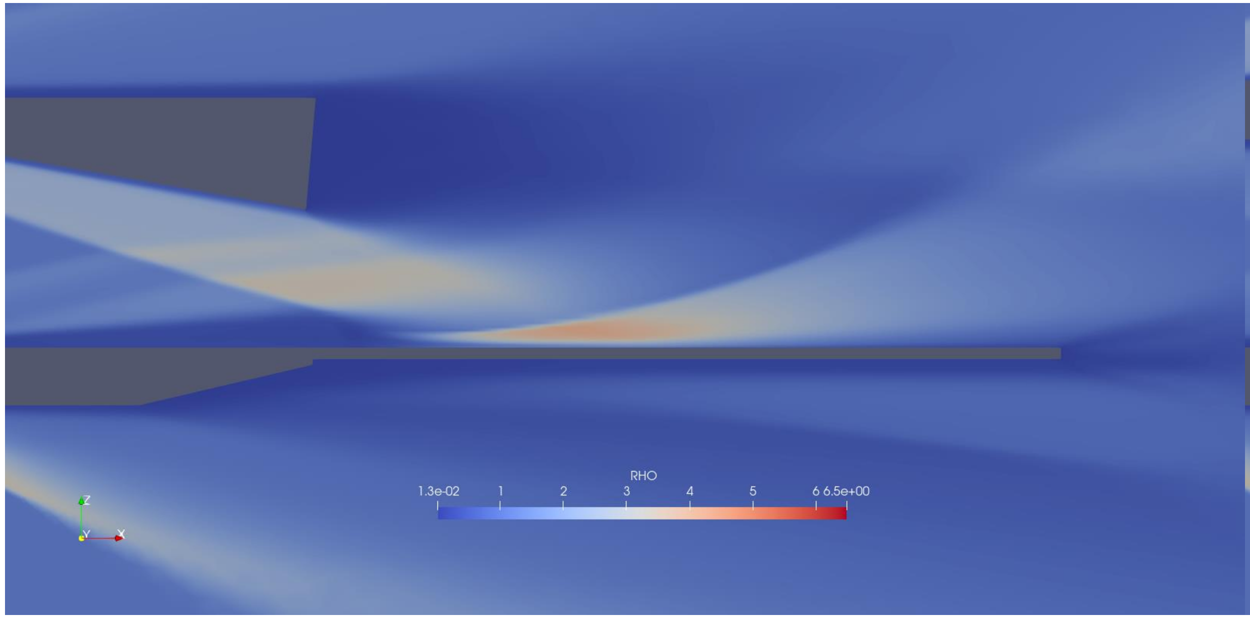
$$D = \frac{Eh^3}{12(1-\nu^2)}$$

  - Depends on flow parameters
    - Free-stream vs. local parameters (post-shock impingement)

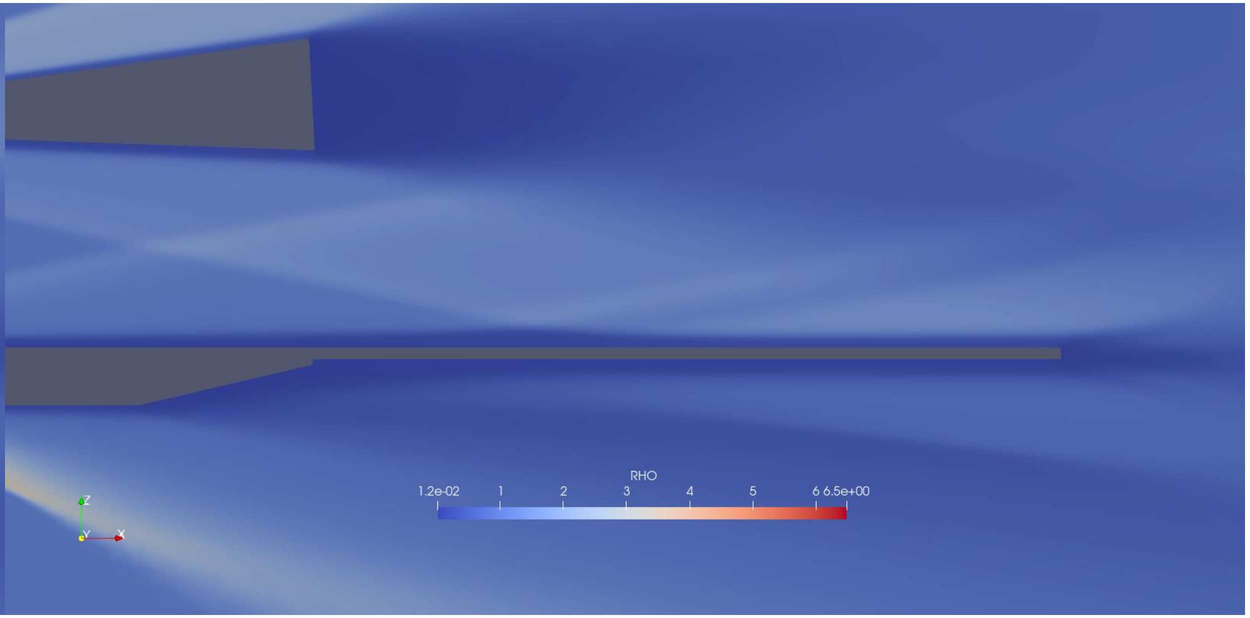
[3]McHugh, K.A., Fredin, M., Kruger Bastos, K., Beran, P., and Dowell, E.H., “Flutter and Limit Cycle Oscillations of Cantilevered Plate in Supersonic Flow,” *Journal of Aircraft,* Vol. 58, No. 2, 2021, pp. 266-278. https://doi.org/10.2514/1.C035992

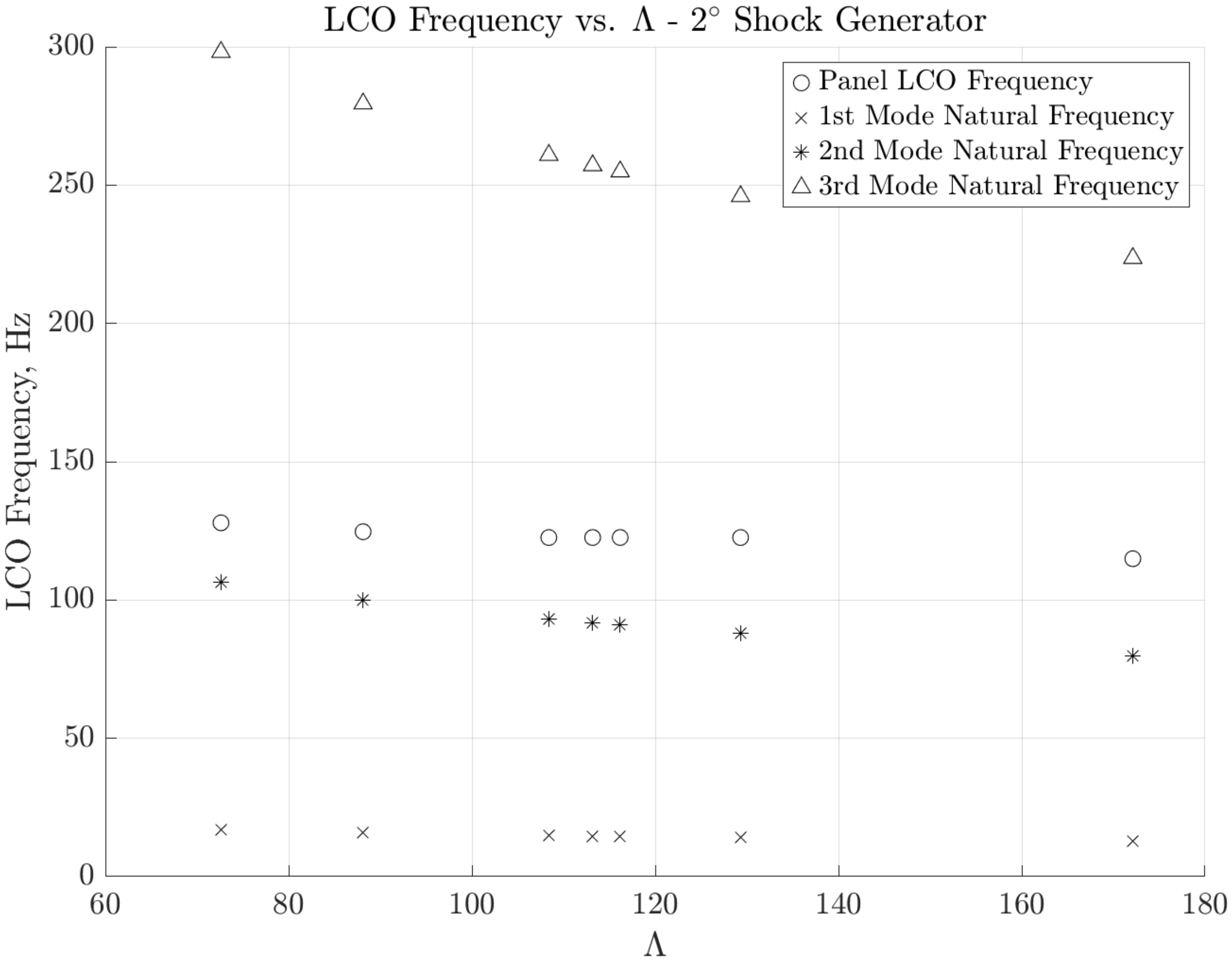
Density Contours

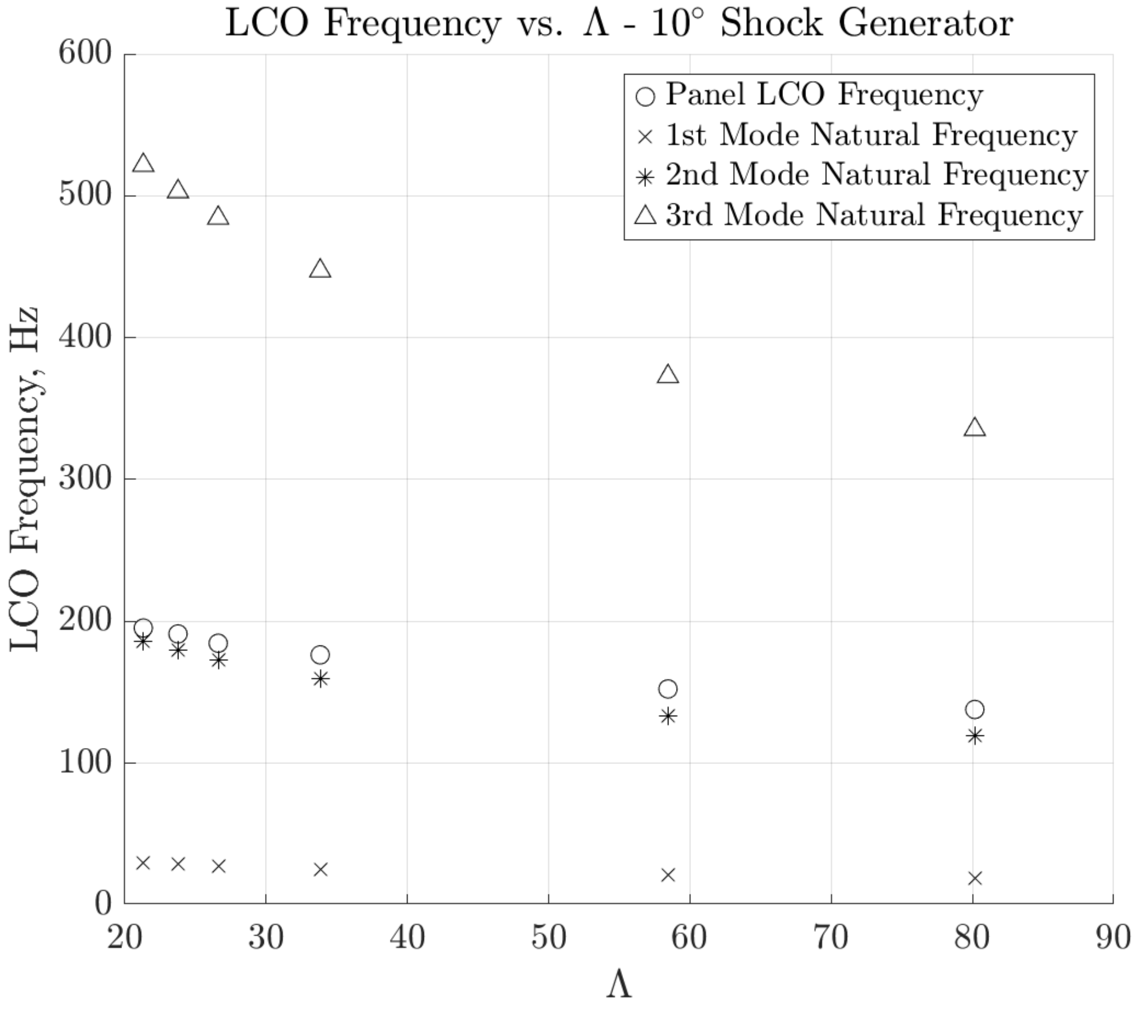
10° Wedge



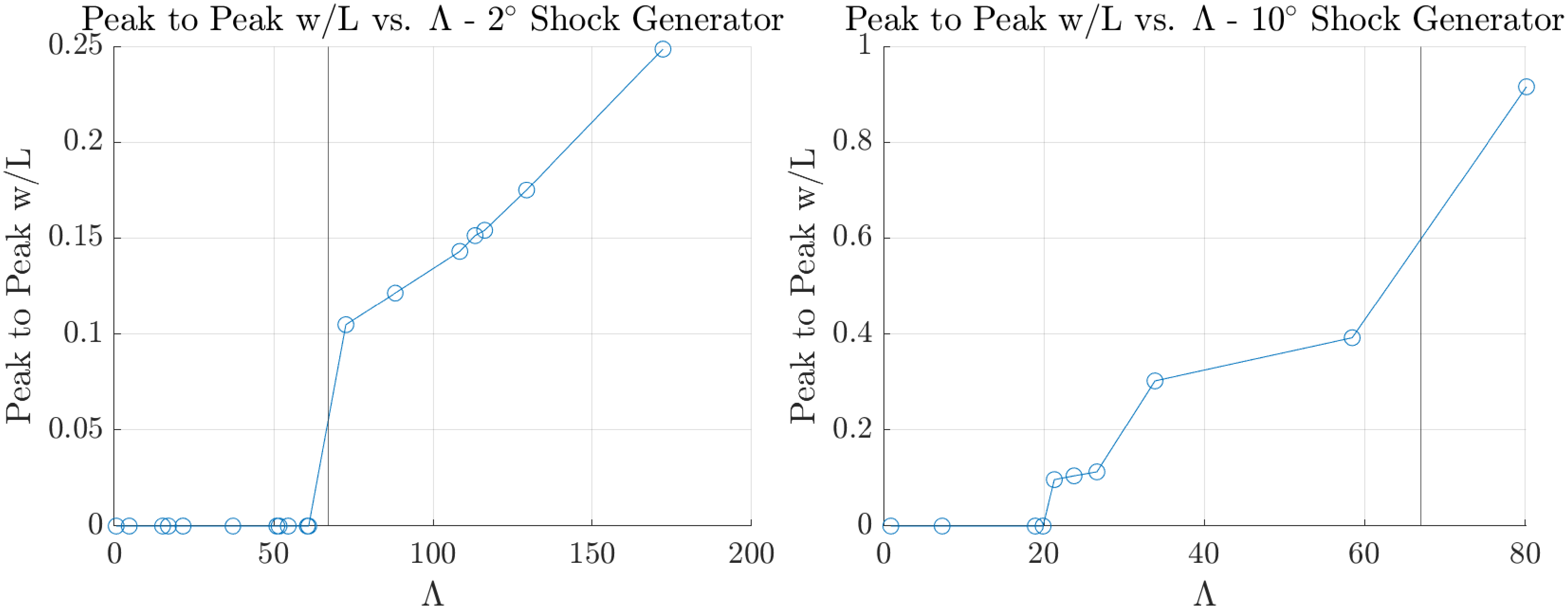
2° Wedge



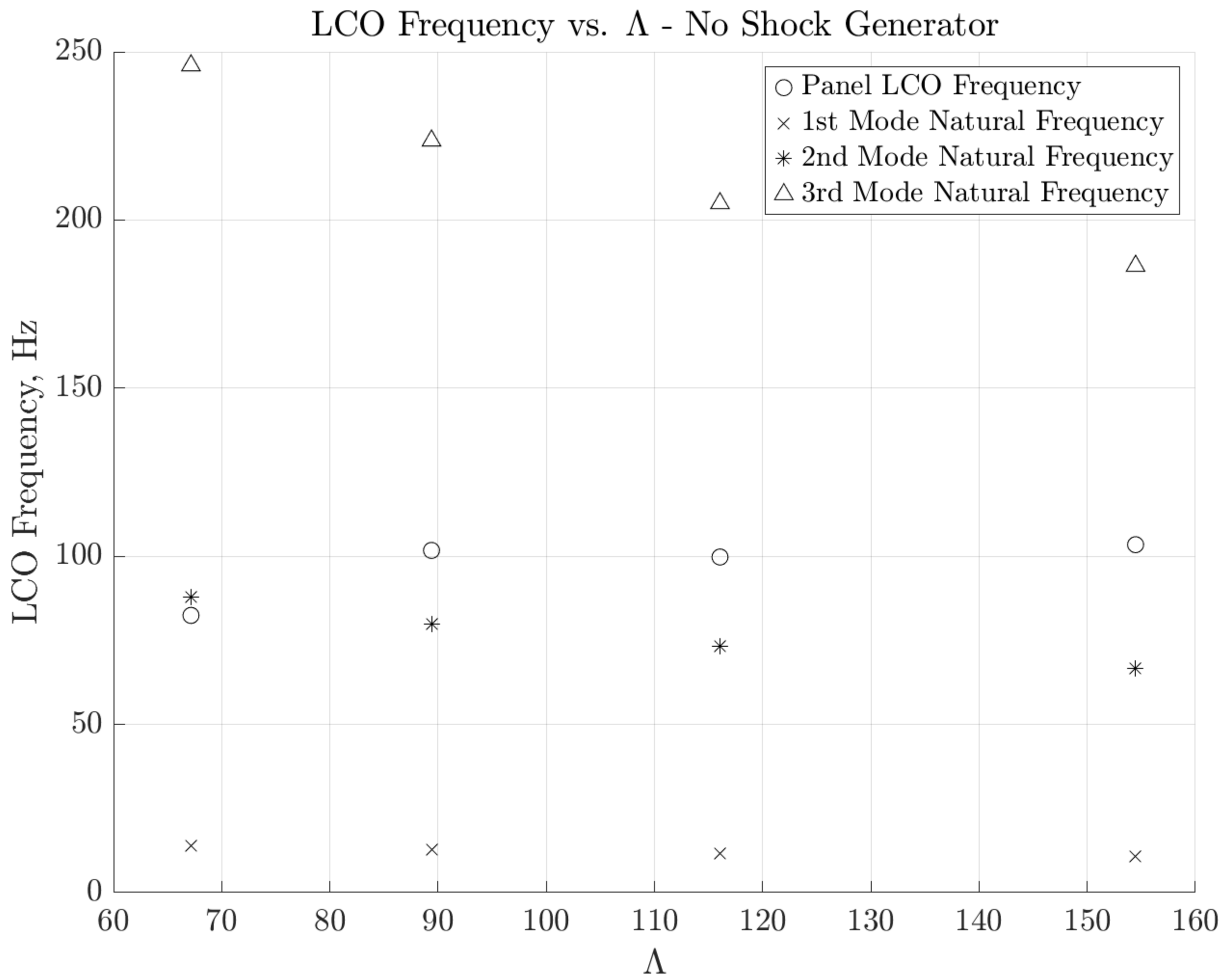




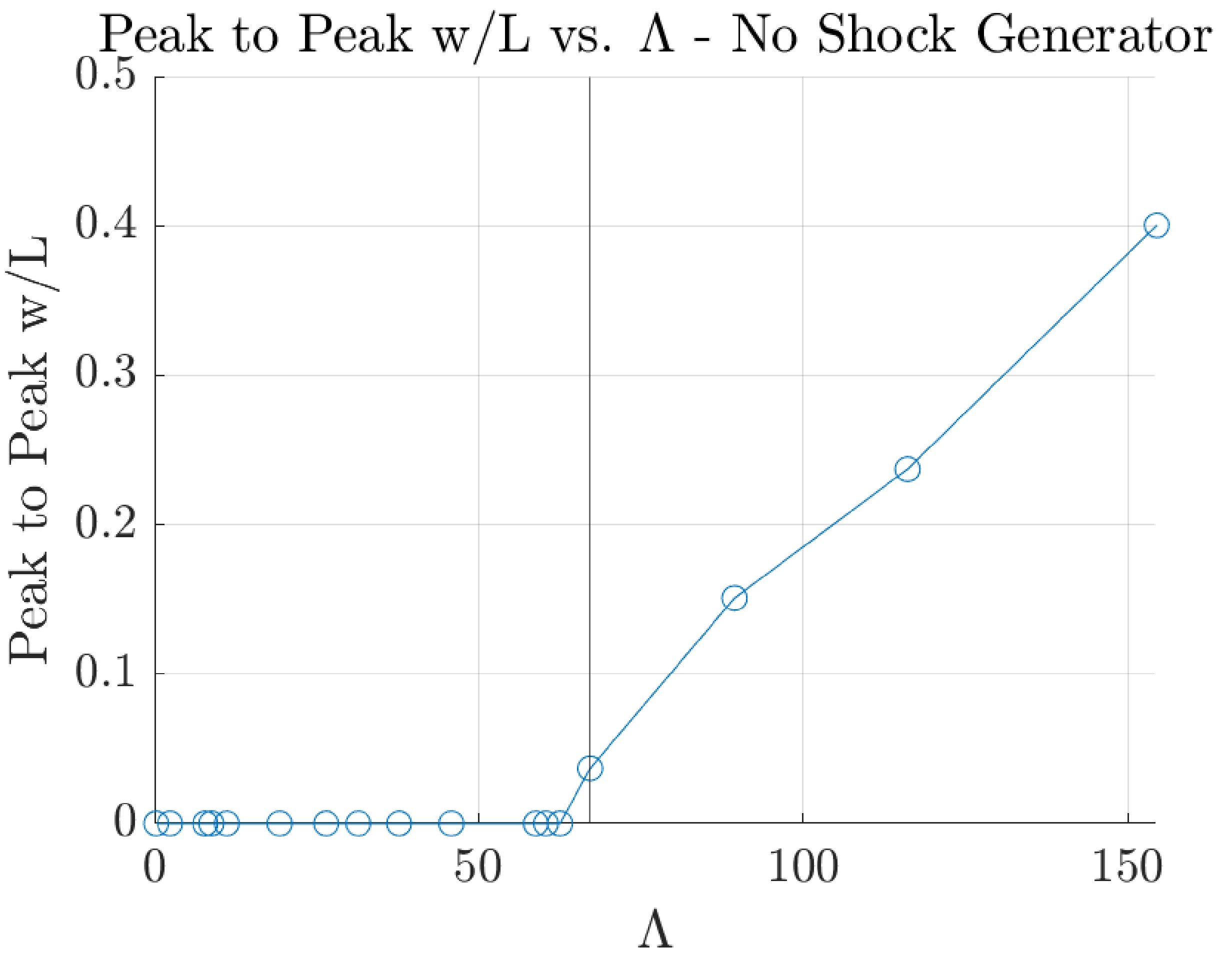
Duke | AEROELASTICITY



Duke | AEROELASTICITY



LCO Frequency vs. Λ - No Shock Generator
Panel LCO Frequency
1st Mode Natural Frequency
2nd Mode Natural Frequency
3rd Mode Natural Frequency
LCO Frequency, Hz
250
200
150
100
50
0
60
70
80
90
100
110
120
130
140
150
160
Λ

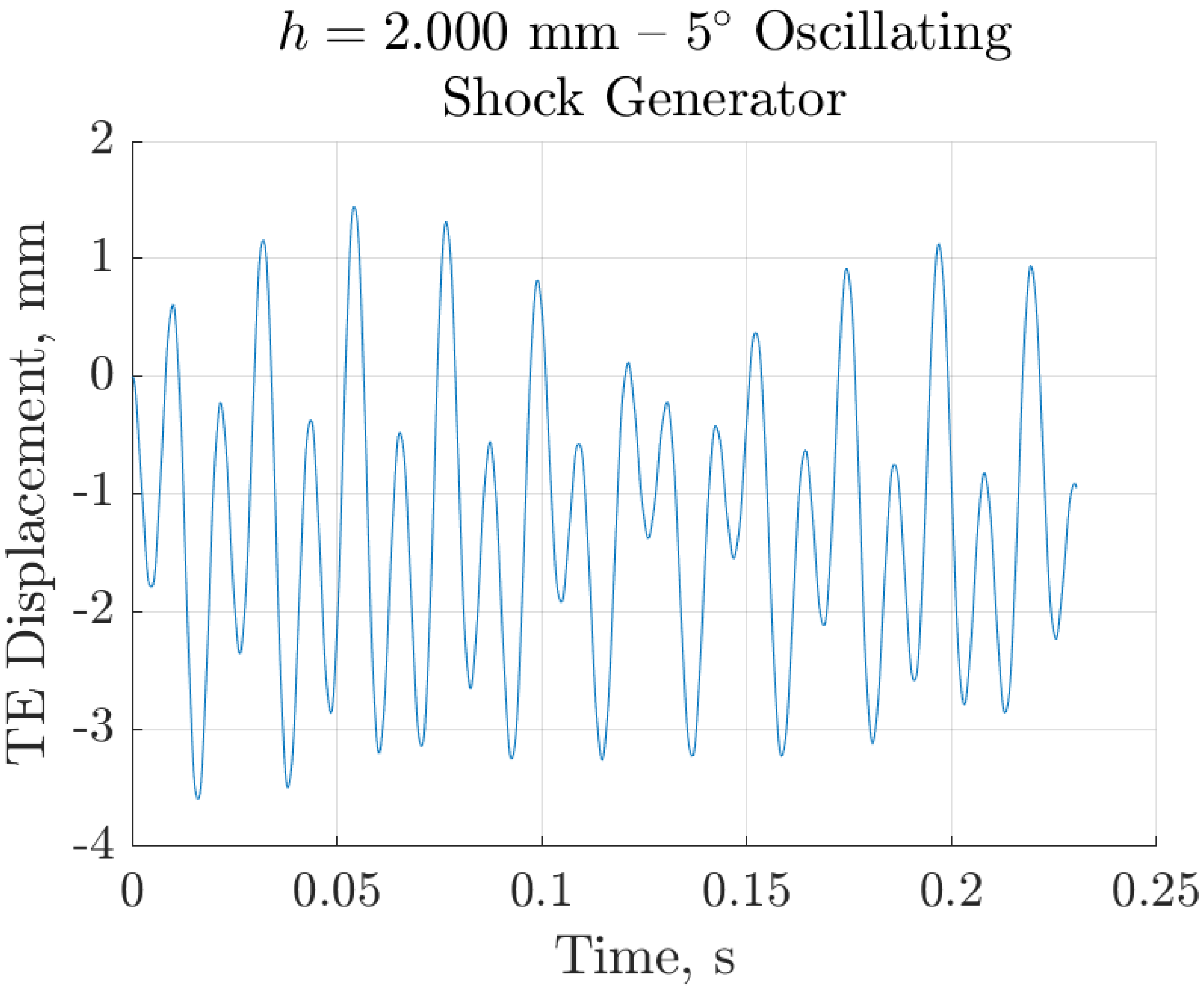


Peak to Peak w/L vs. Λ - No Shock Generator
Peak to Peak w/L
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
Λ

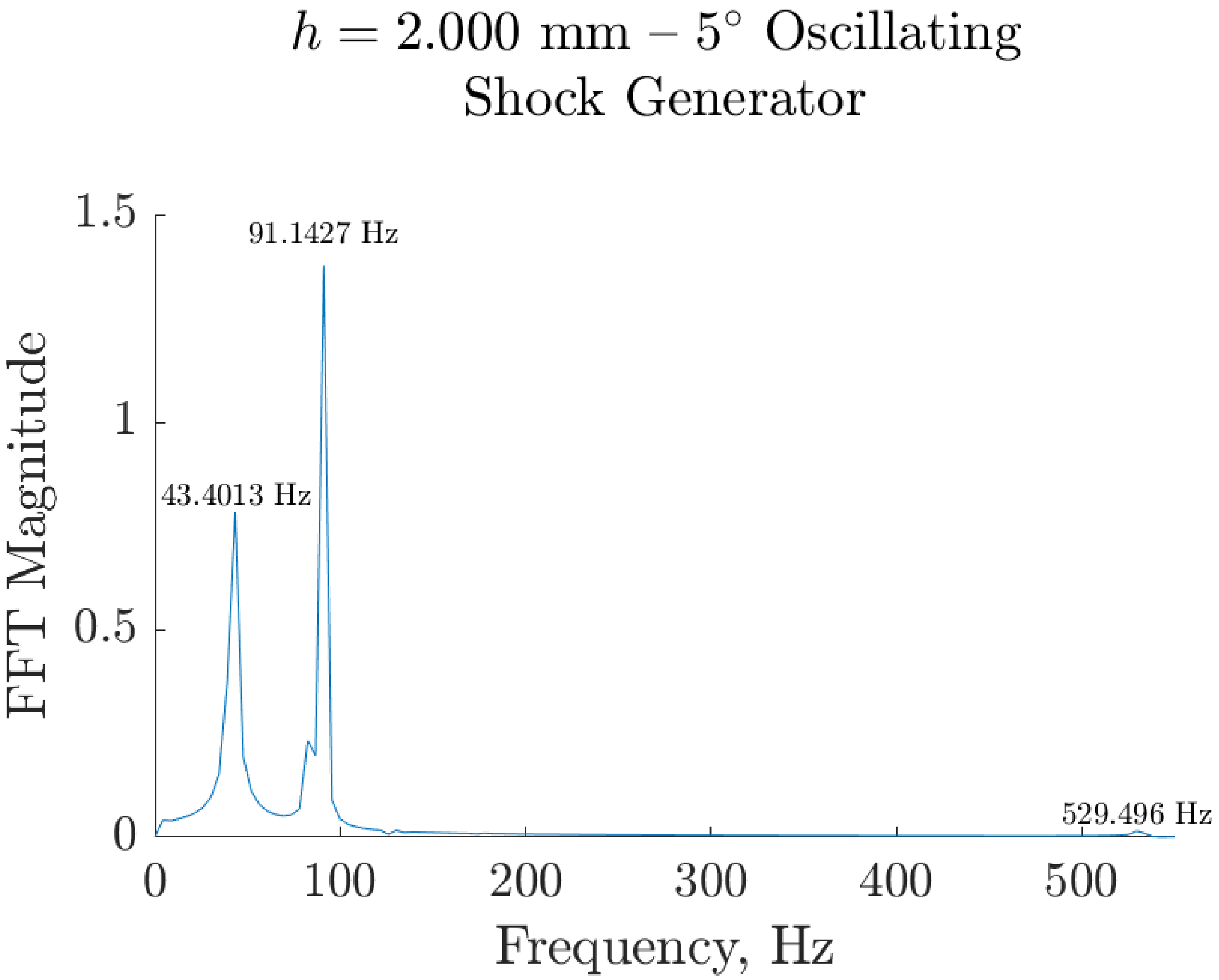
Oscillating Wedge Case

- An optional test case from AePW3
  - Wedge geometry was the same as in the data package
  - The wedge pitches at a frequency of 42 Hz[4]
    - Starts at 5° and oscillates ± 3°

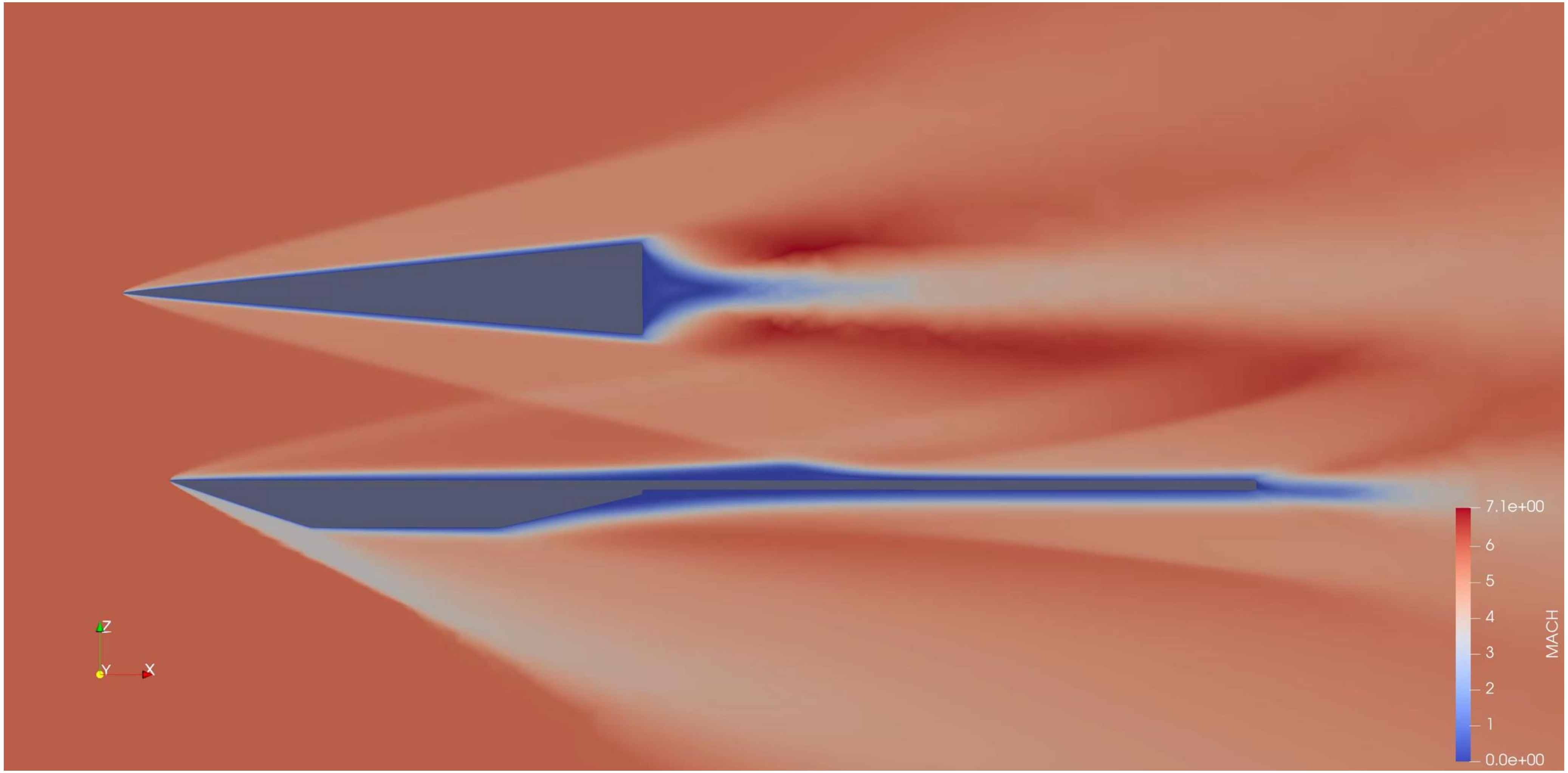
[4]Currao, G.M.D., McQuellin, L.P., Neely, A.J., Gai, S.L., O'Byrne, S., Zander, F., Buttsworth, D.R., McNamara, J.J., and Jahn, I., "Hypersonic Oscillating Shock-Wave/Boundary-Layer Interaction on a Flat Plate," *AIAA Journal*, Vol. 59, No. 3, 2021, pp. 940-959. https://doi.org/10.2514/1.J059590



$h = 2.000$ mm – 5° Oscillating
Shock Generator
TE Displacement, mm
Time, s
2
1
0
-1
-2
-3
-4
0
0.05
0.1
0.15
0.2
0.25



$h = 2.000$ mm – 5° Oscillating
Shock Generator
FFT Magnitude
Frequency, Hz
91.1427 Hz
43.4013 Hz
529.496 Hz
1.5
1
0.5
0
0
100
200
300
400
500



Z
Y
X
7.1e+00
6
5
4
3
2
1
0.0e+00
MACH

Conclusions

- FUN3D Simulations of the HyMAX experiment have been performed
  - For the experimental plate of a certain thickness studied by Currao et al., our results are consistent with that of others, i.e. a stable decaying oscillation of the plate with a frequency near the first natural frequency.
  - Simulations for thinner plates show flutter and limit cycle oscillations (LCO) with and without a shock generator.
  - Without a shock generator, the flutter and LCO results are similar to those found by Kevin McHugh using piston theory aerodynamics.
  - With a shock generator, thicker plates are needed to suppress flutter and LCO. The thickness needed to suppress flutter/LCO increases with increases in shock generator wedge angle.

Future work

- Utilize the FUNtoFEM framework to couple with a FEM solver and compare with current internal modal solver results
  - Use additional modes with modal solver
- Replicate the tunnel start-up through different imposed initial conditions
- Introduce thermal effects to the panel
- Extrude the domain in the spanwise direction and run the simulation as 3D