Aeroelastic Prediction of the BSCW using an enhanced OpenFoam-based CFD Solver (Work in progress)

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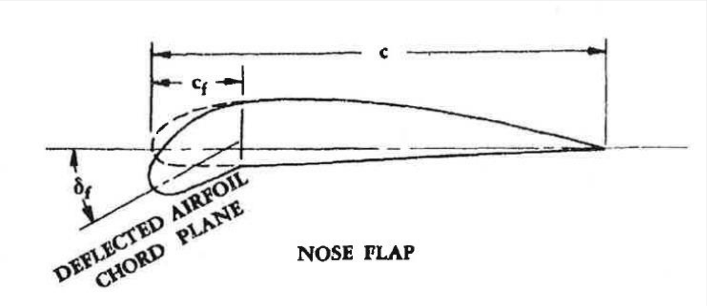
Outline

- Introduction
- OpenFOAM Compressible Solver: rhoCentralFoam
- Enhanced OpenFOAM Coupled Solver
- 2D Simulation: Pitching NACA0012 airfoil
- 3D Simulation: BSCW (case 1 & case 2)

Smart Wing with Integrated Multi-functional Surfaces (SWIMS)

- NRC's participation in AePW-2 supported by Aeronautics for 21st century (Aero21) program through the **SWIMS** project
- Multi-disciplinary project coordinated by several groups at NRC
- Focuses on the design of an airfoil with a **drooped leading** edge



- Goals:
  - A morphing wing with a continuous surface that adapts to various flight conditions for generating maximum lift and minimum drag
  - Drooped nose deflection δ_F =15 degrees
  - About 5% increase in the chord length

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Open Field Operation and Manipulation (OpenFOAM)

- Our group is responsible for performing an **aeroelastic analysis** on a wing with a drooped leading edge
- OpenFOAM is going to be the primary CFD simulation tool for the aeroelastic analysis
- C++ based CFD toolbox
- Simple Structural Dynamic Model: **sixDofRigidBodyMotion** solver
- CFD compressible solver: **rhoCentralFoam**

rhoCentralFoam

rhoCentralFoam: segregated solver

Euler equation:

$$\frac{\partial}{\partial t}\int_{\Omega} \vec{W}\, d\Omega + \oint_{\partial\Omega} \vec{F}_c\, dS = 0$$

$$\vec{W} = \begin{pmatrix} \rho \\ \rho\vec{U} \\ \rho E \end{pmatrix}, \vec{F}_c = \begin{pmatrix} \rho\vec{U}.\vec{n} \\ \rho\vec{U}\left(\vec{U}.\vec{n}\right) + p\vec{n} \\ (\rho E + p)\vec{U}.\vec{n} \end{pmatrix}$$

Discretized equation:

$$\frac{d}{dt}\left(\vec{W}_i V_i\right) + \sum_{Faces(i)} \vec{F}_c \Delta S = 0$$

Kurganov-Tadmor (KT) and Kurganov-Noelle-Petrova (KNP)

- Convective terms

$$\int_V \nabla.[u\Psi]dV = \int_S dS.[u\Psi] \approx \sum_f \mathrm{S_f}.u_f\Psi_f = \sum_f \phi_f\Psi_f$$

$$\sum_f \phi_f \Psi_f = \sum_f \left[\left(a^+ {\phi_f}^+ - aSf\right){\Psi_f}^+ + \left((1-a^+){\phi_f}^- + aSf\right){\Psi_f}^-\right]$$

$$a^+ = \begin{cases} \dfrac{a_p}{a_p - a_m} & KNP \\ \dfrac{1}{2} & KT \end{cases} \qquad aSf = \begin{cases} \dfrac{a_m a_p}{a_p - a_m} & KNP \\ -\dfrac{1}{2}\max\left(|a_m|, |a_p|\right) & KT \end{cases}$$

$$a_p = \max\left({\phi_f}^+ + {c_f}^+|\mathrm{S}_f|, {\phi_f}^- + {c_f}^-|\mathrm{S}_f|, 0\right)$$
$$a_m = \min\left({\phi_f}^+ - {c_f}^+|\mathrm{S}_f|, {\phi_f}^- - {c_f}^-|\mathrm{S}_f|, 0\right)$$

Kurganov-Tadmor (KT) and Kurganov-Noelle-Petrova (KNP)

- Gradient terms

$$\int_V \nabla\Psi \, dV = \int_S dS\,\Psi \approx \sum_f S_f \Psi_f$$

$$\sum_f S_f\,\Psi_f = \sum_f \left[a^+ S_f {\Psi_f}^+ + (1 - a^+) S_f {\Psi_f}^-\right]$$

Coupled CFD Solver Derived from rhoCentralFoam

- Segregated Solver

$$\frac{d}{dt}\left(\vec{W}_i V_i\right) + \sum_{Faces(i)} \vec{F}_c \Delta S = 0$$

- Coupled Solver

$$\left[\vec{F}_c\right]^{n+1} = \left[\vec{F}_c\right]^{n} + \left[\frac{\partial \vec{F}_c}{\partial \vec{W}}\right]^{n} \left(\vec{W}^{n+1} - \vec{W}^{n}\right) + O\left\{\left(\Delta \vec{W}\right)^2\right\}$$

$$\frac{d}{dt}\left(\vec{W}_i V_i\right) + \sum_{Faces(i)} \left[\frac{\partial \vec{F}_c}{\partial \vec{W}}\right]^{n} \Delta S \Delta \vec{W} = - \sum_{Faces(i)} \left[\vec{F}_c\right]^{n} \Delta S$$

Lower-Upper Symmetric Gauss –Seidel (LU-SGS)

- Approximation

$$(D + L + U)x = b$$
$$(D + L + U) \approx (D + L)D^{-1}(D + U) = (D + U + L + LD^{-1}U)$$

- Two-step process:

Forward Sweep: $Dx^1 = b - Lx^1$
Backward Sweep: $Dx = b - Lx^1 - Ux$

Dual Time Stepping

$$\frac{d}{dt}\left(\vec{W}_i V_i\right) + \sum_{Faces(i)} \left[\frac{\partial \vec{F}_c}{\partial \vec{W}}\right]^n \Delta S \Delta \vec{W} = -\sum_{Faces(i)} \left[\vec{F}_c\right]^n \Delta S$$

- First Order

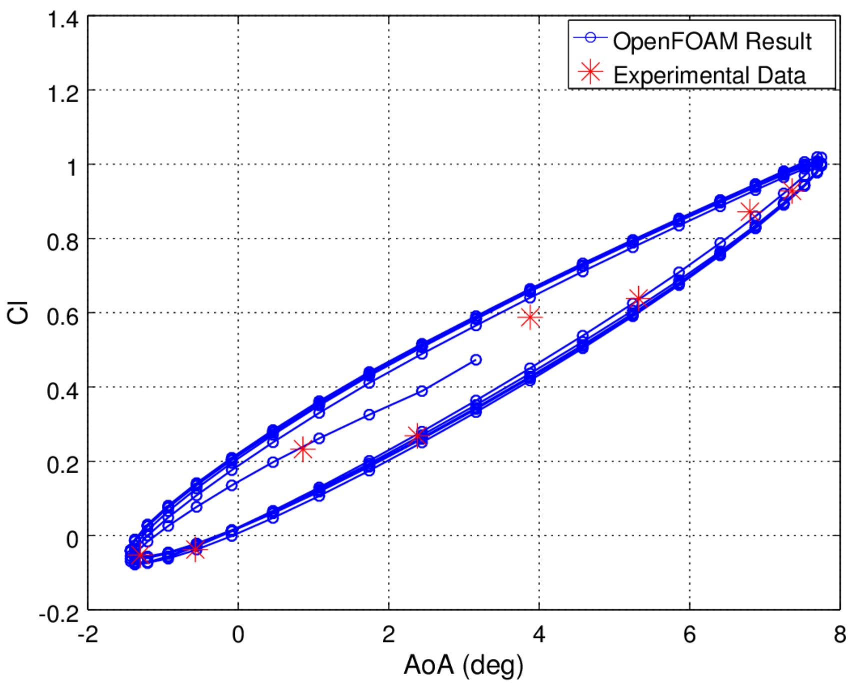
$$\left(\frac{V_i^{\,n+1}}{\Delta t} + \frac{V_i^{\,n+1}}{\Delta t^*} + \sum_{Faces(i)} \left[\frac{\partial \vec{F}_c}{\partial \vec{W}}\right]^n \Delta S\right) \Delta \vec{W}_i^{\,k} = \frac{V_i^{\,n+1}}{\Delta t} \vec{W}_i^{\,k} + \frac{V_i^{\,n}}{\Delta t} \vec{W}_i^{\,n} - \sum_{Faces(i)} \left[\vec{F}_c\right]^n \Delta S$$

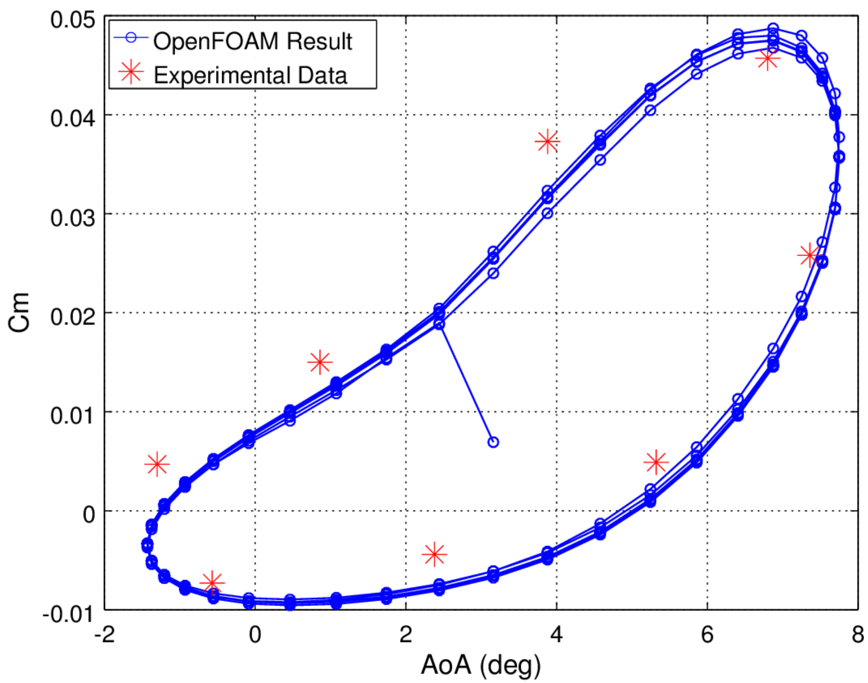
- Second Order

$$\left(\frac{3}{2}\frac{V_i^{\,n+1}}{\Delta t} + \frac{V_i^{\,n+1}}{\Delta t^*} + \sum_{Faces(i)} \left[\frac{\partial \vec{F}_c}{\partial \vec{W}}\right]^n \Delta S\right) \Delta \vec{W}_i^{\,k} = -\frac{3}{2}\frac{V_i^{\,n+1}}{\Delta t} \vec{W}_i^{\,k} + 2\,\frac{V_i^{\,n}}{\Delta t} \vec{W}_i^{\,n} - \frac{1}{2}\frac{V_i^{\,n-1}}{\Delta t} \vec{W}_i^{\,n-1} - \sum_{Faces(i)} \left[\vec{F}_c\right]^n \Delta S$$

2D Simulation: Pitching NACA0012 Airfoil

- Pitching angle $\alpha = 3.16^{\circ} + 4.59^{\circ} \sin(2\pi \times 5\, t)$
- Reduced frequency $k = \dfrac{\omega c}{2U_{\infty}} = 0.081$
- Mach number $M = 0.6$





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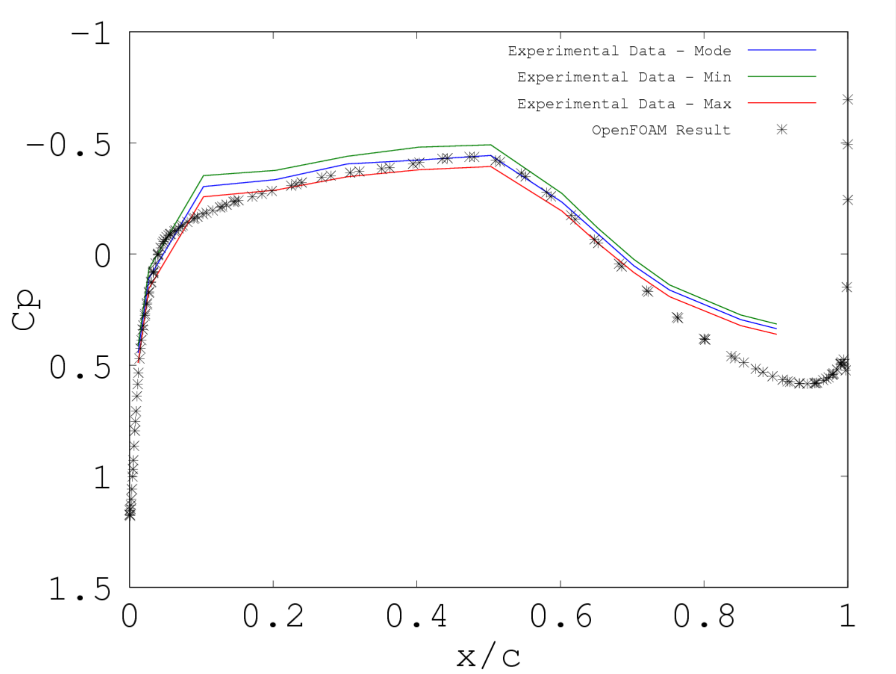
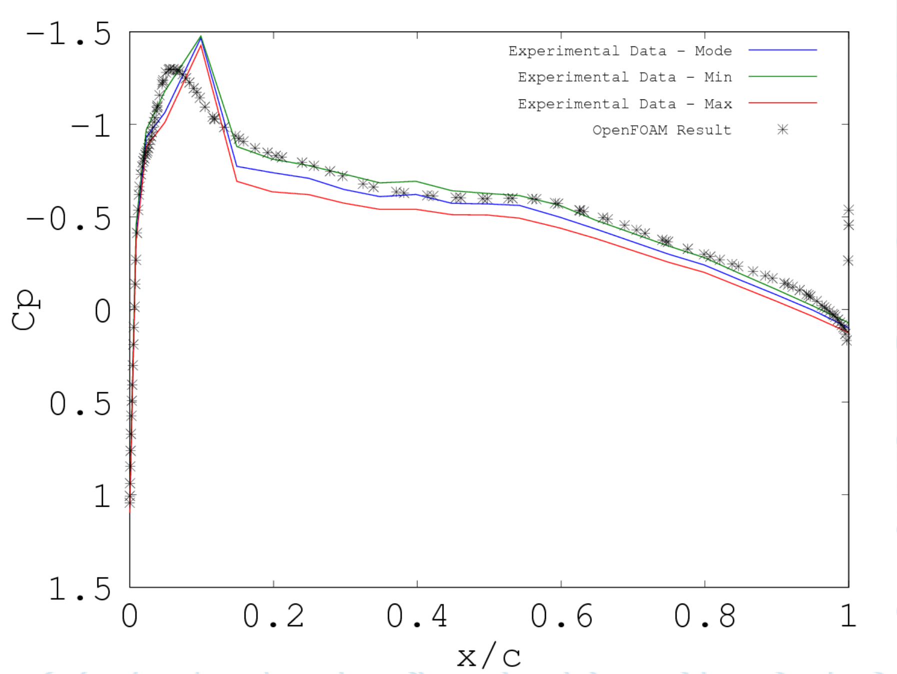
3D Simulation: BSCW (Case 1)

- Steady State
- All the results: Coarse Mesh, Euler solution
- Pressure Coefficient at the 60% Spanwise Location
- Max courant number: 10 and 100



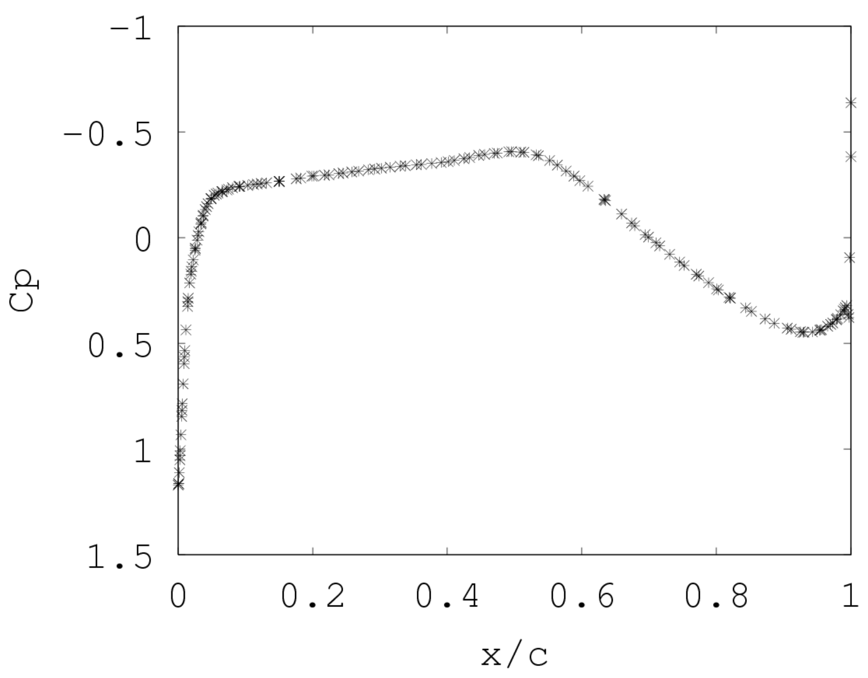
Lower Surface



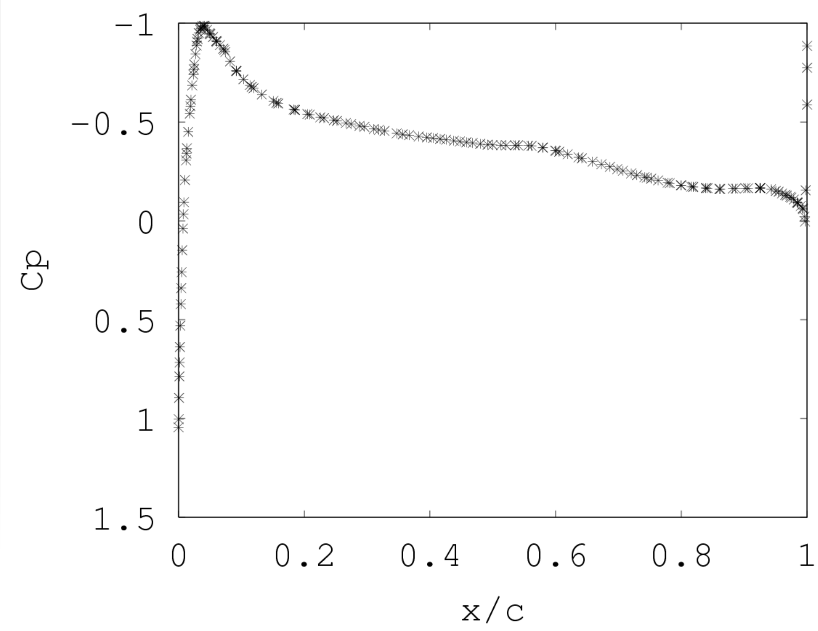
Upper Surface

3D Simulation: BSCW (Case 1)

- Steady State
- Pressure Coefficient at the 95% Spanwise Location



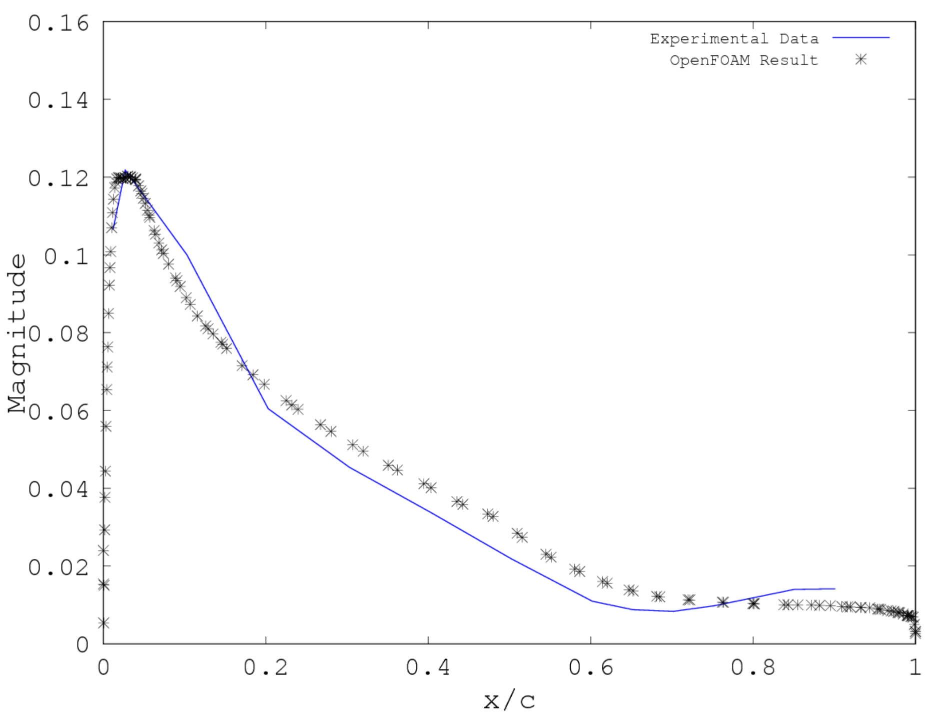
Lower Surface



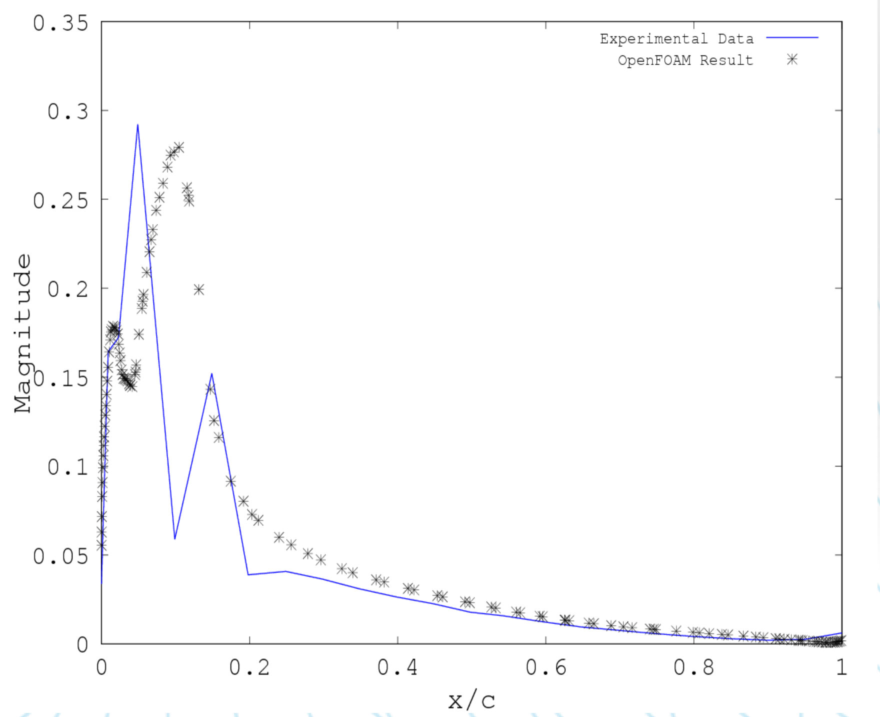
Upper Surface

3D Simulation: BSCW (Case 1)

- Forced Case
- FRF magnitude at the 60% Spanwise Location
- Time steps: $\Delta T = 5 \times 10^{-4}$, number of dual time steps: 200



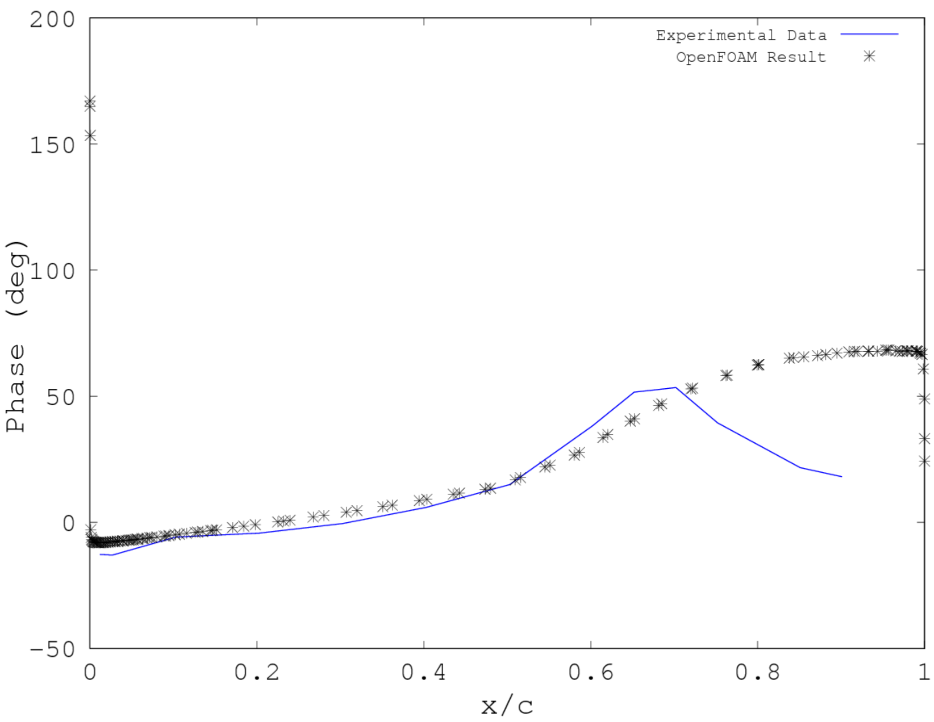
Lower Surface



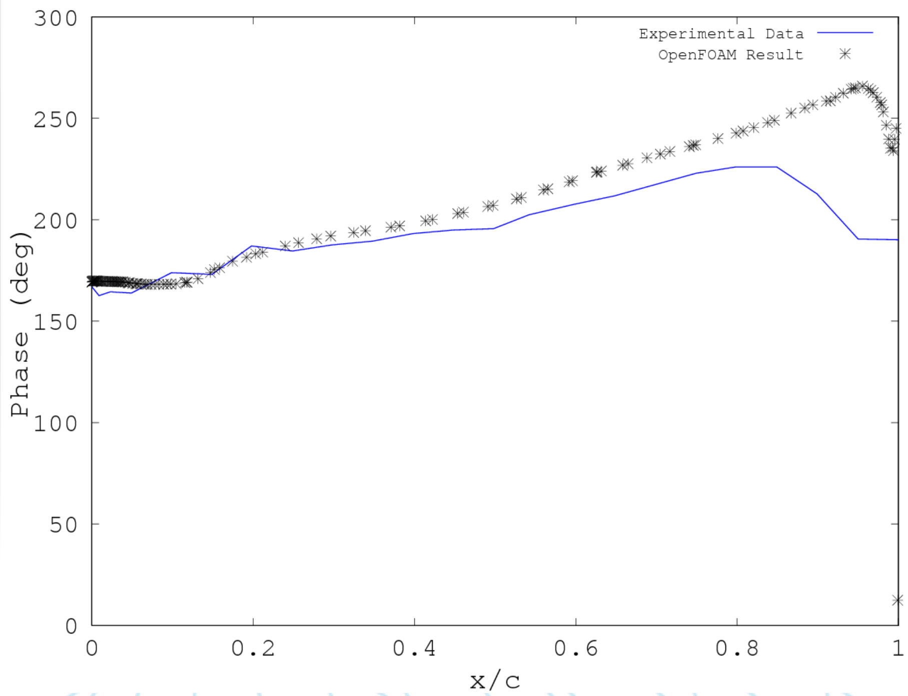
Upper Surface

3D Simulation: BSCW (Case 1)

- Forced Case
- FRF Phase at the 60% Spanwise Location



Lower Surface



Upper Surface

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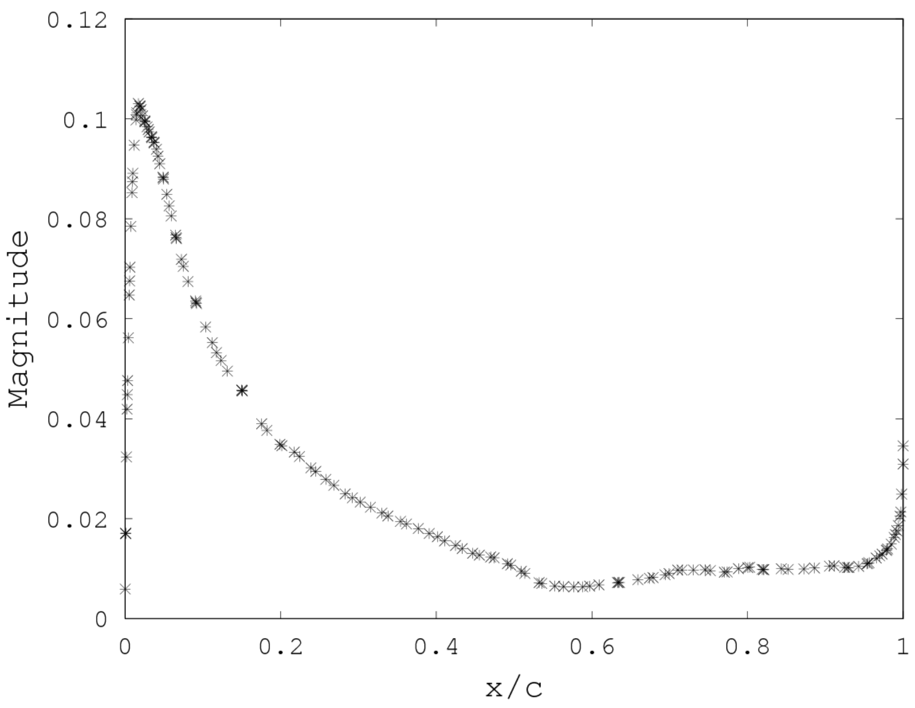
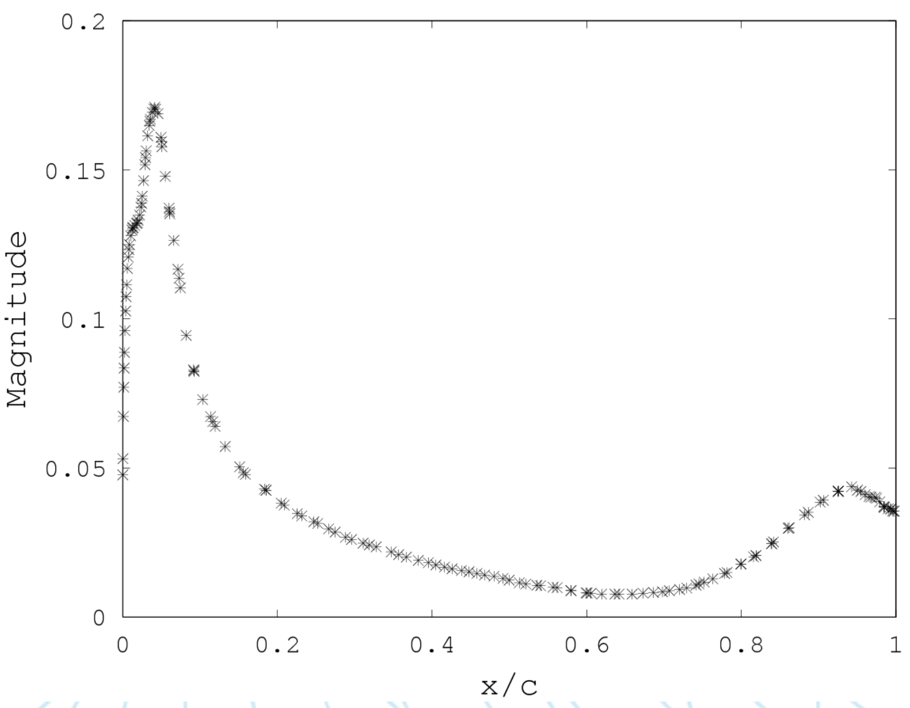
3D Simulation: BSCW (Case 1)

- Forced Case
- FRF magnitude at the 95% Spanwise Location



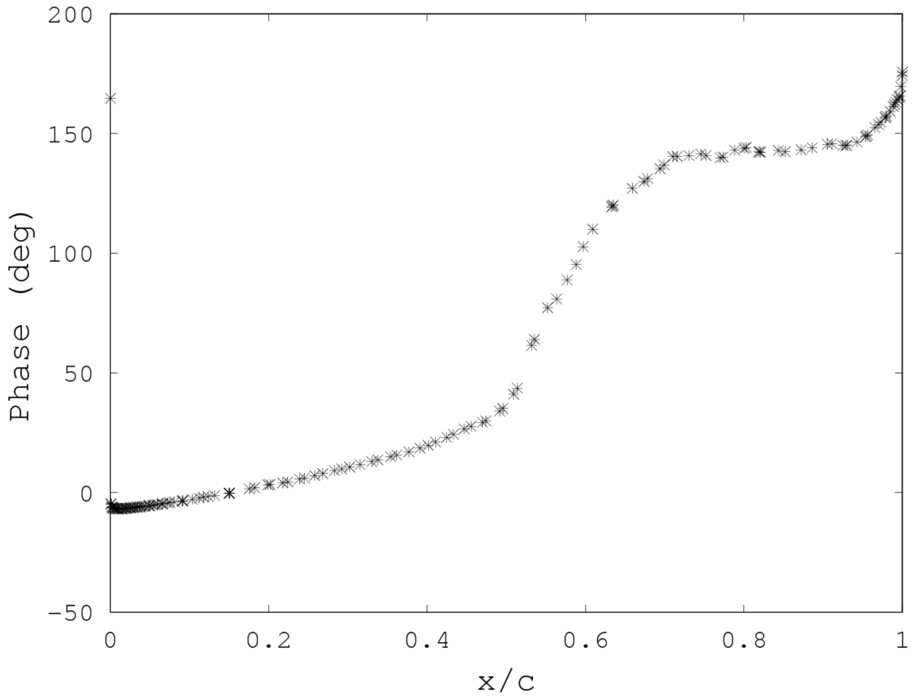
Lower Surface

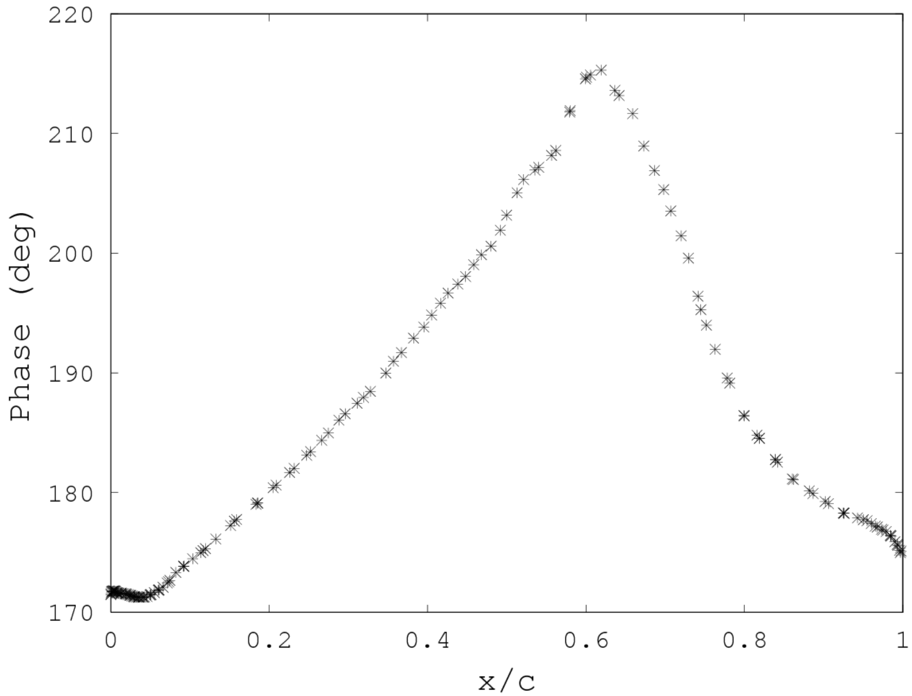


Upper Surface

3D Simulation: BSCW (Case 1)

- Forced Case
- FRF Phase at the 95% Spanwise Location





Lower Surface

Upper Surface

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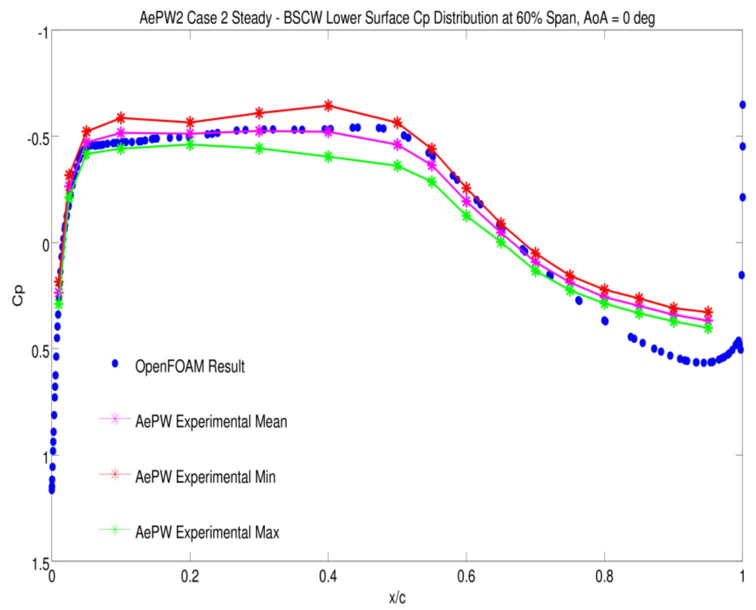
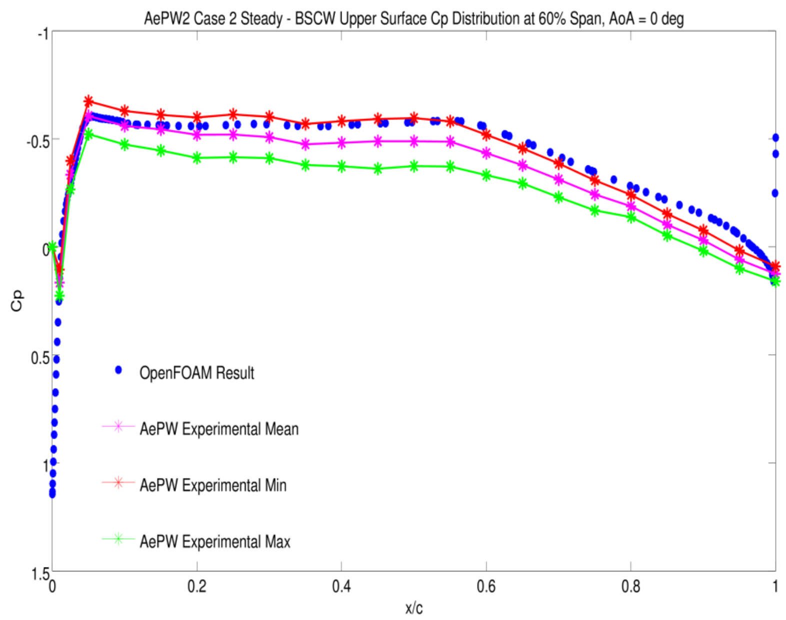
3D Simulation: BSCW (Case 2)

- Steady State
- Coarse Mesh
- Pressure Coefficient at the 60% Spanwise Location
- Max courant number: 10 and 100



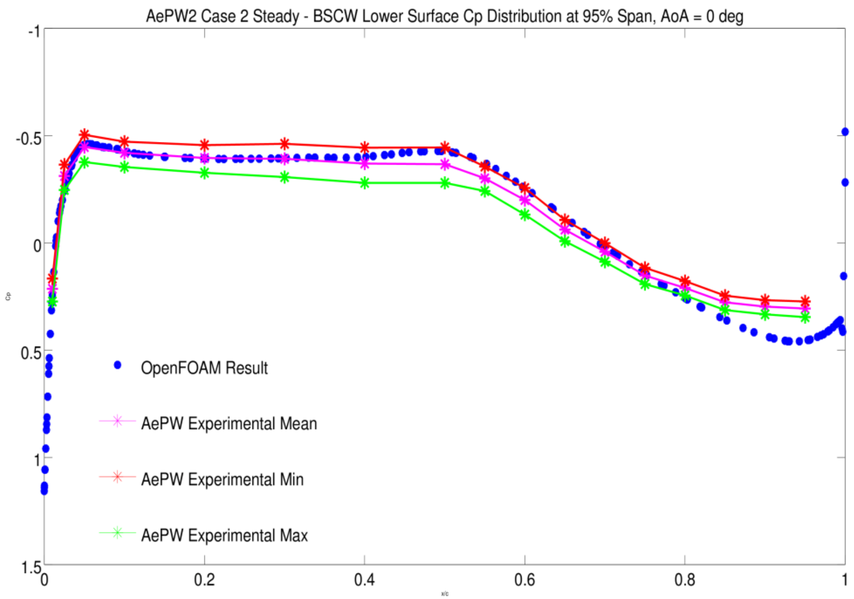
Lower Surface



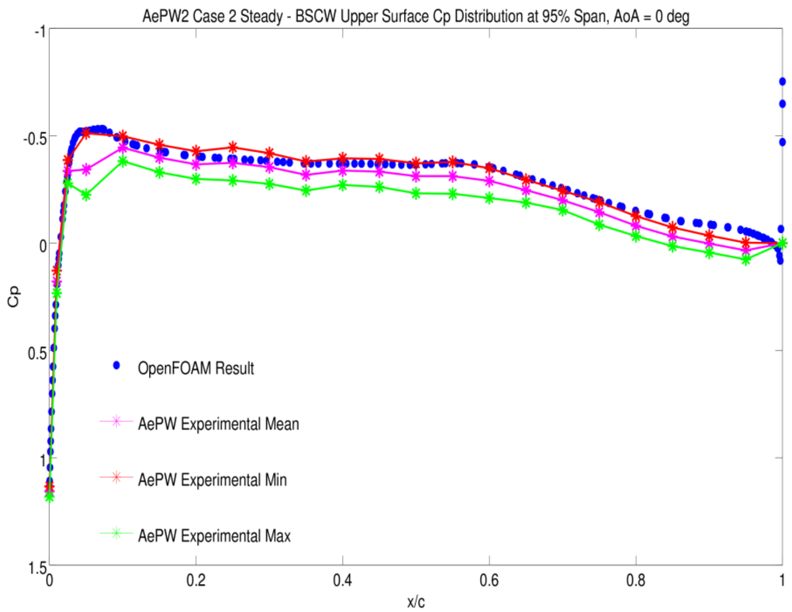
Upper Surface

3D Simulation: BSCW (Case 2)

- Steady State
- Coarse Mesh
- Pressure Coefficient at the 95% Spanwise Location
- Max courant number: 10 and 100



Lower Surface



Upper Surface

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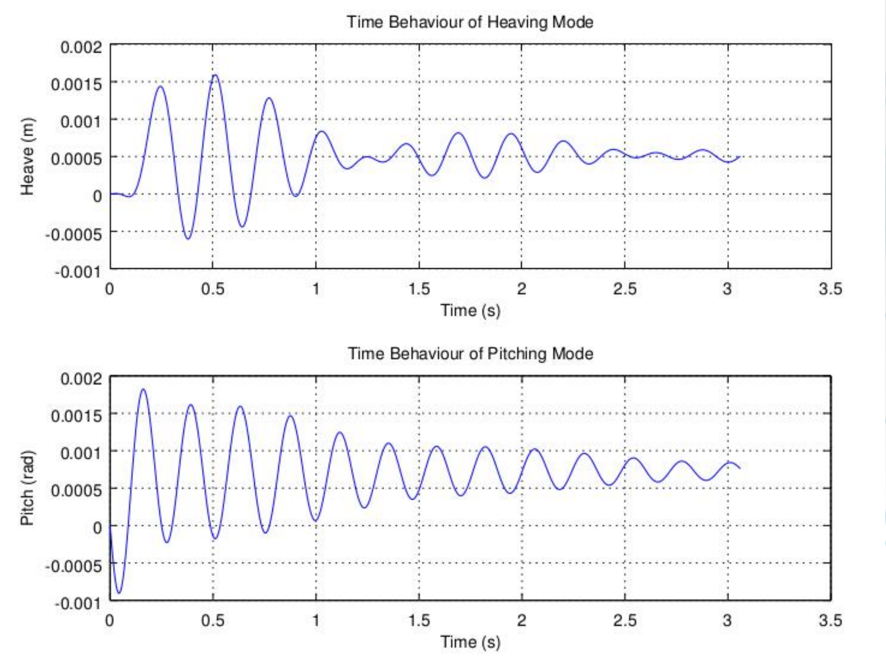
3D Simulation: BSCW (Case 2)

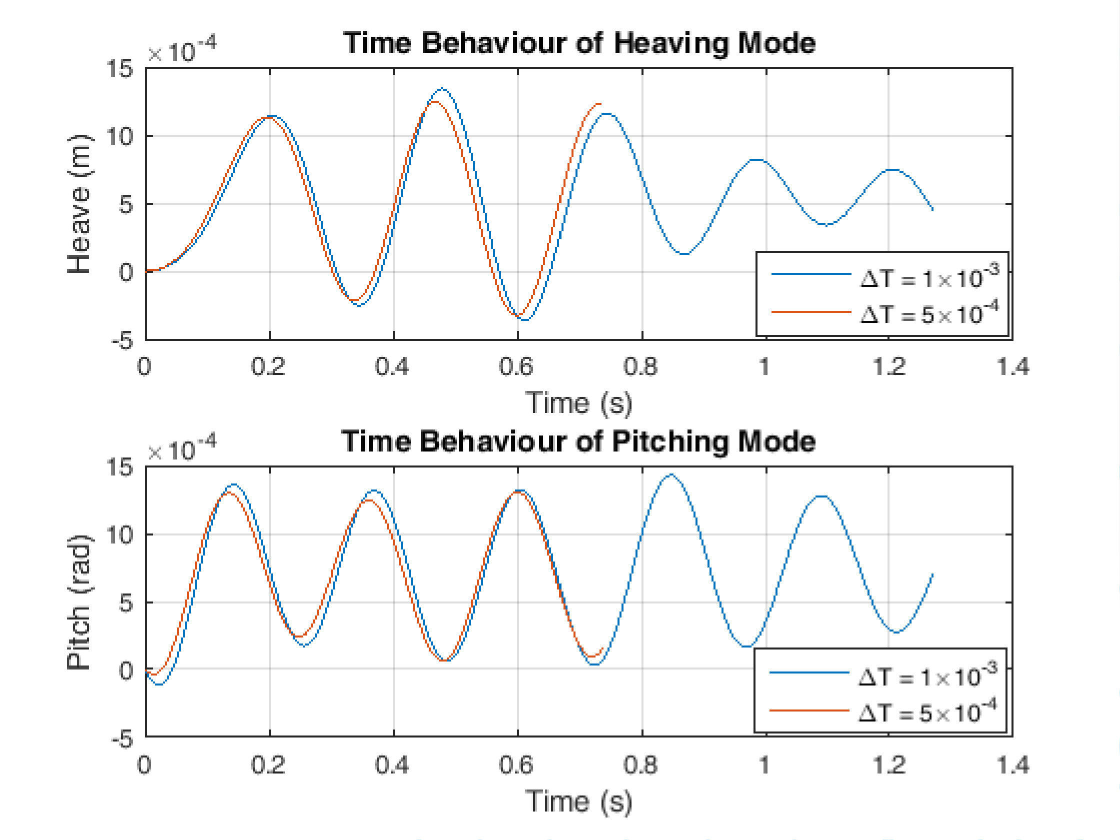
- Flutter case
- Coarse Mesh
- How did we start the dynamic case?



$$\Delta T = 5 \times 10^{-3}$$

3D Simulation: BSCW (Case 2)

- Flutter case
- Coarse Mesh



Future Work

- Complete Case 2 flutter analysis for inviscid case
- Further code development to consider viscous flux Jacobian
- Re-run cases 1, 2 with viscous forces
- Attempt URANS simulations for case 3

THANK YOU