3D Fluid–Structure Interaction simulation of **NASA SC(2)-0410** airfoil

Exam Presentation

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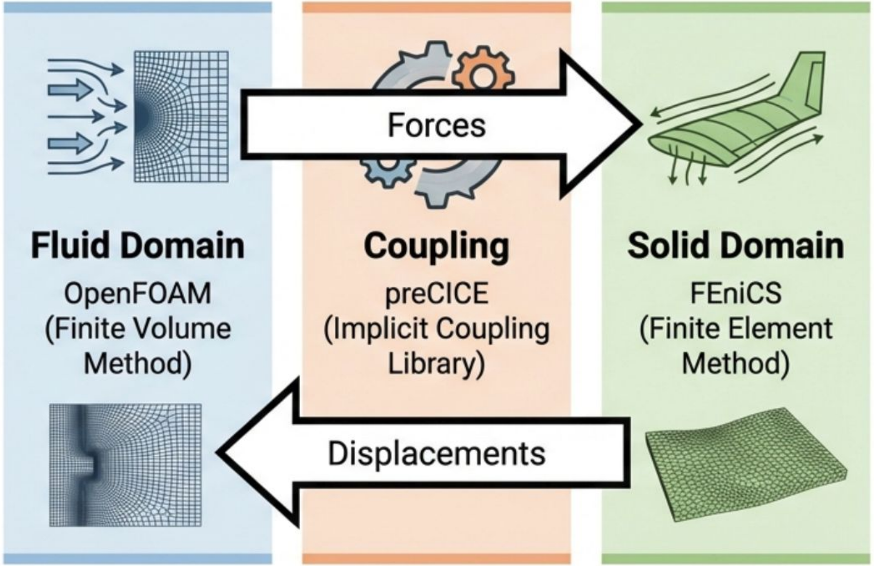
Problem Description & Goals

- **What is Fluid Structure Interaction**
- **Key Goals:**

› Implement a 3D aeroelastic model of an airfoil

› Evaluate structural response under aerodynamic loads

› Leverage HPC resources for complex partitioned coupling



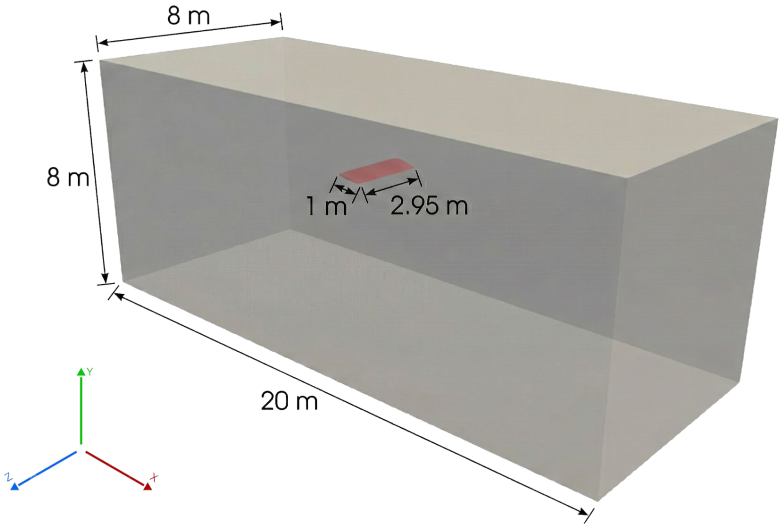
Softwares

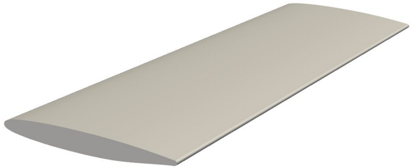
- **OpenFOAM**: fluid solver
- **FEniCS**: structural solver
- **preCICE**: coupling library

› **Partitioned Approach:** Each domain is solved by a specialized, independent solver.

› Containerized environment using Docker for full reproducibility.

Simulation Parameters

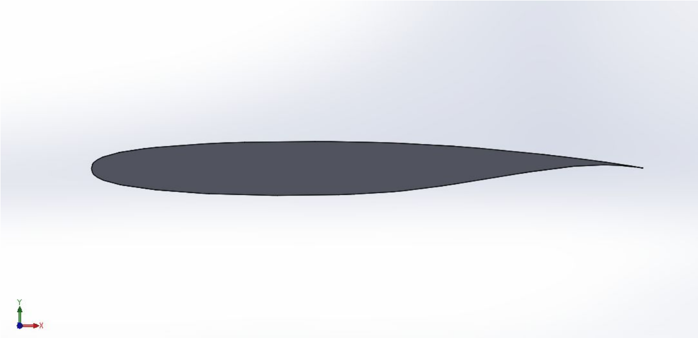




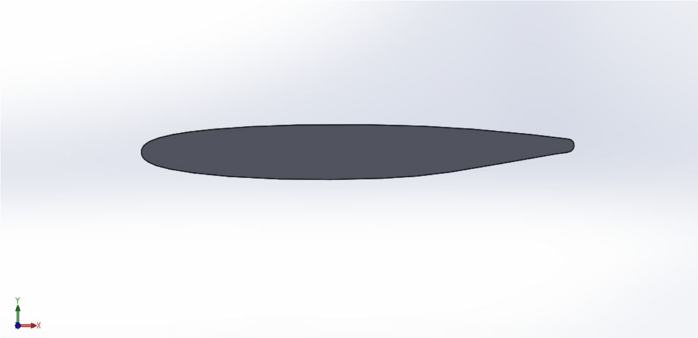
Fluid and Flow Properties		
Fluid Velocity	U_∞	$100\,\mathrm{m/s}$
Reynolds Number	Re	6.67×10^6
Fluid Density	ρ_f	$1.225\,\mathrm{kg/m^3}$
Kinematic Viscosity	ν	$1.5 \times 10^{-5}\,\mathrm{m^2/s}$
Geometrical Properties		
Chord Length	c	$1\,\mathrm{m}$
Wingspan	s	$2.95\,\mathrm{m}$
Angle of Attack	α	$5°$
Tunnel Length	L	$20\,\mathrm{m}$
Tunnel Section	$W \times H$	$8\,\mathrm{m} \times 8\,\mathrm{m}$
Structural Properties		
Young's Modulus	E	$71.7\,\mathrm{GPa}$
Poisson's Ratio	ν	0.33
Solid Density	ρ_s	$2810\,\mathrm{kg/m^3}$

Geometry Generation

- **SOLIDWORKS**: .dat file with airfoil coordinate points
- **Trailing Edge Problem**
- **Two main file for the meshes:** .STL & .STEP



Sketch used for the fluid dynamic simulation



Sketch used for the FSI simulation

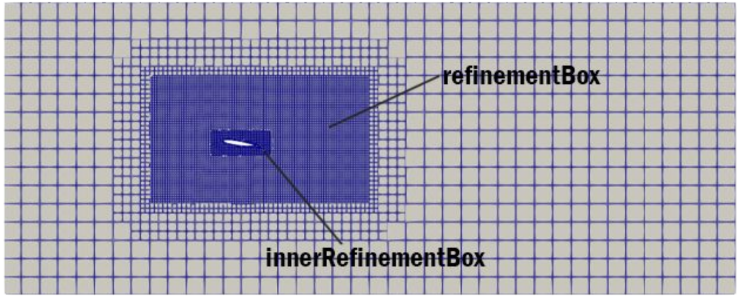
Fluid Mesh

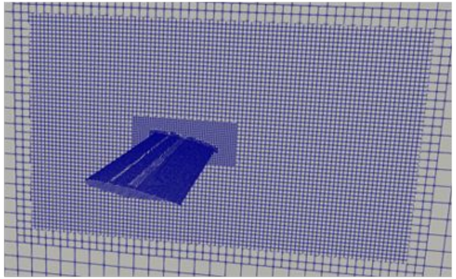
Mesh generation technique

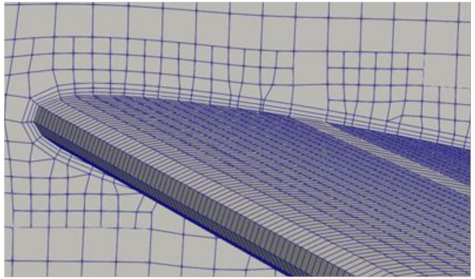
- blockMesh
- surfaceFeatureExtract
- snappyHexMesh

Refinement boxes

- refinementBox
- innerRefinementBox







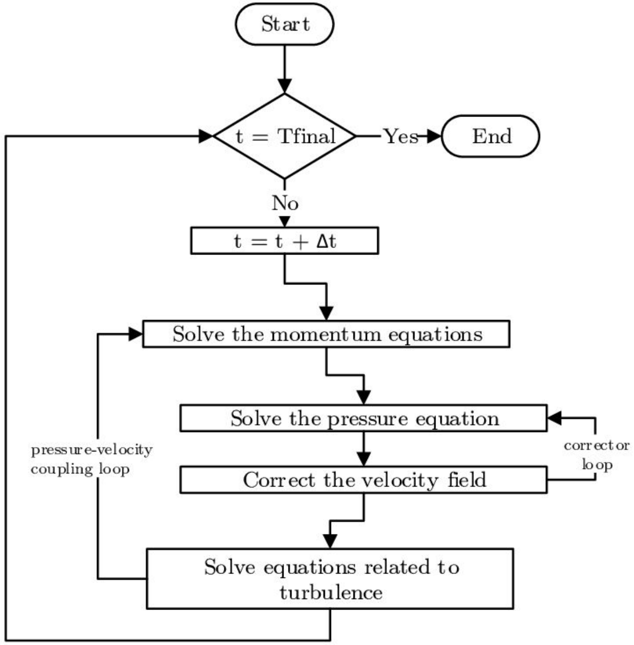
Fluid Solver

PimpleFoam

- Transient
- Incompressible (*Ma* ≈ 0.3)

Turbulence model

- *k*-*ω* SST
- Use of Wall Functions for near-wall treatment

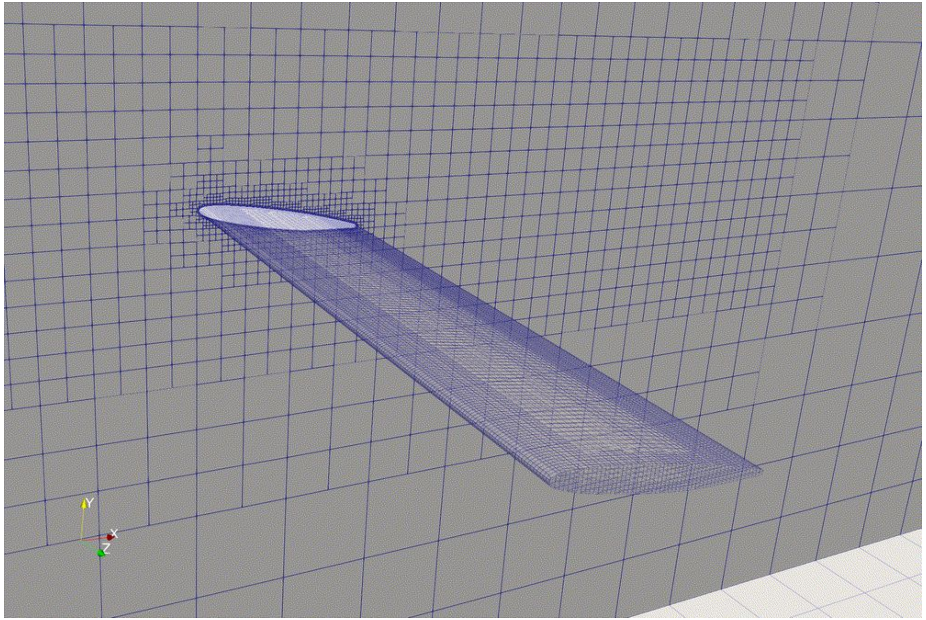


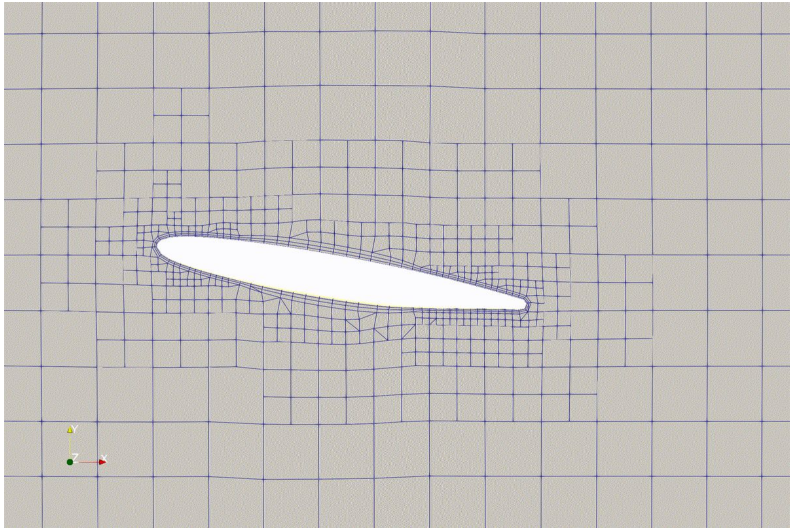
`PimpleFoam` algorithm, essential steps

Dynamic Mesh

- **displacementLapacian** solver

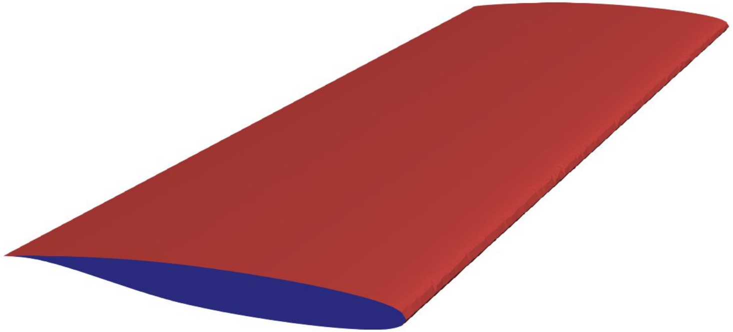
$$\nabla \cdot (\gamma \nabla \mathbf{u}_\Omega) = 0$$





Boundary Conditions

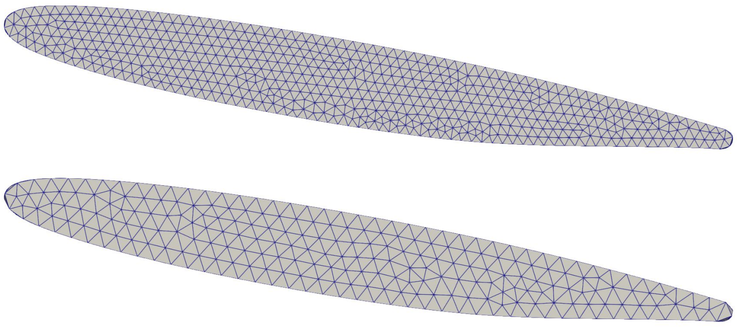
Patch Name	Velocity ($\mathbf{u}$)	Pressure (p)
inlet	fixedValue	zeroGradient
outlet	zeroGradient	fixedValue (0)
walls	noSlip	zeroGradient
NASA	movingWallVelocity	zeroGradient



- **DIRICHLET:** rigid constraints applied at the wing root (blue)
- **NEUMANN:** coupling interface (red)

Solid Mesh

- The mesh was generated using the open-source finite element generator Gmsh
- First-order tetrahedral elements
- Partition into specific groups:
  - Volume
  - Fixed Boundary
  - Coupling Interface
- Two configurations were tested to ensure numerical accuracy



Generalized-alpha Method

- A second-order accurate, one-step, three-stage algorithm used to solve the structural equation of motion in the time domain
- Parameters are set based on the spectral radius, which controls the damping level
- The mass form and the stiffness form are combined into a residual equation

$$\rho_s \ddot{\mathbf{u}} - \nabla \cdot \boldsymbol{\sigma} = \mathbf{f} \quad \text{in } \Omega_s$$

$$\boldsymbol{\sigma}(\mathbf{u}) = \lambda(\nabla \cdot \mathbf{u})\mathbf{I} + 2\mu\boldsymbol{\epsilon}(\mathbf{u})$$

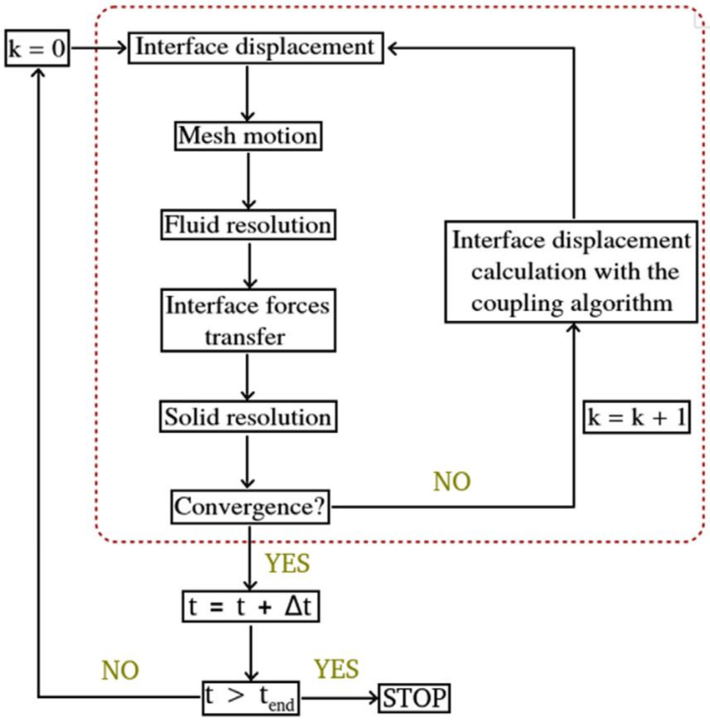
$$\boldsymbol{\epsilon}(\mathbf{u}) = \frac{1}{2}\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)$$

$$\begin{aligned}
\mathbf{u}_{n+1-\alpha_f} &= (1-\alpha_f)\mathbf{u}_{n+1} + \alpha_f \mathbf{u}_n \\
\mathbf{v}_{n+1-\alpha_f} &= (1-\alpha_f)\mathbf{v}_{n+1} + \alpha_f \mathbf{v}_n \\
\mathbf{a}_{n+1-\alpha_m} &= (1-\alpha_m)\mathbf{a}_{n+1} + \alpha_m \mathbf{a}_n
\end{aligned}$$

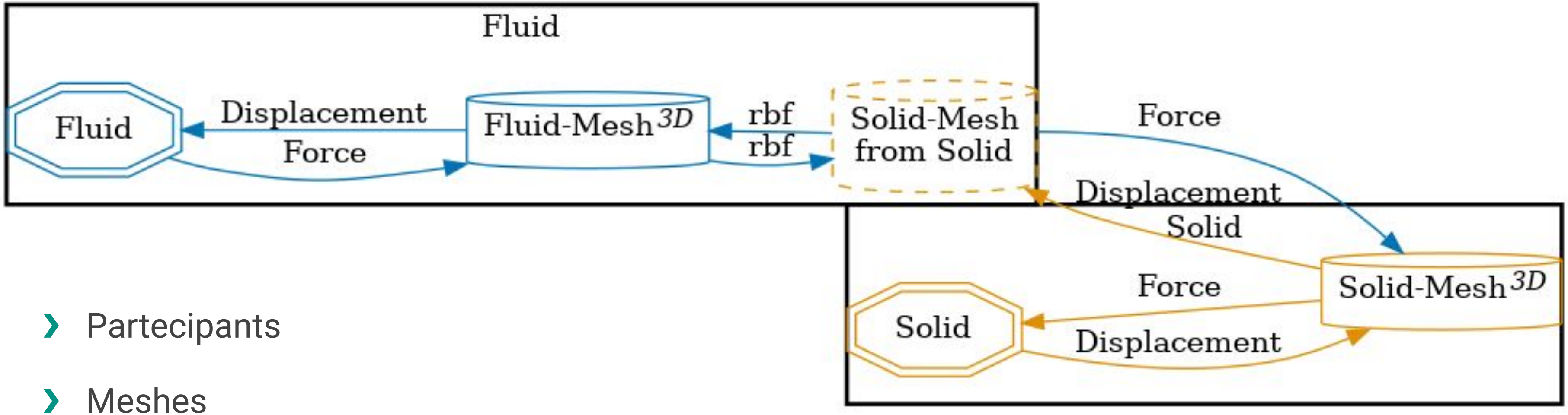
$$\alpha_m = \frac{2\rho_\infty - 1}{\rho_\infty + 1}, \quad \alpha_f = \frac{\rho_\infty}{\rho_\infty + 1}$$

Checkpointing Logic

- **1:** FEniCS saves a "snapshot" of the current structural **state variables**
- **2:** Fluid and structural solvers **exchange interface data** and **solve** for the current sub-step
- **3: Convergence** criteria are evaluated after each iteration.
- **4:** If convergence is NOT met, a **rollback** is triggered
- **5:** Once convergence is reached the structural and fluid fields are finalized and **updated**



preCICE flow diagram



- Partecipants
- Meshes
- Mapping
- Data exchange

preCICE configuration

```xml
  <participant name="Fluid">
    <export:vtk directory="../precice-exports" every-n-time-windows="10" />
    <provide-mesh name="Fluid-Mesh" />
    <receive-mesh name="Solid-Mesh" from="Solid" />
    <write-data name="Force" mesh="Fluid-Mesh" />
    <read-data name="Displacement" mesh="Fluid-Mesh" />
    <mapping:rbf direction="write" from="Fluid-Mesh" to="Solid-Mesh"
constraint="conservative">
      <basis-function:compact-polynomial-c6 support-radius="0.1" />
    </mapping:rbf>
    <mapping:rbf direction="read" from="Solid-Mesh" to="Fluid-Mesh" constraint="consistent">
      <basis-function:compact-polynomial-c6 support-radius="0.1" />
    </mapping:rbf>
  </participant>
```

- Fluid Partecipant
- Mapping

preCICE configuration

```xml
<participant name="Solid">
   <export:vtk directory="../precice-exports" every-n-time-windows="10" />
   <provide-mesh name="Solid-Mesh" />
   <write-data name="Displacement" mesh="Solid-Mesh" />
   <read-data name="Force" mesh="Solid-Mesh" />
   <watch-point mesh="Solid-Mesh" name="LE-Tip" coordinate="0.0344982;0.147963;2.95"/>
   <watch-point mesh="Solid-Mesh" name="TE-Tip" coordinate="0.80073;0.0168795;2.95" />
   <watch-point mesh="Solid-Mesh" name="C-Tip" coordinate="0.356267;0.0840917;2.95" />
 </participant>
```

- Solid Partecipant
- Mapping

preCICE configuration

```xml
<m2n:sockets acceptor="Fluid" connector="Solid"
             port="20000"
             network="eth0"
             exchange-directory=".."
             enforce-gather-scatter="true" />
```

- Communication

preCICE configuration

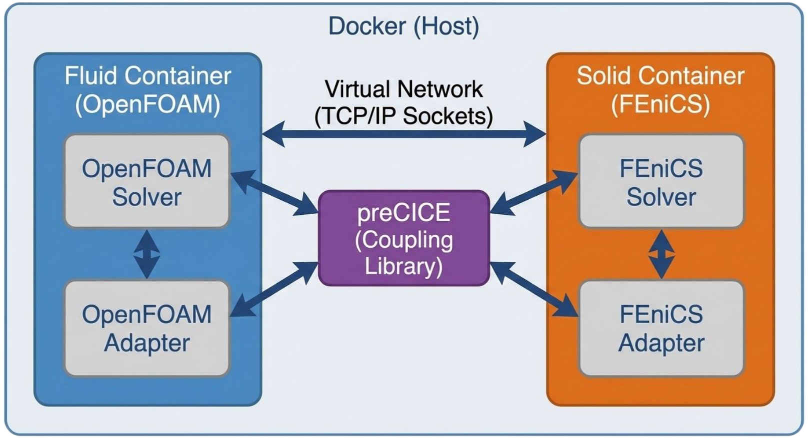
```
<coupling-scheme:parallel-implicit>
    <time-window-size value="0.001" />
    <max-time value="2.0" />
    <participants first="Fluid" second="Solid" />
    <exchange data="Force" mesh="Solid-Mesh" from="Fluid" to="Solid" />
    <exchange data="Displacement" mesh="Solid-Mesh" from="Solid" to="Fluid" />
    <max-iterations value="50" />
    <relative-convergence-measure limit="5e-3" data="Displacement" mesh="Solid-Mesh"
/>  <relative-convergence-measure limit="5e-3" data="Force" mesh="Solid-Mesh" />
    <acceleration:IQN-ILS>
      <data name="Displacement" mesh="Solid-Mesh" />
      <data name="Force" mesh="Solid-Mesh" />
      <preconditioner type="residual-sum" />
      <filter type="QR2" limit="1e-3" />
      <initial-relaxation value="0.5" />
      <max-used-iterations value="100" />
      <time-windows-reused value="15" />
    </acceleration:IQN-ILS>
  </coupling-scheme:parallel-implicit>
</precice-configuration>
```

- Time Settings
- Coupling Scheme
- Acceleration

Computational Environment with Docker

Docker (containerized Structure):

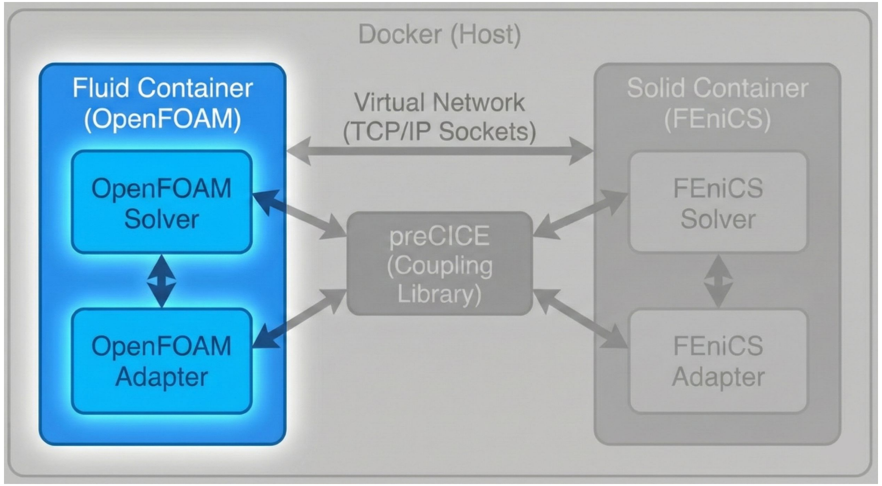
- Orchestration: Managed via **Docker Compose**
- Isolation: Two independent "Participant" containers
- Immutability: Host-independent and reproducible stack
- Network: Dedicated fsi_net bridge



Computational Environment with Docker

Fluid Container (OpenFOAM):

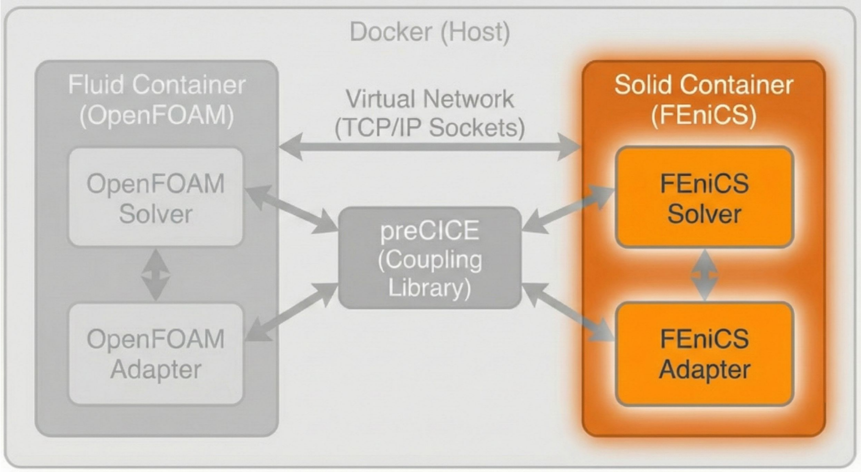
- Base Image: opencfd/openfoam-default:2306
- Role: CFD Solver (Fluid Dynamics)
- Environment: C++ based stack
- Build: Compiles preCICE and Adapter **from source**



Computational Environment with Docker

Solid Container (FEniCS):

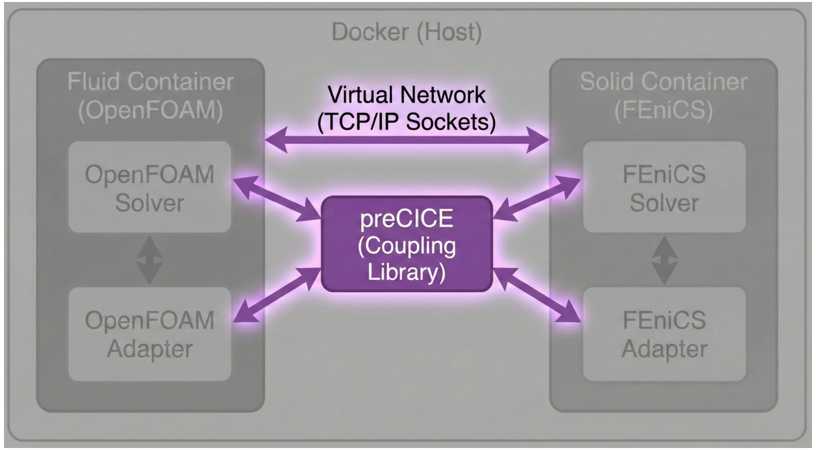
- Base Image: fenics-gmsh
- Role: **FEM Solver** (Structural Mechanics)
- Environment: Python 3 stack
- Build: Compiles preCICE and Adapter from source



Computational Environment with Docker

Coupling & Network:

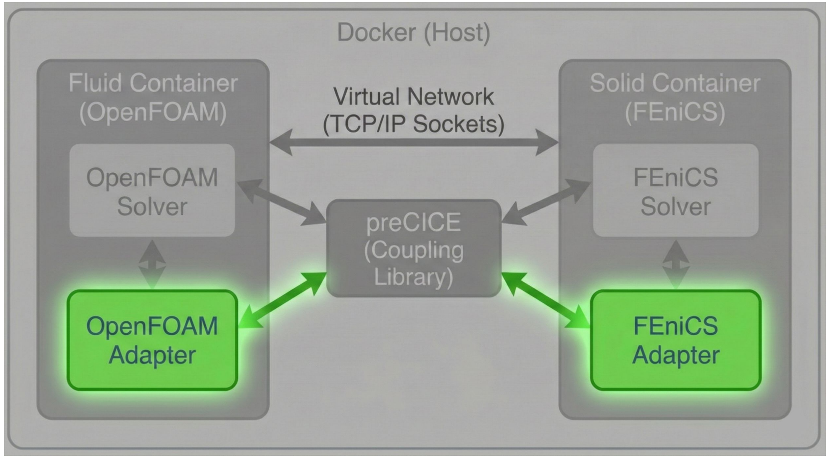
- Core: preCICE v3.3.0 coupling library
- Protocol: **TCP/IP** Sockets via **Virtual Network**
- Function: connecting container and synchronize solver
- Data Exchange: forces and displacements



Computational Environment with Docker

Solver Adapters:

- Goal: Interfacing solvers with Precice
- Openfoam adapter:
  - Compiled Function Object (External Plugin)
- Fenics adapter:
  - Direct integration into structural scripts



Mesh & Domain independence analysis

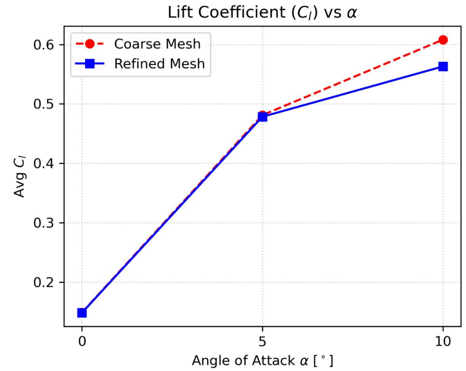
Mesh independence analysis

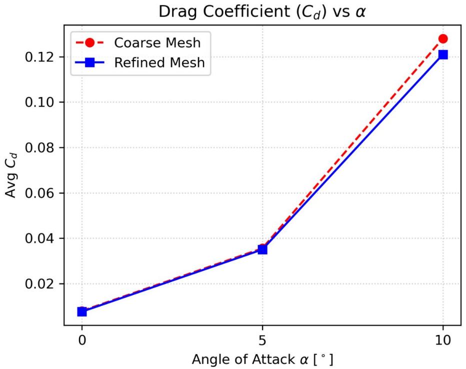
- Two mesh configurations
- Multiple angle of attacks

Domain independence analysis

- Two additional domains (1.25x, 1.5x)
- Aerodynamic coefficients compared

Domain Configuration	Avg C_l	Avg C_d
Original (Baseline)	0.563	0.121
1.25× Extended	0.593	0.123
1.5× Extended	0.585	0.123



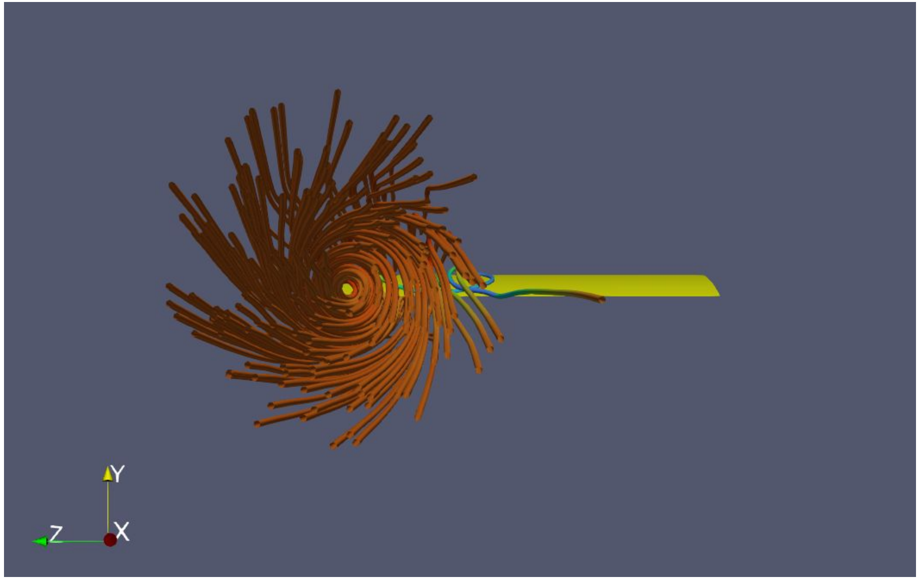


Validation

Comparison against literature

- 2D Experimental Data vs 3D CFD
- Additional drag induced by the finite-wing effects (wingtip vortices)
  - computed using the Lifting Line Theory

AoA	Simulated C_d	Theoretical C_d
$0°$	0.0076	0.0084
$5°$	0.0350	0.0387
$10°$	0.1210	0.0552



Scalability Analysis

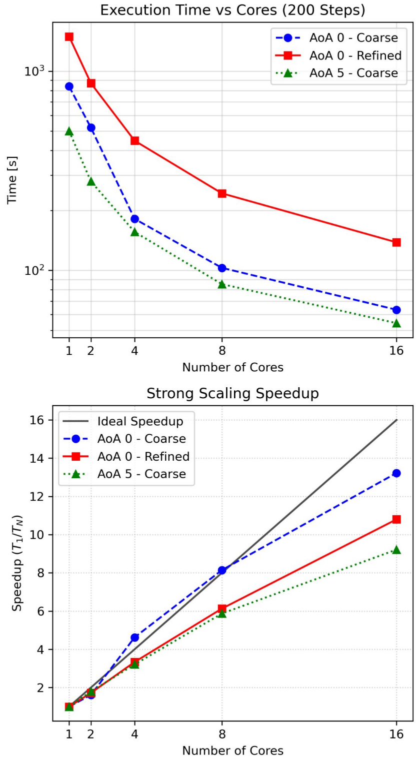
- Run on the dida.q queue of the Calimero cluster
- Warm-up and Run phases

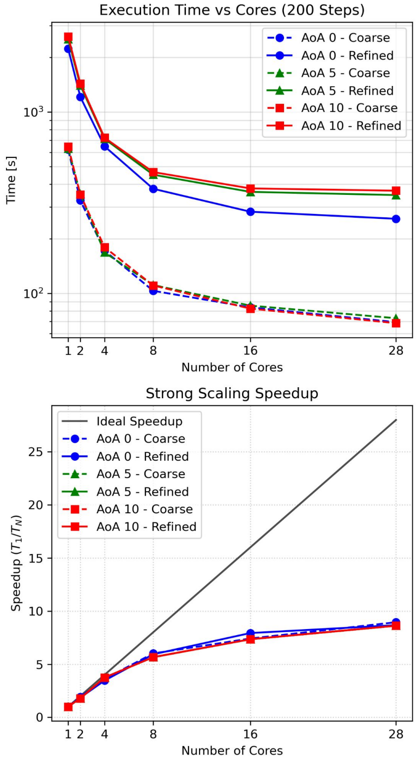
First analysis

- Subset of configurations
- Near-linear results

Second analysis

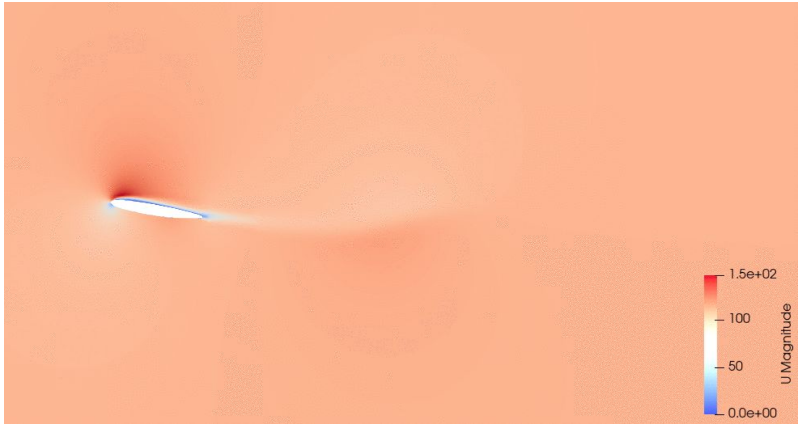
- Complete dataset
- Sub-linear results





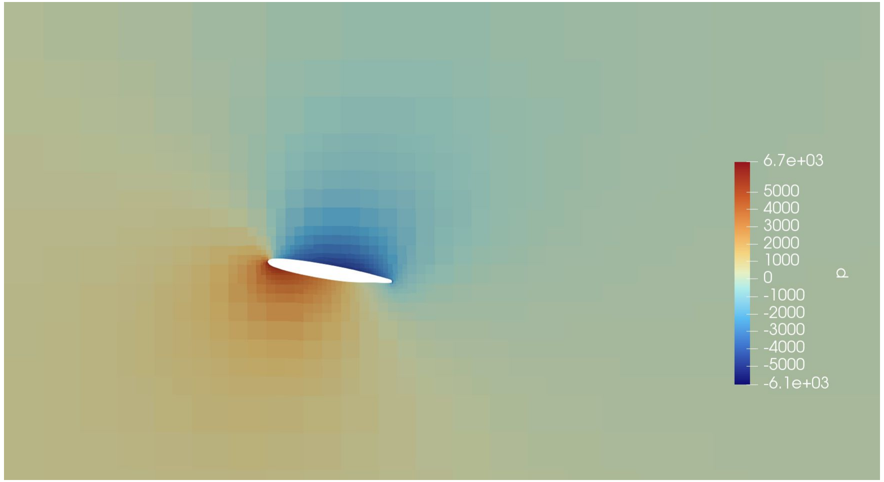
Velocity

- Separation around the trailing edge
- Three key aerodynamic regions can be identified:
  - **Stagnation point**
  - **Suction Side Acceleration**
  - **Wake Region**



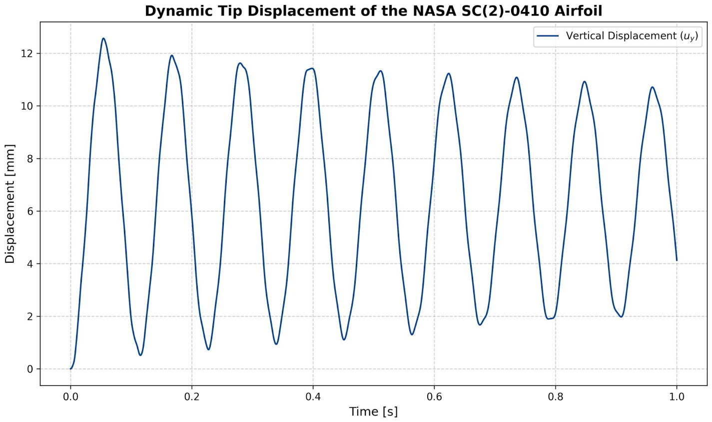
Pressure

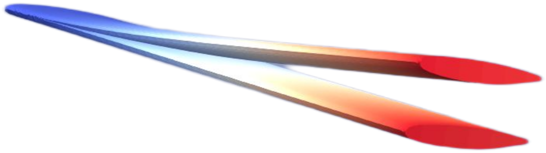
- The aerodynamic loads acting on the wing are driven by the static pressure distribution
- Three key pressure regions can be identified:
  - **Stagnation Region**
  - **Suction Side on the upper surface**
  - **Pressure Recovery**



Tip displacement

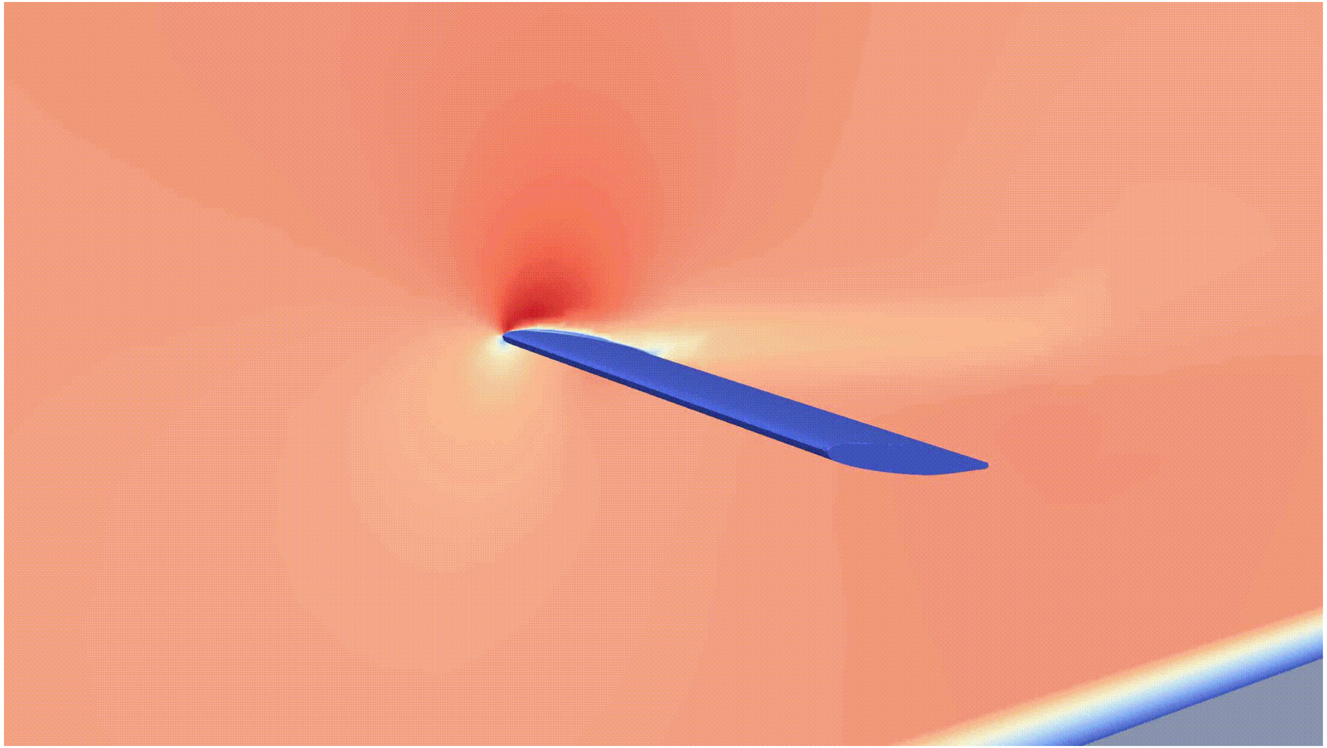
- Direct measure of the wing's deformation under the aerodynamic loads
- Based on the displacement time-history, the following observations can be made:
  - **Transient and Periodic Behavior**
  - **Displacement Range**
  - **Numerical Stability**





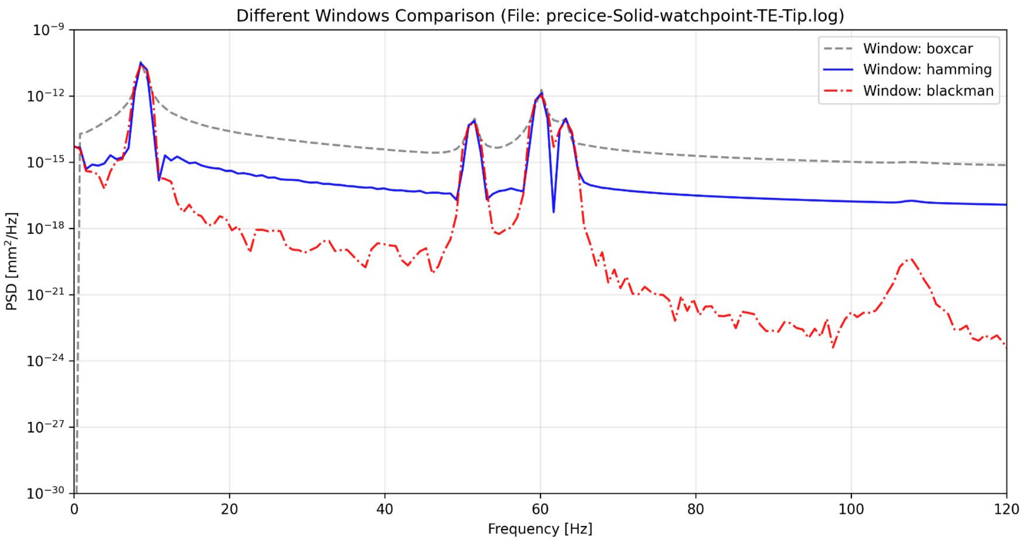
Warped displacement visualization

Tip displacement



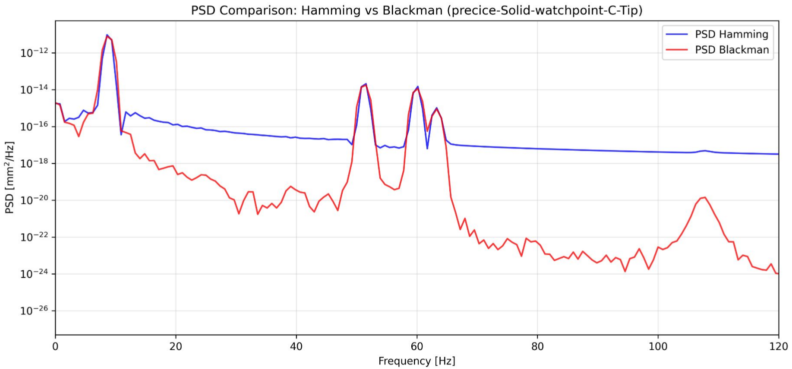
Spectral analysis

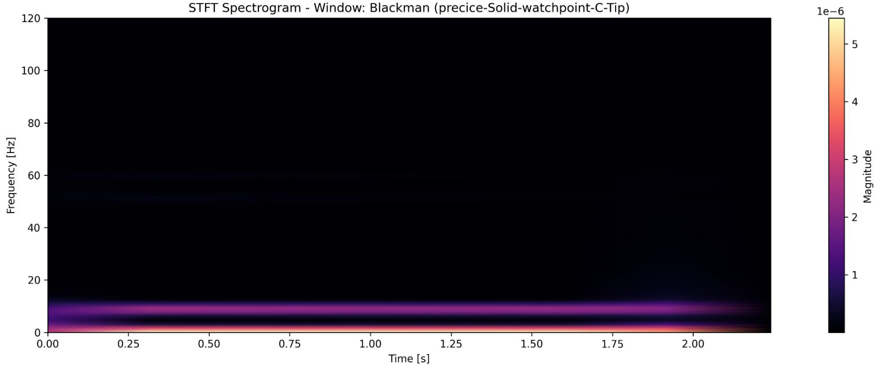
- Different **windowing** methods analyzed to compare noise attenuation
- PSD analysis on three different **watchpoint**, set inside `preciceconfig.xml`
  - Leading Edge (**LE-Tip**)
  - Center (**C-Tip**)
  - Trailing Edge (**TE-Tip**)



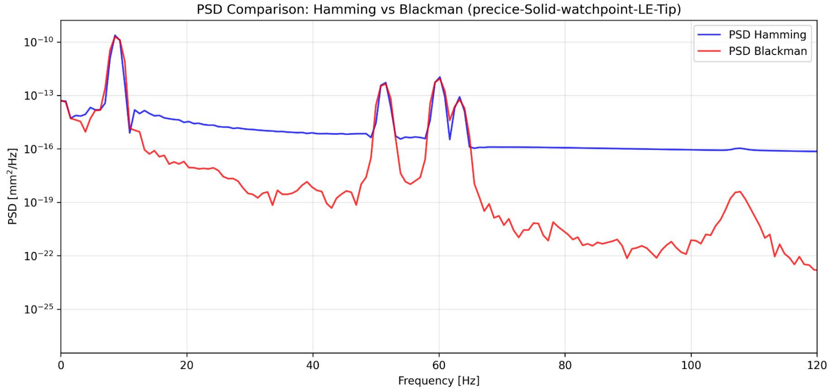
Spectral analysis

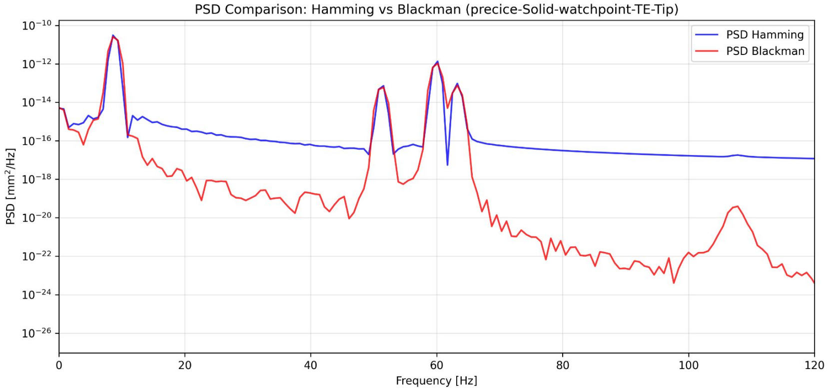
- **Stability** evaluated with a **STFT**, generating spectrograms for the simulation duration
- Damped oscillation of the aluminum structure capture by the coupled simulation
- The system operates in a stable regime without aeroelastic instability (**flutter**)
- First two flessional frequency around x at 8 and 50 Hz, first torsional frequency at 60 Hz

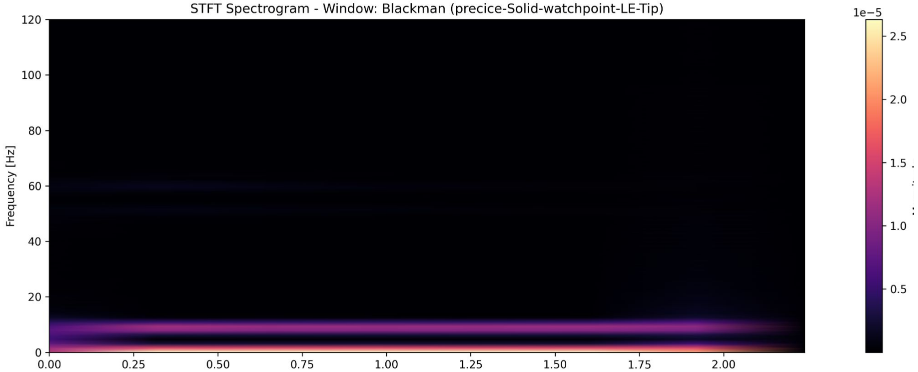


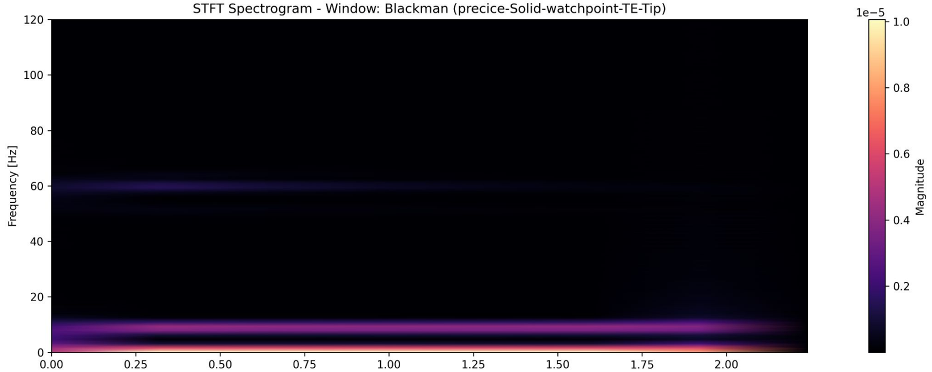


Spectral analysis









Thanks for the attention

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