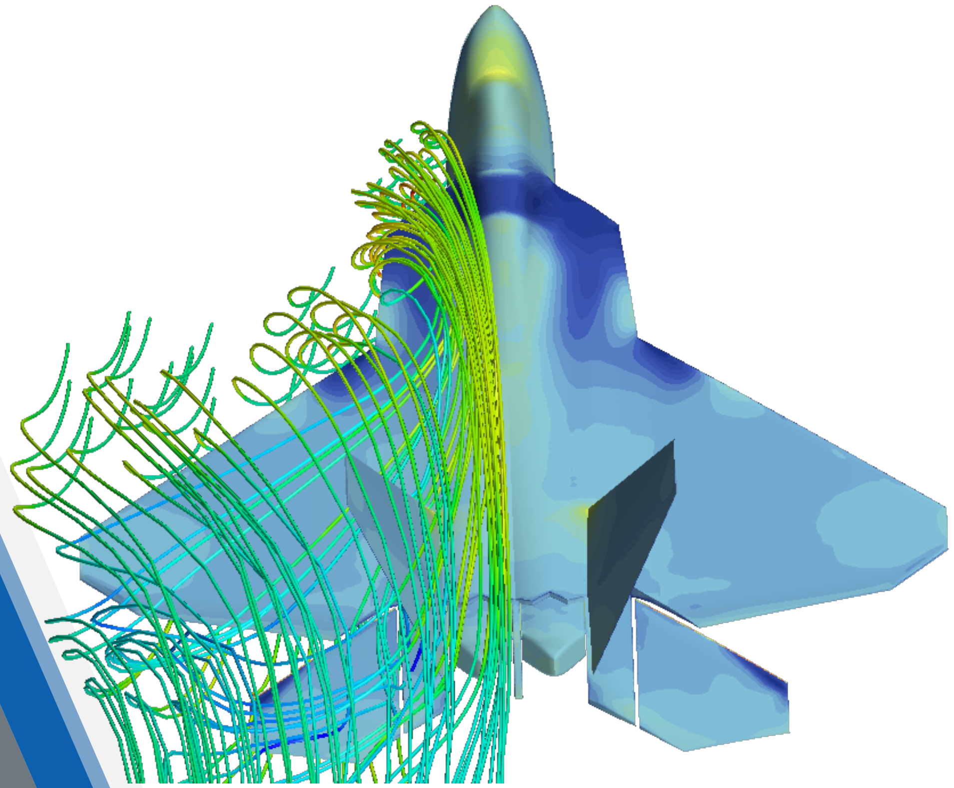
ATA ENGINEERING, INC.

Transonic Wing Flutter Analysis Using Simcenter STAR-CCM+ and Simcenter Nastran Co-Simulation

Date: 09/17/2023



Speakers:

- Host: Adam Green, ATA Engineering, Inc.
- Chris Ostoich, ATA Engineering, Inc.

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Who Are ATA Engineering?

We are an **employee-owned** small business with a **full-time staff of over 200**, more than 170 of whom are degreed engineers

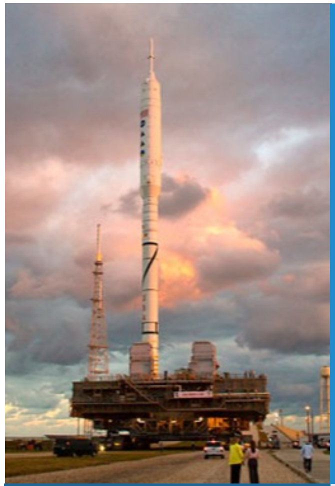
11
Registered Professional Engineers

Subject-matter experts recognized by

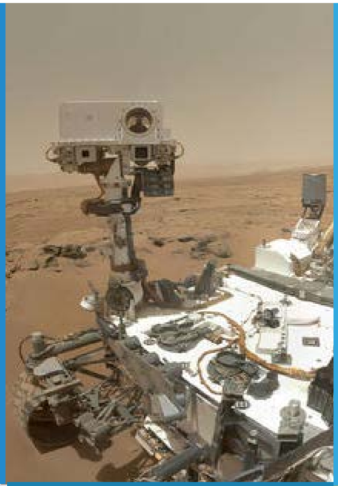
- Society of Experimental Mechanics
- American Society of Mechanical Engineers
- American Institute of Aeronautics and Astronautics

15
Average years of experience

ATA Engineering's **high-value engineering services** help solve the toughest product design challenges



Aerospace

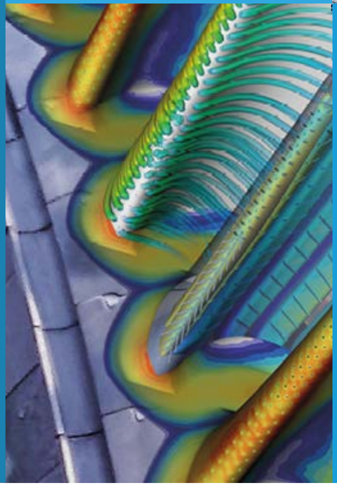


Spacecraft

Hypersonics & Composites

Defense

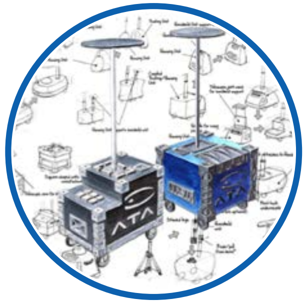
Power Generation



Themed Entertainment

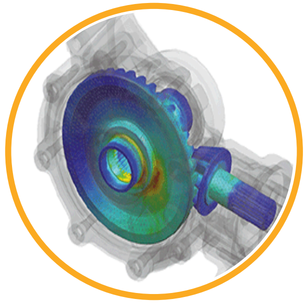
Our Services

We provide our customers with **complete, integrated solutions**



Design

From initial concept development to detailed structural design



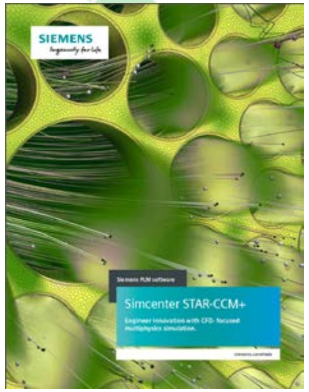
Analysis

Comprehensive structural, fluid, acoustic, and thermal analysis services

Test

Industry-leading structural test services for extreme loading environments

ATA Engineering is also a **Siemens Platinum Level** Solution Partner.



Our Software Services

ATA is a Platinum-level Solution Partner for **Siemens Digital Industries Software**

Siemens Value Added Reseller

Hotline Support

Nastran Training Material

Software Implementation

Siemens Preferred Training Provider

Software Integration

ATA Engineering is recognized as a Certified Expert Partner with validated expertise in Femap, STAR-CCM+, and Simcenter 3D.

Expert Partner
Digital Industries Software
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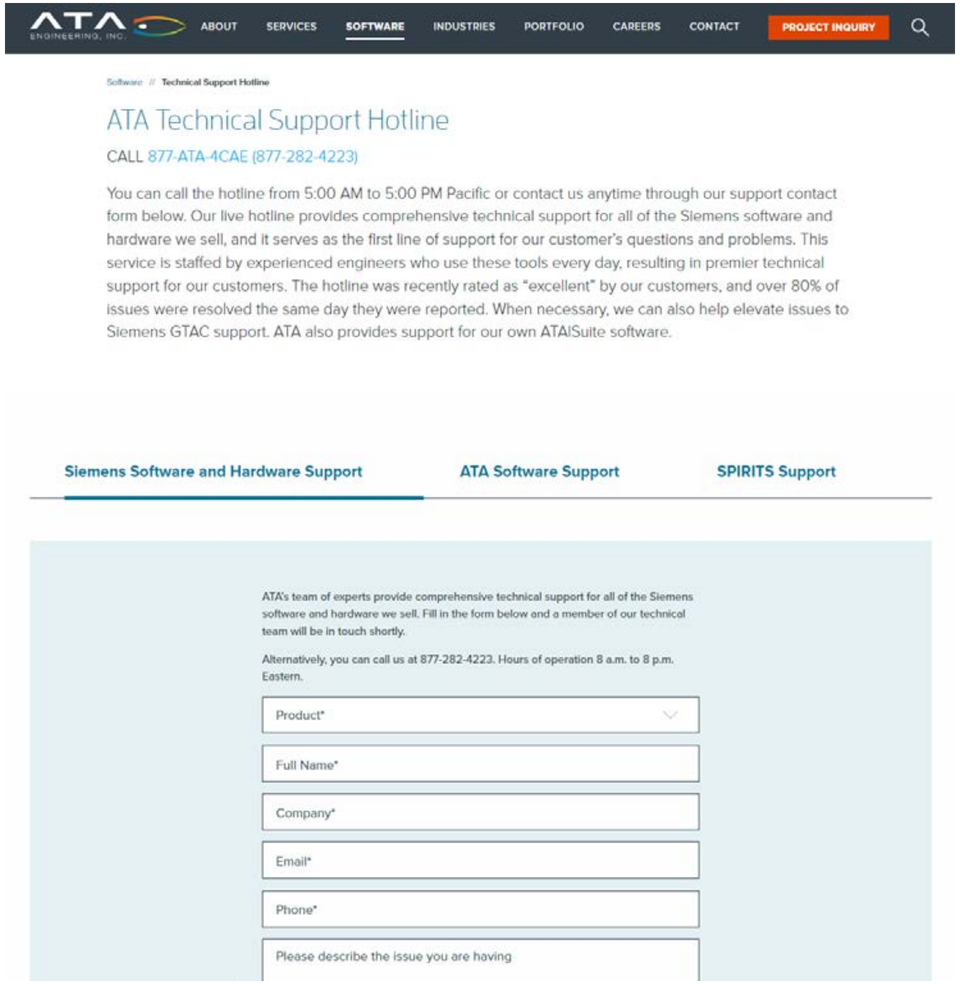
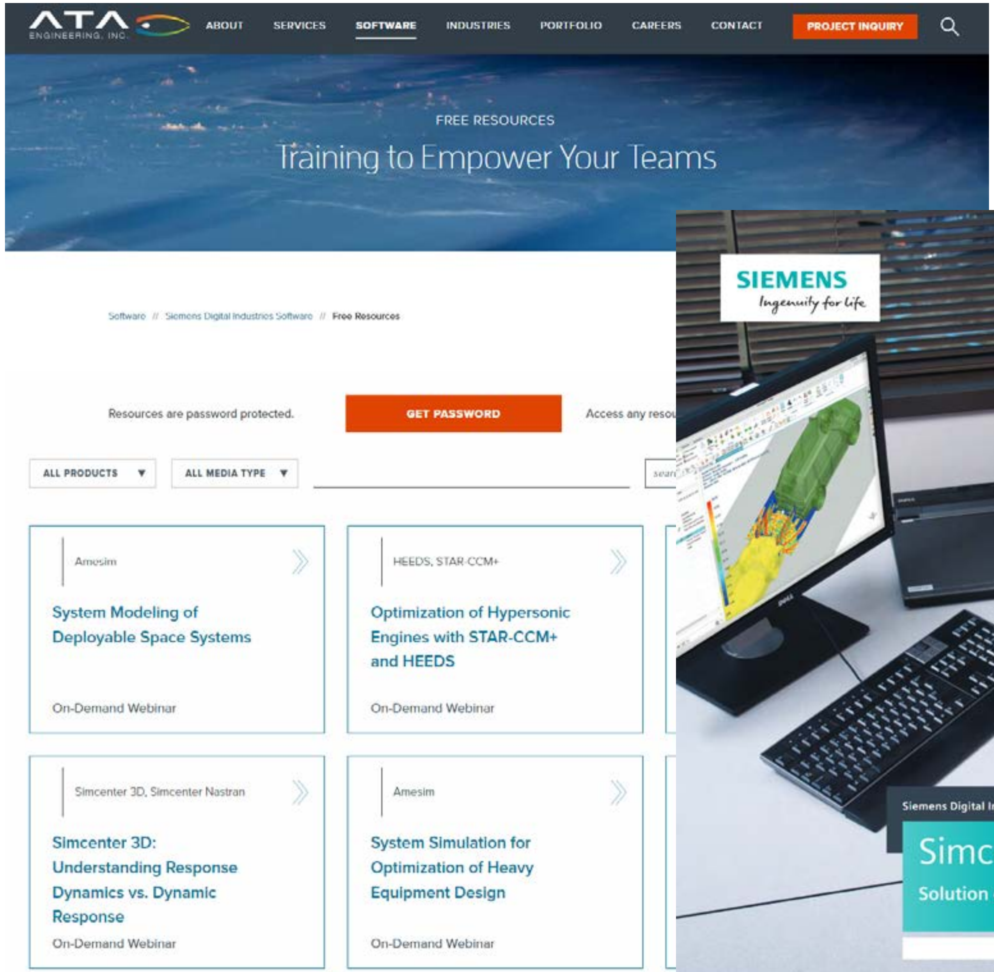
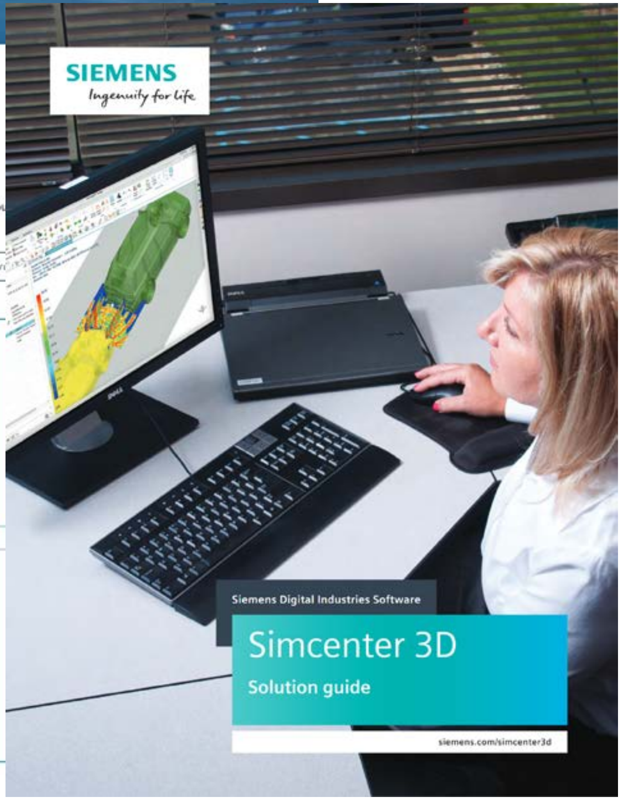
https://www.ata-e.com/







For More Information, Contact:

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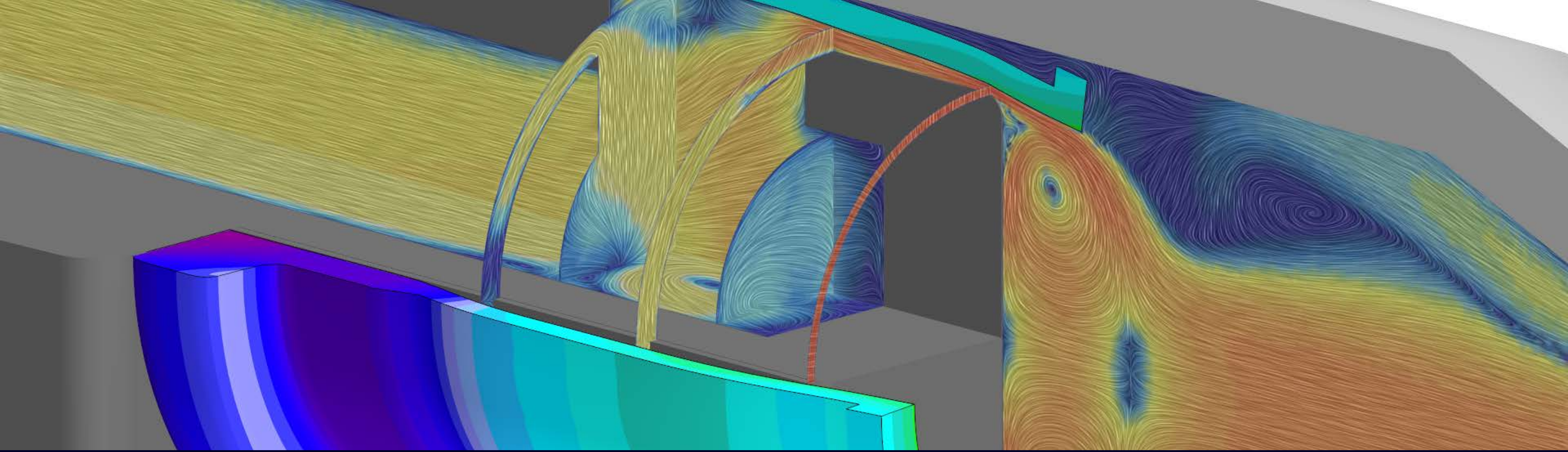
Smarter decisions. Better products. Faster.



Simcenter STAR-CCM+

Fluid-Structure Interaction (FSI)

Technology Spotlight | Last updated version: 2210*

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Overview:
Fluid-Structure Interaction (FSI)

Fluid-Structure Interaction Applications

Oil & Gas
- Riser VIV and FIV
- Pigging

Ground Transportation
- Fuel Sloshing
- Shock Absorber

Chemical Processing
- Mixing Tanks

Aerospace & Defense
- Aeroelasticity
- Wing Flutter

FSI

Energy
- Wind Turbines
- Turbomachines

Nuclear
- Rod Bundles

Life Science
- Stents
- Heart Valves

Marine & Offshore
- Slamming
- Free Falling Lifeboats

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FSI in Simcenter STAR-CCM+

- Wide Application Coverage
- Accurate
- Robust
- Efficient
- Provide Engineering Insight
- Supporting Collaboration

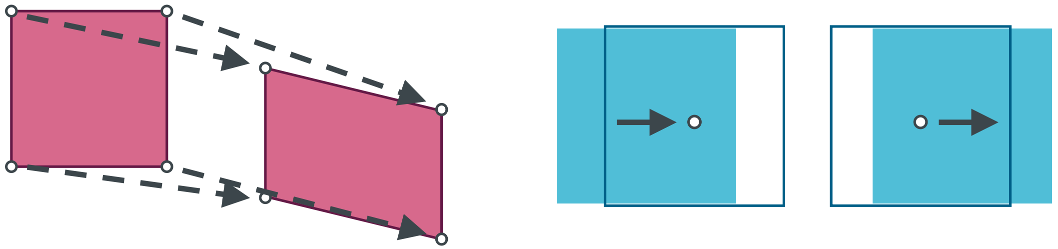
Spotlight on FSI

- Partitioned FSI using best-in-class discretization methods
- Accurate, robust and efficient methods to map surface data
- Range of methods for displacement of the fluid mesh
- Solution stabilization of the coupled system
- Modelling deformable structures attached to rigid 6-DOF bodies
- Providing engineering insight through data analysis
- Collaborate by exchanging data between toolsets

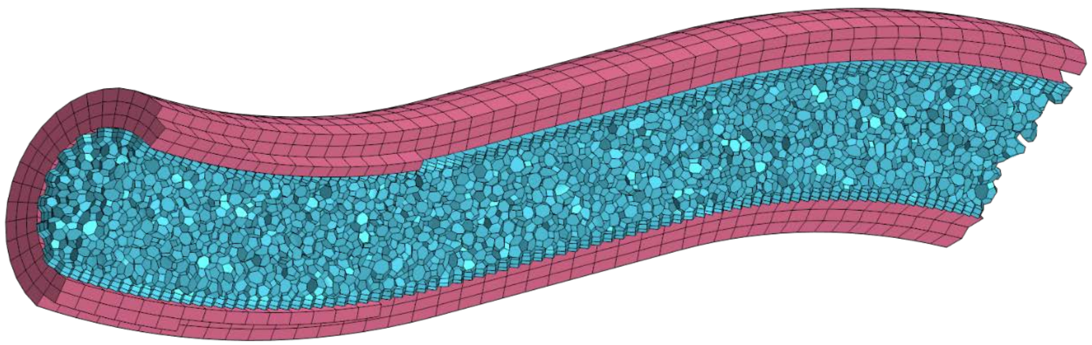
Modeling FSI in Simcenter STAR-CCM+

Partitioned FSI using best-in-class discretization methods

- Finite Volume (Eulerian frame) is the most successful, versatile and best established discretization method in Computational Fluid Dynamics (CFD)
- Finite Element (Lagrangian frame) is equally successful, versatile and established for structural mechanics
- Simcenter STAR-CCM+ combines both methods to offer the most comprehensive solution for partitioned FSI



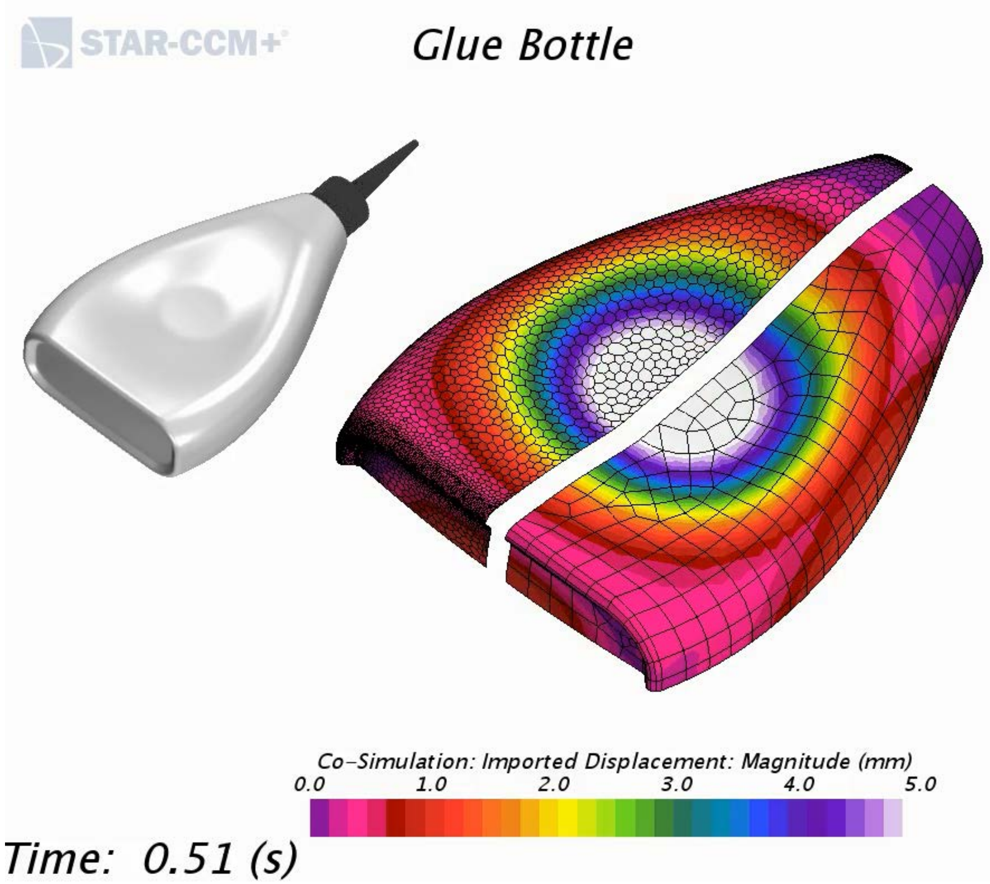
Lagrange Frame (FE) & Euler Frame (FV)



Modeling FSI in Simcenter STAR-CCM+

Accurate, robust and efficient methods to map surface data

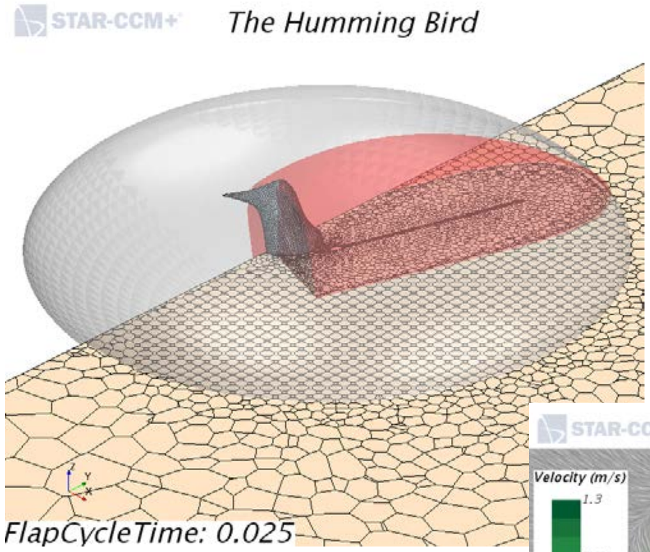
- Communication between fluid and structural models relies on mapping field values between the meshes
- The fluid-structure interface topology is non-conformal
- Simcenter STAR-CCM+ offers data mappers with state-of-the-art interpolation methods
  - Structure to fluid: Nearest neighbor, shape functions and least squares
  - Fluid to structure: Nearest neighbor, least squares, exact imprint and approximate imprint

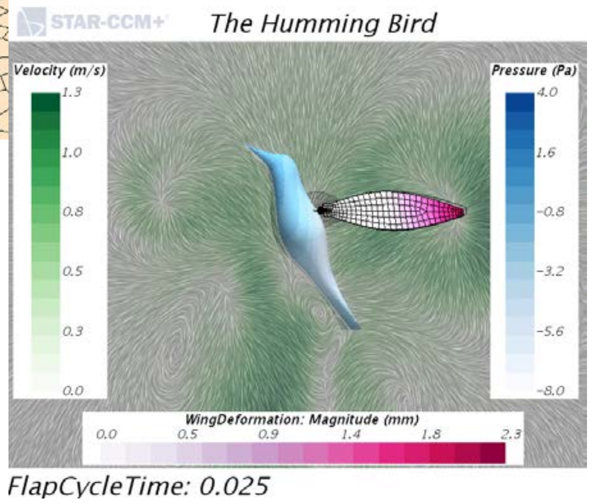


Modeling FSI in Simcenter STAR-CCM+

Range of methods for displacement of the fluid mesh

- Displacement at the fluid-structure interface is computed by the structural model, however the fluid domain must be deformed accordingly
- This displacement may be a combination of both rigid body motion and deformation
- Simcenter STAR-CCM+ offers:
  - Radial Basis Function (RBF) based morpher
  - B-Spline based morpher
  - Overset mesh motion (chimera mesh)
- There is no need for time consuming remeshing of the fluid domain no matter how large the rigid body motion





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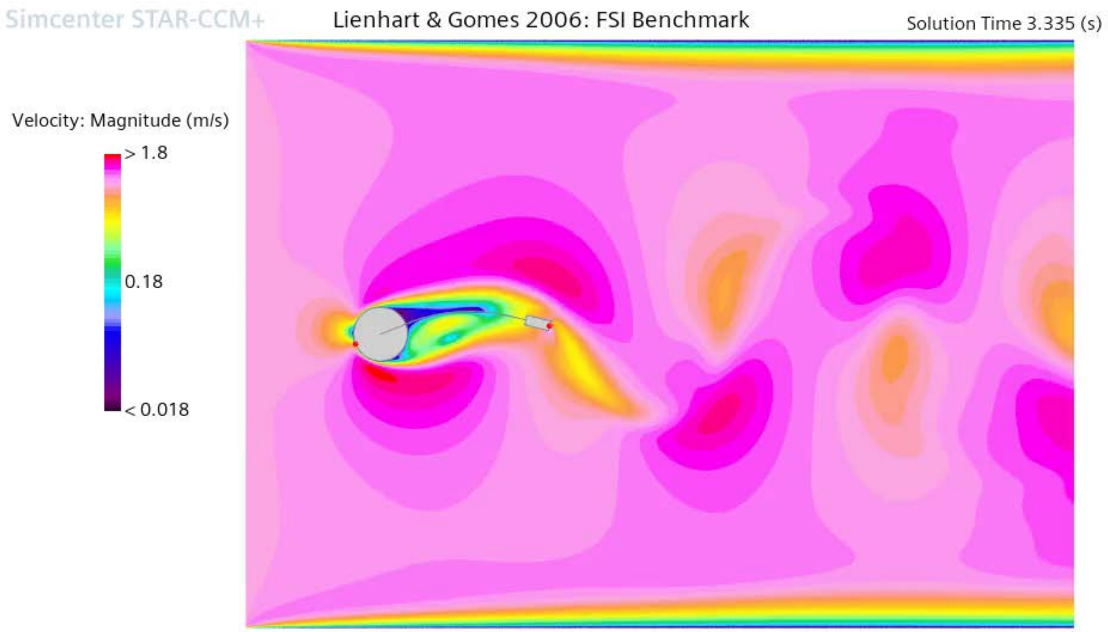
Modeling FSI in Simcenter STAR-CCM+

Solution stabilization of the coupled system

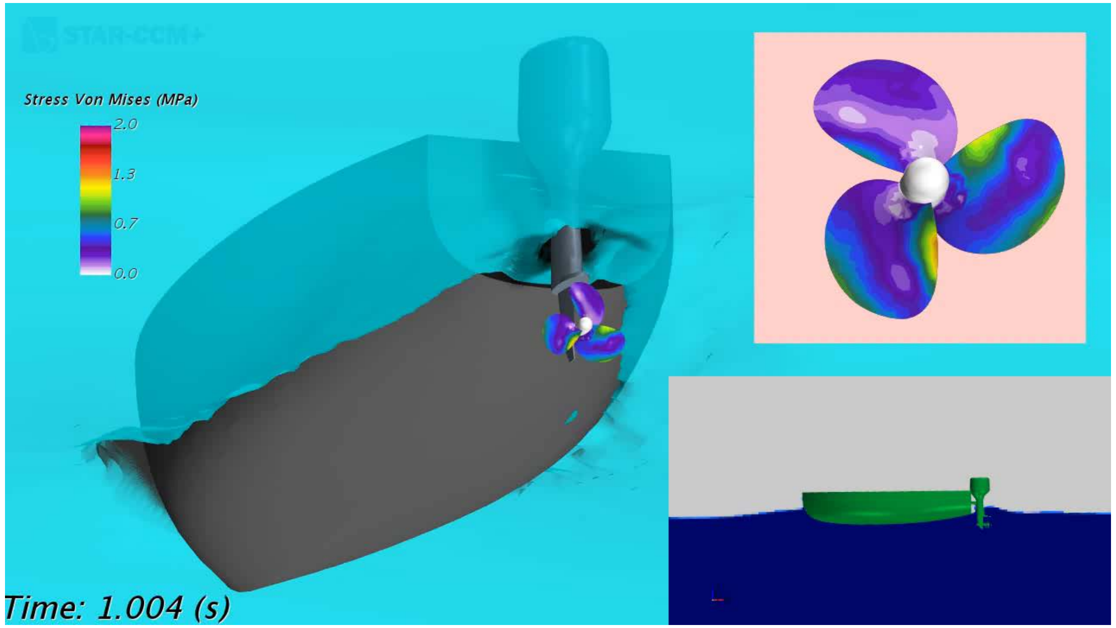
- Pressure at the fluid-structure interface is computed by the fluid model, mapped to the structural model and applied as a pressure load
- Simcenter STAR-CCM+ offers:
  - Explicit coupling of the models (data exchange occurs once every x units of time)
  - Iterative coupling of the models (data exchange occurs multiple times per time step)
  - For iterative coupling, solution stabilization methods are available including added mass pre-conditioning and displacement under-relaxation



Modeling FSI in Simcenter STAR-CCM+

Modelling deformable structures attached to rigid 6-DOF bodies

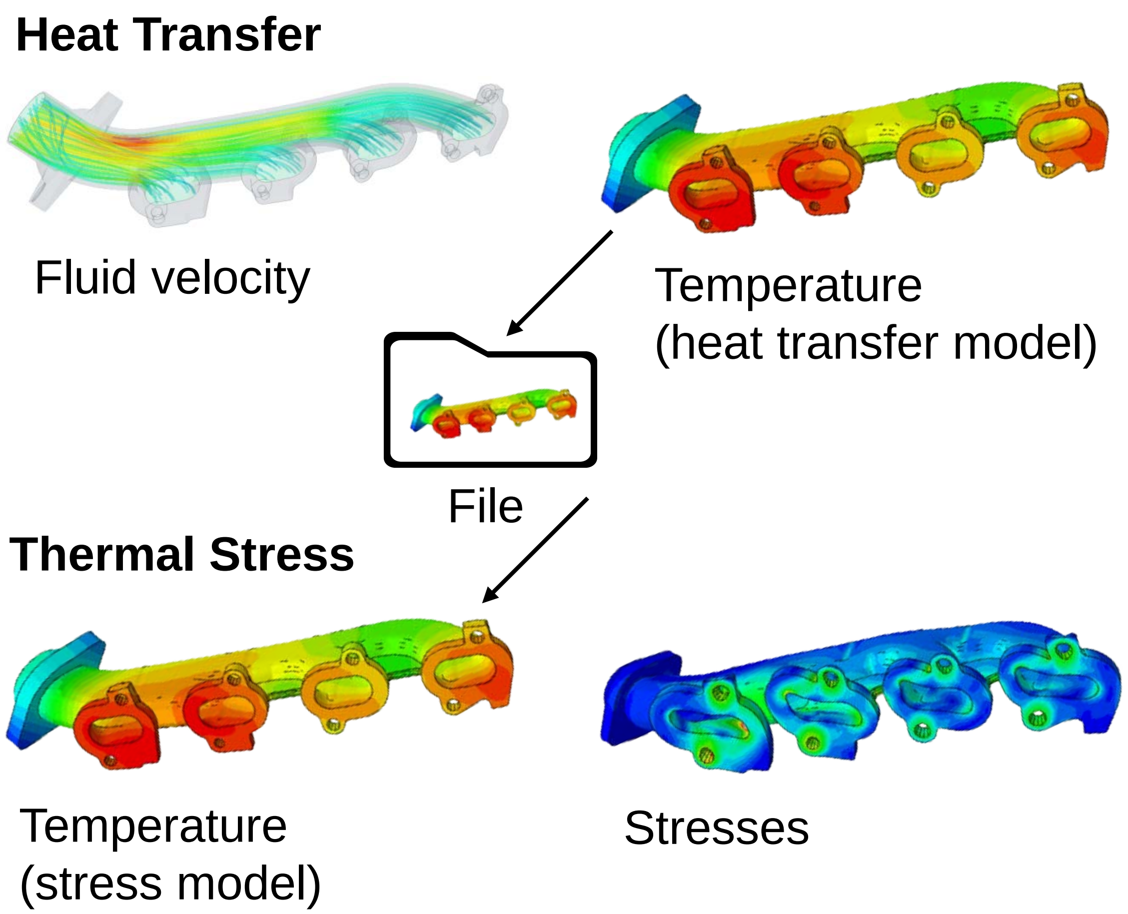
- For many FSI applications the structural displacement is a combination of rigid body motion and deformation
- Simcenter STAR-CCM+ is able to perform FSI simulation with objects which are undergoing rigid body motion (either prescribed or computed)
  - For example - deformation of propeller spinning at fixed RPM on a moving boat
- The structural model computes only the deformation, with rigid body motion being handled by a 6-DOF solver
- As deformations are typically small, there is no need for large displacement theory (non-linear geometry)



Modeling FSI in Simcenter STAR-CCM+

Collaborate by exchanging data between toolsets

- Although Simcenter STAR-CCM+ can perform all-in-one fluid and structural analysis, for some classes of FSI simulation it is desirable to perform the two studies separately
- In large organizations, the ability to exchange data between different toolsets is a key enabler for collaborative design
- Simcenter STAR-CCM+ can read a range of 3rd party formats, making it possible to import meshes and fields
- The imported fields can be mapped from the imported mesh to the internal mesh for subsequent usage
- Simcenter STAR-CCM+ can also export mesh and field data in various formats



Summary

- Predict and understand fluid-structure interaction
- Explore many design variants early in development

Wide Application Coverage

Accurate

Robust

Efficient

Provide Engineering Insight

Supporting Collaboration

Simcenter STAR-CCM+

- Best in class discretization techniques for flow and structural models
- A versatile partitioned FE-FV approach for any application
- Accurate data mappers, flexible data exchange protocols and efficient mesh deformation models
- Efficient solution procedures for 1-way, weak 2-way or even strong 2-way coupled applications
- Integrated post processing and support for various model and solution data formats

Modelling 1-Way Coupled Physics

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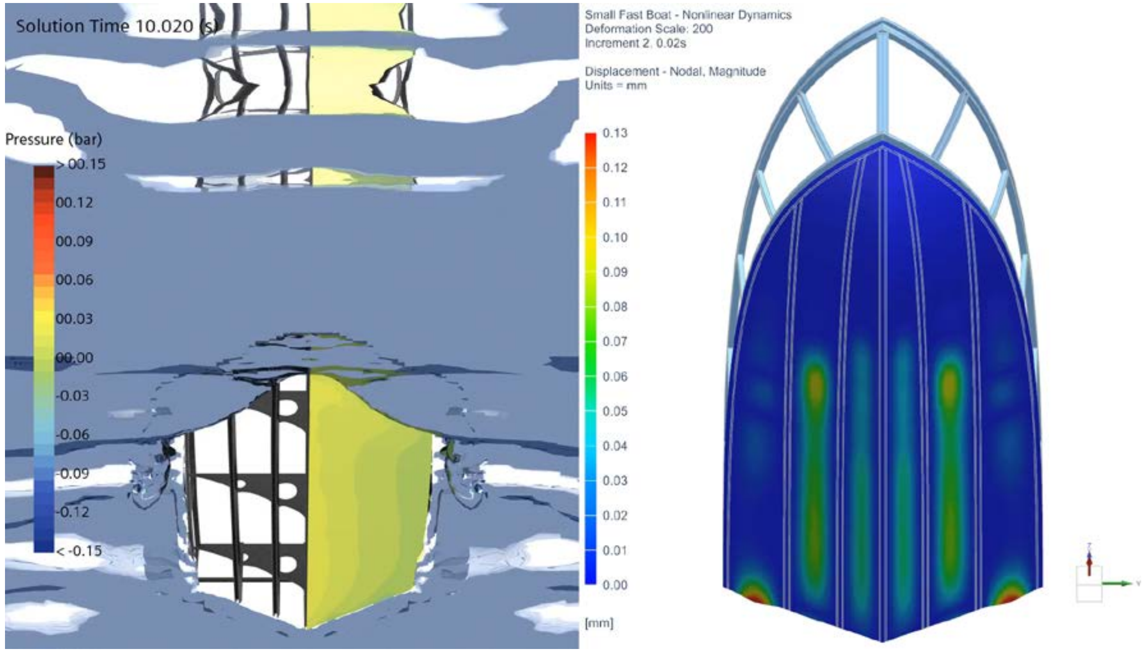
Example: 1-way coupled fluid to structure

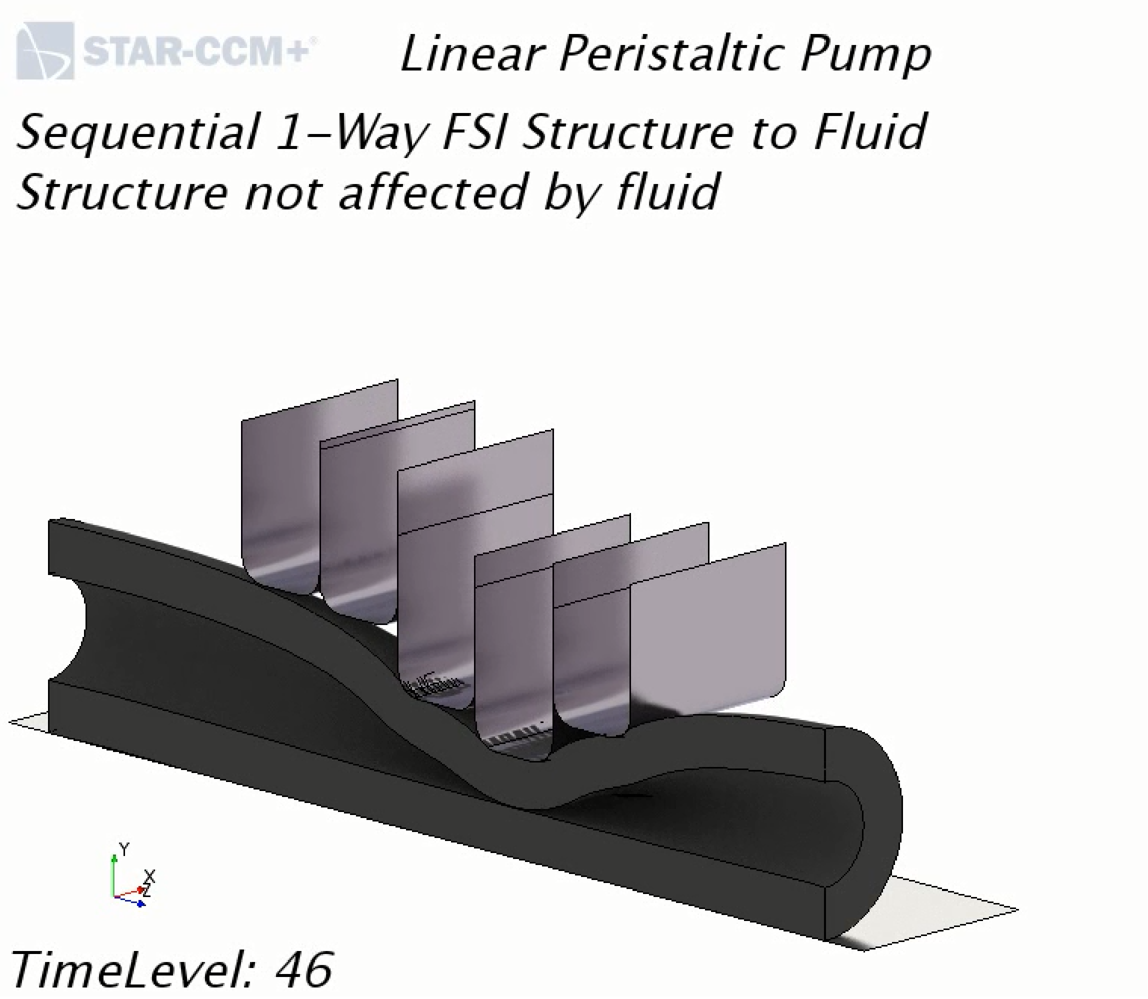
- The assumption behind 1-way coupling fluid to structure is: The fluid flow is not affected by deformations of the structure
- The accuracy of this approximation depends on the application and engineering question
- Fluid and structure can be solved in sequence
- No coupling stability problems and no fluid mesh deformation (morphing) required
- The results from one single flow simulation are sufficient to analyze any structural design, as long as the wet surface doesn't change (change of material, mounting, material fiber orientation, internal stiffeners…)



Additional information can be found in this blog:
[CFD-FEA coupling in Simcenter – lowering pressure and stress]

Example: 1-way coupled structure to fluid

- The assumption behind 1-way coupling structure to fluid is: The structure is not affected by the fluid flow
- The accuracy of this approximation depends on the application and engineering question
- Fluid and structure can be solved in sequence
- No coupling stability problems
- The results from one single structure simulation are sufficient to analyze any set of fluid flow boundary conditions (change of flow velocity, pressure difference…)



1-way coupled models

Pros and Cons

Whenever the engineering question allows it the application should be setup as a 1-way coupled model using files for the data exchange

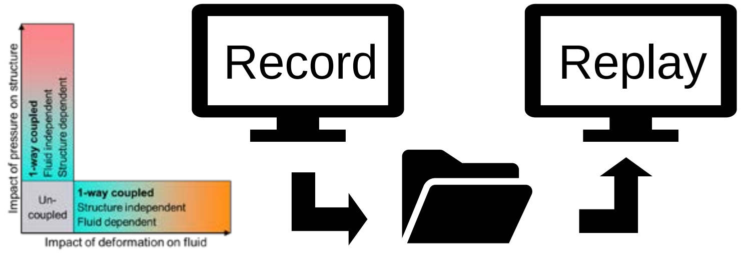
Pros:

- Low computational costs
- Straight forward, no stability problems
- Suitable for design space exploration

Cons:

- Only accurate if the assumption of 1-way coupled physics is valid for the given application and engineering question

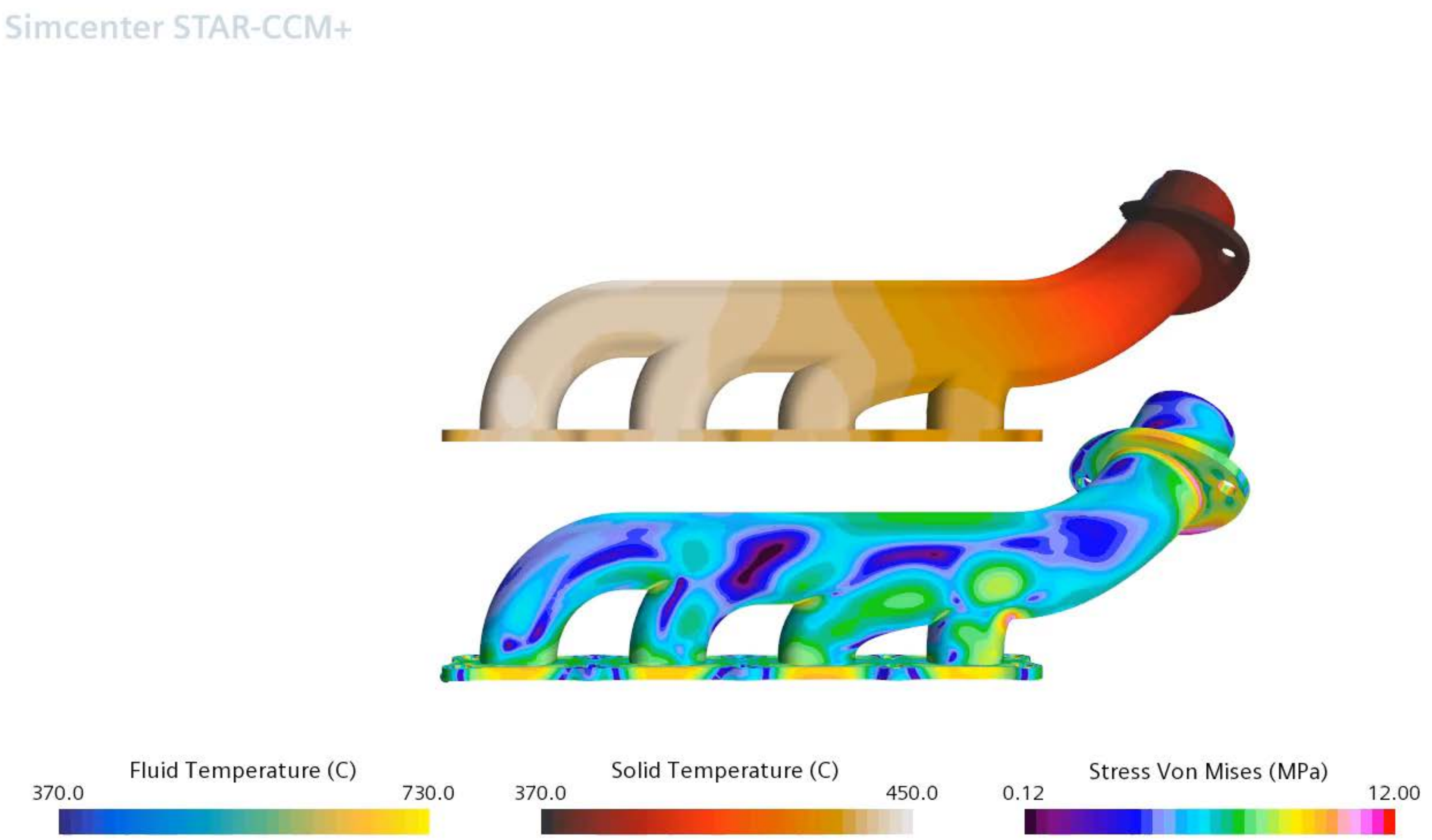
Solution Strategy



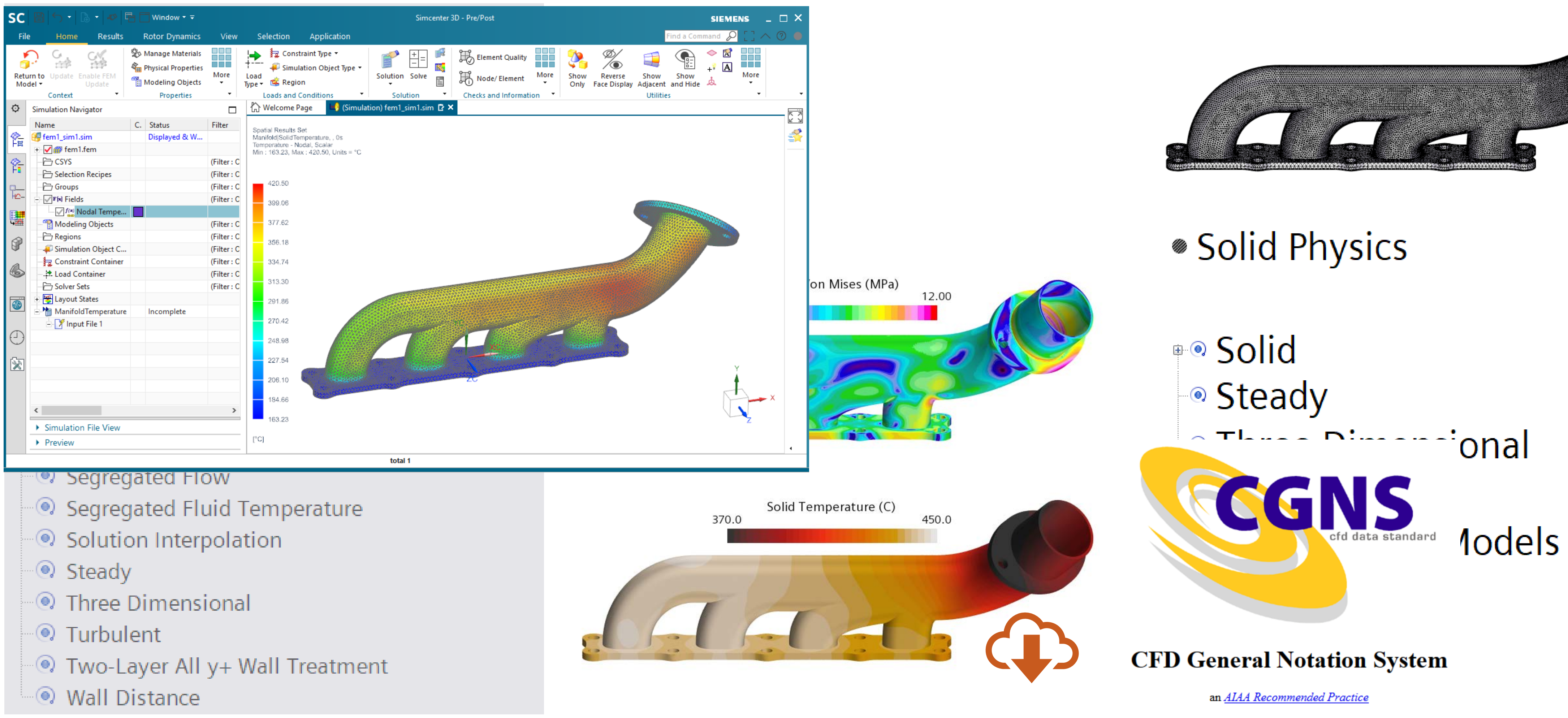
Compute the independent solution, record solution data to a file, replay the recorded solution data as boundary condition

Recording the solution data makes it possible to study variations of the dependent model without having to solve the independent model again

Heat transfer and thermal stress
Exhaust Manifold



Heat transfer and thermal stress
Exhaust Manifold Continued



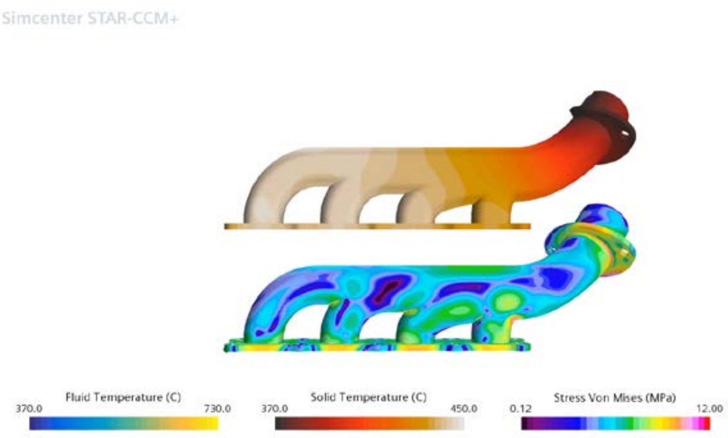
Key Enablers

Conjugate fluid-solid heat transfer using

- Finite volumes for the fluid
- Finite elements for the solid

Thermal stress using finite elements

➢ Only one single mesh for the solid

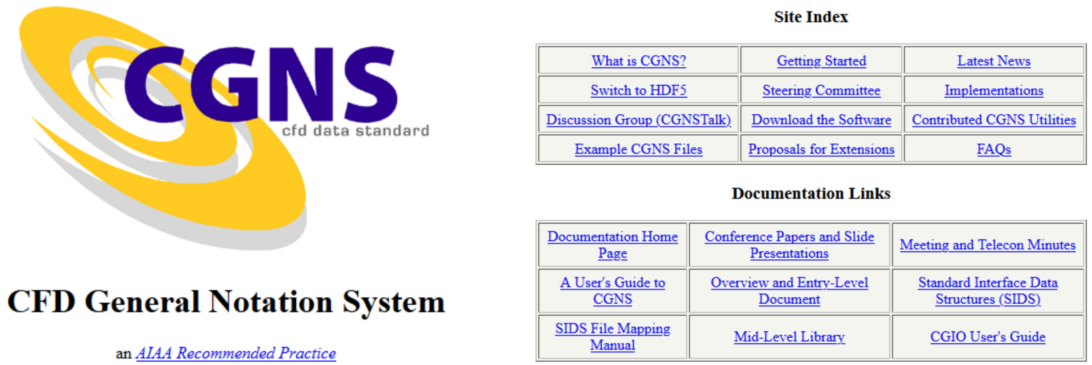


Export & import of meshes and fields via CGNS files through links in the simulation tree

➢ Storing the temperature enables minor modifications of the stress model without having to repeat the heat transfer simulation

➢ Convenient workflow & traceability of data

➢ Data exchange with other CAE tools

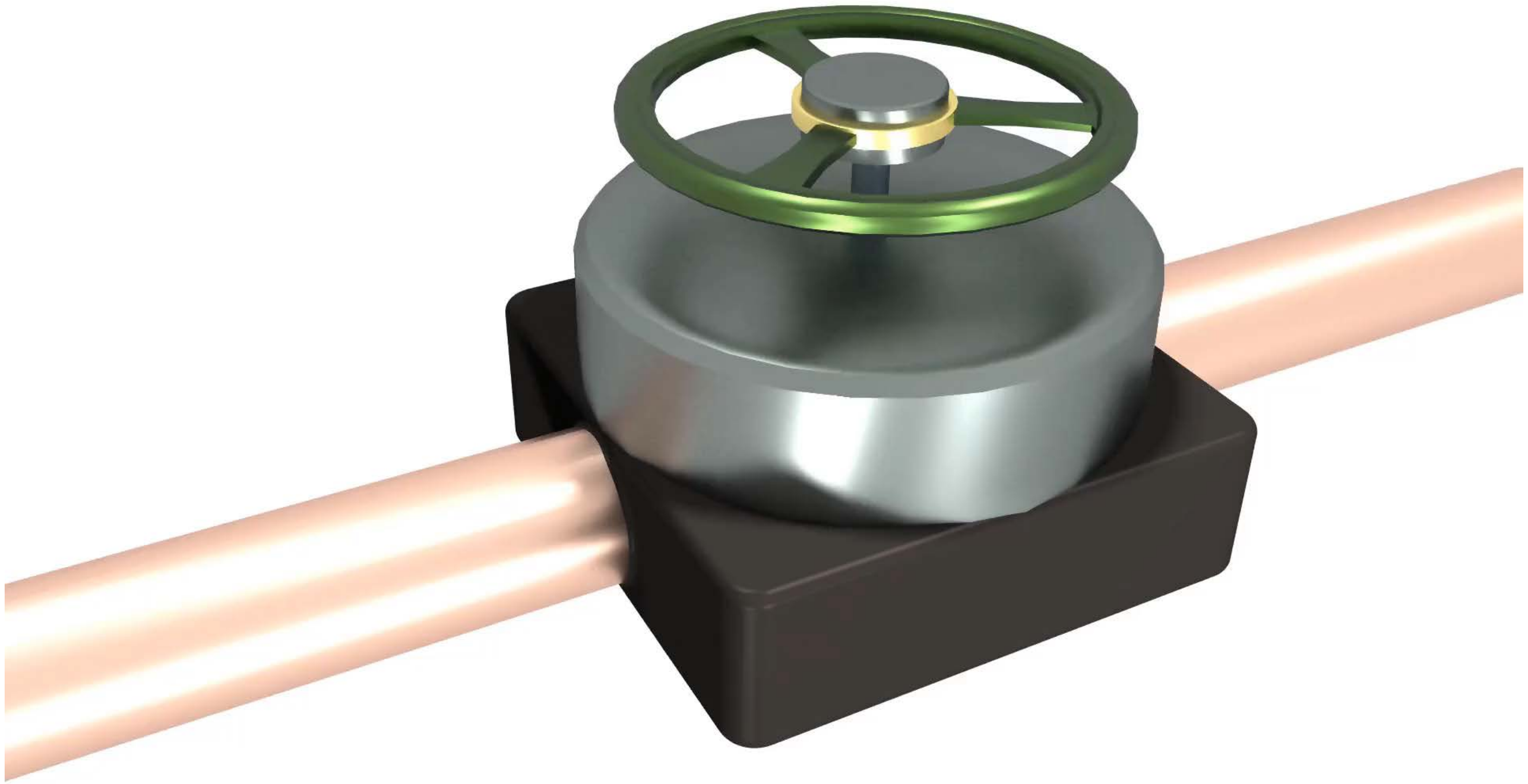


https://cgns.github.io/

Simcenter STAR-CCM+ Finite Element Solid Stress and Finite Element Solid Energy Capability Sheet

Material Laws	Linear-elastic & elastic-plastic (isotropic, orthotropic, anisotropic), hyperelastic (isotropic)
Solvers	Direct & iterative (iterative for Finite Element Solid Energy only)
Solution	Static (steady), dynamic (transient), linear geometry, non-linear geometry
Elements	3D continuum elements only, hex, tet, wedge, pyramid, 1st & 2nd order
Mechanical BCs	On point, line & surface segments: Force, pressure, traction, displacement On boundaries (surface): Symmetry On regions (volume): Body load & body load derivative
Thermal BCs	On boundaries (surface): Adiabatic, Heat Flux, Heat Source, Temperature, Convection On regions (volume): Volumetric Heat Source, Total Heat Source, Specific Heat Source
Interfaces	Conformal and non-conformal (surface to surface and node to surface formulation)
Comments	Supports the concept of Simcenter STAR-CCM+ motions including DFBI / 6DOF. Frictionless contact of an elastic body with a rigid tessellated geometry part is available starting 2022.1

Frictionless contact with a moving rigid and infinite plane



Available as tutorial: Tutorials > Solid Stress > FSI with Opening and Closing Flow Paths: Diaphragm Valve

Modelling 2-Way Coupled Physics

Strong and weak 2-way coupled physics

Weak 2-way coupled physics

Fluid: Low density and compressible (gases)
Structure: Heavy and stiff
Ratio of fluid density to solid density: << 1
Example: Aeroelasticity

Strong 2-way coupled physics

Fluid: High density and incompressible (liquids)
Structure: Light and flexible
Ratio of fluid density to solid density: ~ 1
Example: Hydroelasticity

2-way coupled models

Pros and Cons

An application should only be modeled as 2-way coupled if the physics and the engineering question requires two way coupling. A multi-physics single simulation or co-simulation is most suitable.

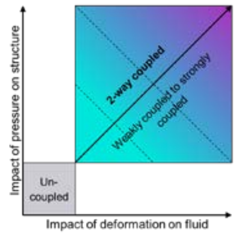
Pros:

- Always valid, no simplification or assumption

Cons:

- High computational costs
- Challenging

Solution Strategy



Both physics must be solved at the same time

Solution data must be exchanged with a high frequency

The data should be exchanged in memory and not via files (superior speed)

Multi-physics single simulation or co-simulation

Capability Chart 2-Way FSI

Last updated for: 2022.1	Single Simulation	Co-Simulation	Co-Simulation
Structure Model	Simcenter STAR-CCM+	Simcenter Nastran	Abaqus
Coupling	Implicit	Explicit	Explicit & implicit
Solution Stabilization	Preconditioner, displacement relaxation	None	Anderson Acceleration, displacement relaxation
Coupled physics	Weak to very strong	Weak only	Weak to very strong
Save and restart	Fully supported	Not supported	Partially supported
Elements	3D continuum	3D continuum, shells, beams*	3D continuum, shells, beams*
Additional Licenses	None	Simcenter Nastran	Abaqus
Comments	Hyperelasticity, some mechanical contact	No hyperelasticity, mechanical contact	Hyperelasticity, mechanical contact
Advantage	One license & tool, ease of use, tight coupling	Possible to couple to an existing structure model	

Transonic Wing Flutter Analysis Using Simcenter STAR-CCM+ and Simcenter Nastran Co-Simulation

Prepared by: Chris Ostoich, ATA Engineering

Date: 09/13/2023

San Diego • Los Angeles • Berkeley • Albuquerque • Denver • Huntsville • Washington D.C.

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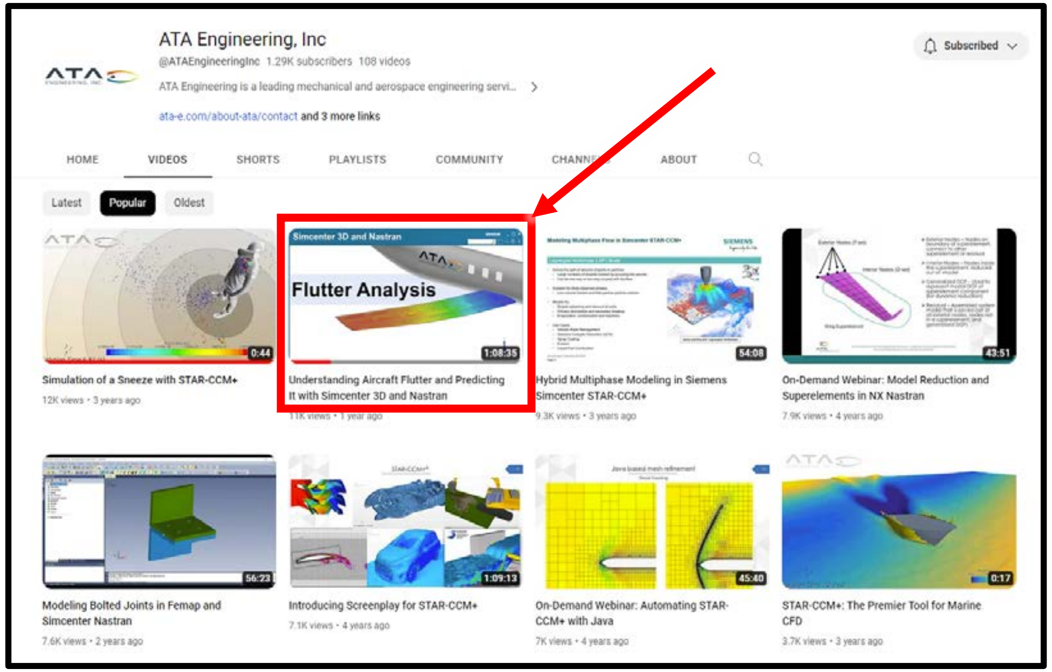
Wing Flutter Can Have Catastrophic Consequences

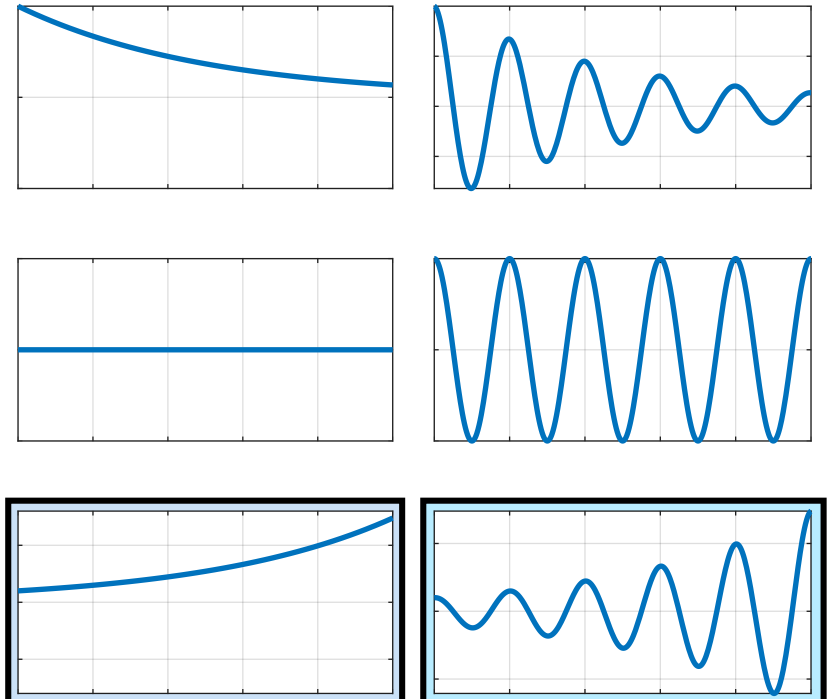
- F-117A fell apart during a 1997 airshow due to fluttering wing and missing fasteners
- Pilot ejected moments before impact, but loss of asset and nearby property

Aeroelasticity Investigated in Previous Webinar

- "Understanding Aircraft Flutter and Predicting It with Simcenter 3D and Nastran" by Dr. Anthony Ricciardi
- Can be found on our YouTube page

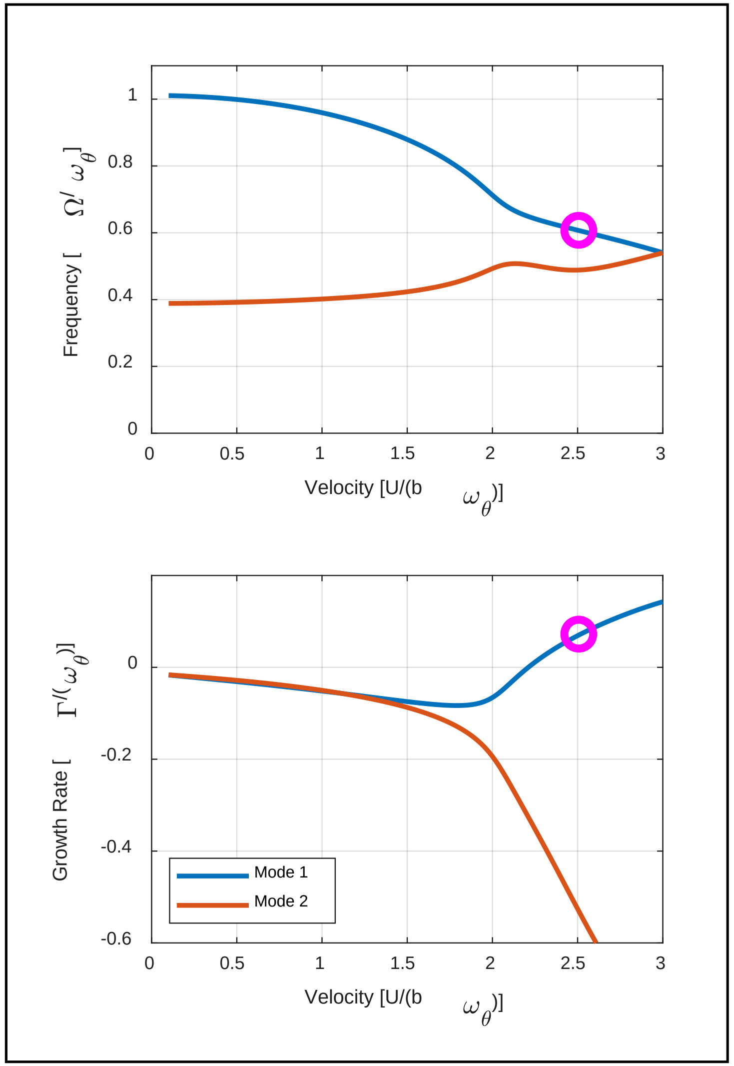


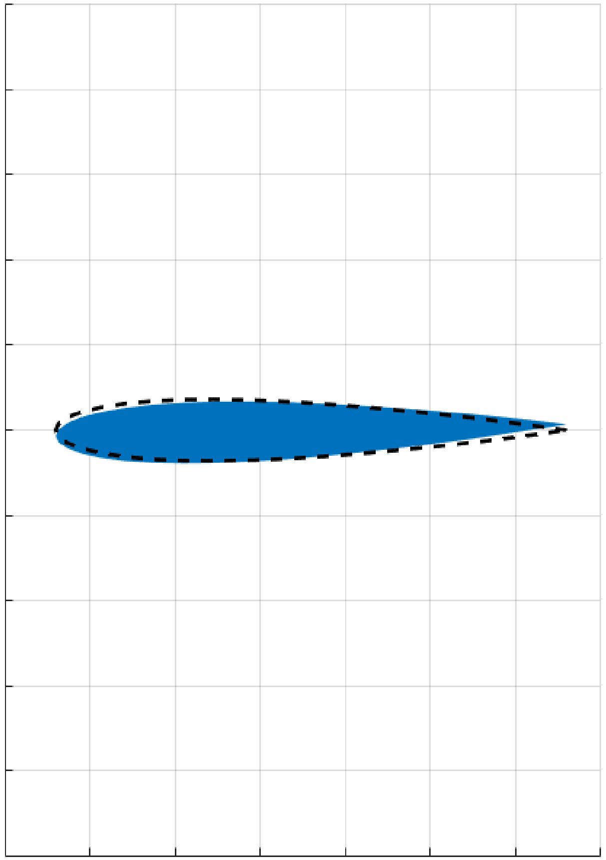
$$\boldsymbol{u}(t) = \tilde{\boldsymbol{u}}_k e^{s_k t} \qquad s = \sigma \pm i\omega$$

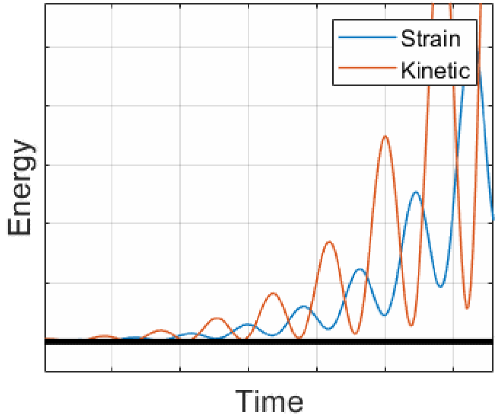


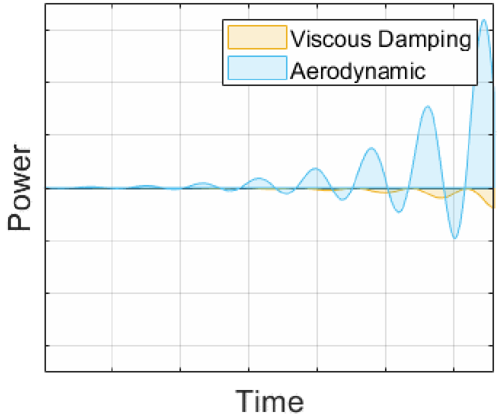
	Static $\omega = 0$	Dynamic $\omega > 0$
Stable $\sigma < 0$		
Neutrally Stable $\sigma = 0$		
Unstable $\sigma > 0$		
General Terms:	Static Instability	Dynamic Instability
Aeroelasticity Terms:	Divergence	Flutter

2D Demonstration of Flutter Boundary: Particular Modes are Unstable Above a Certain Velocity

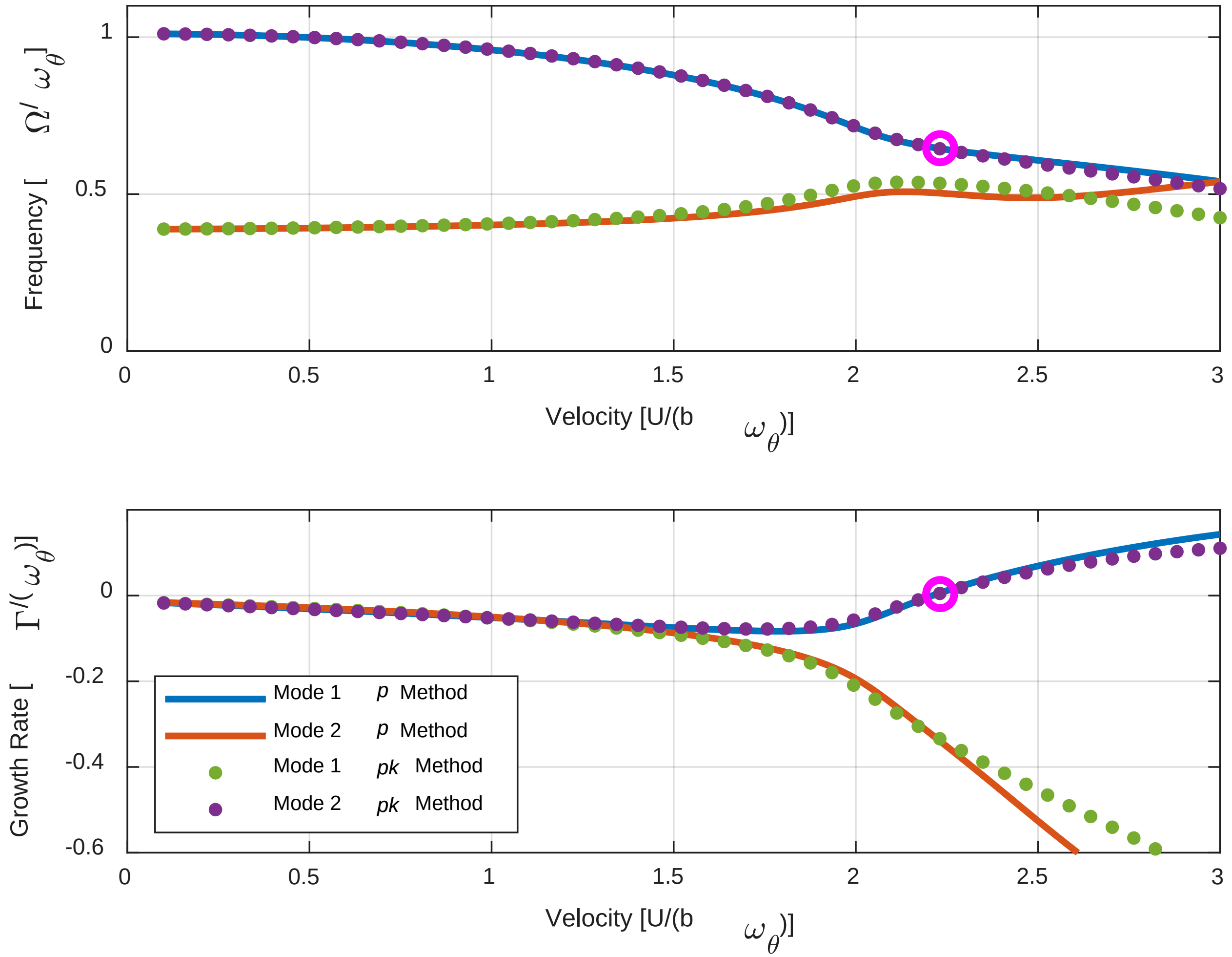








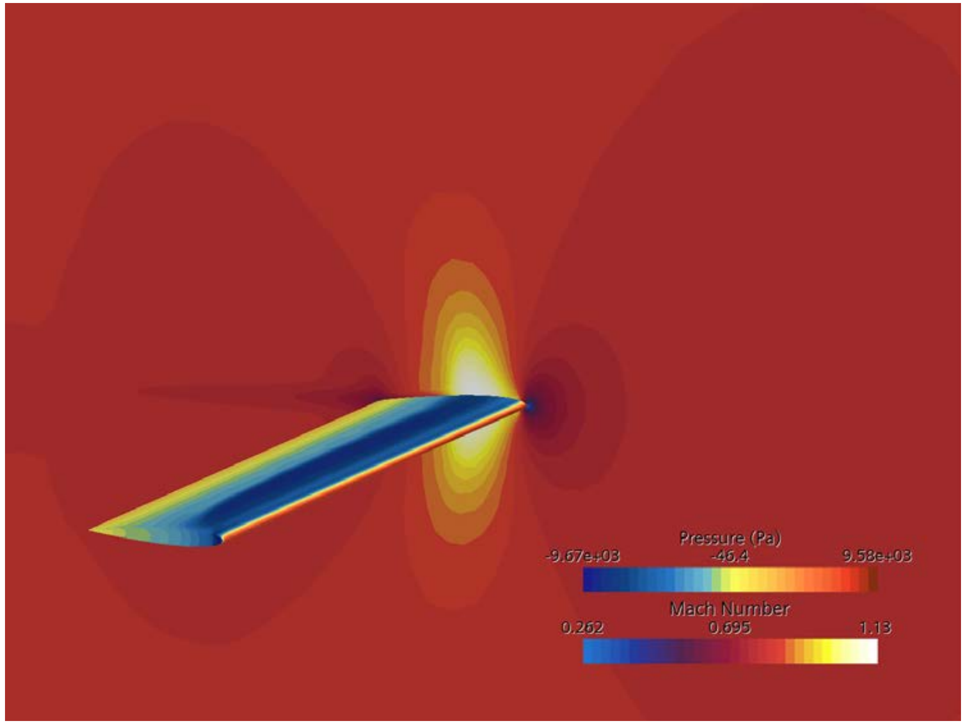
Demonstrated Flutter Prediction on 3D Wing in Simcenter3D



Flutter Onset Prediction with STAR-CCM+/NASTRAN Co-Simulation

STAR-CCM+/NASTRAN Co-Simulation of Wing Flutter

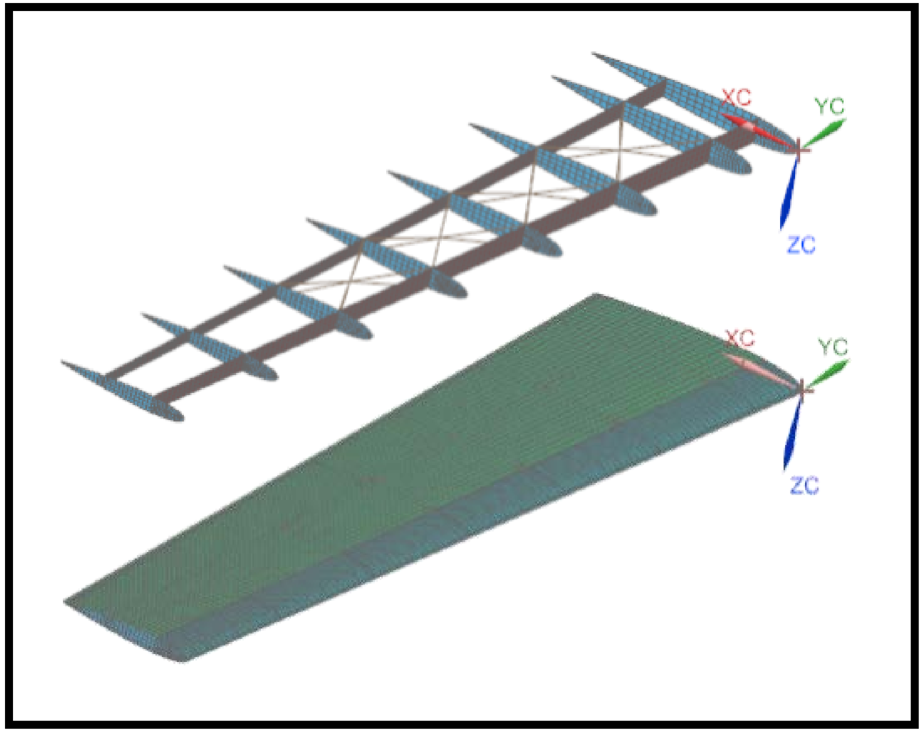
STAR-CCM+ calculates time-accurate fluid solution on a finite volume grid



$\vec{\tau}$ P

$\vec{x}$

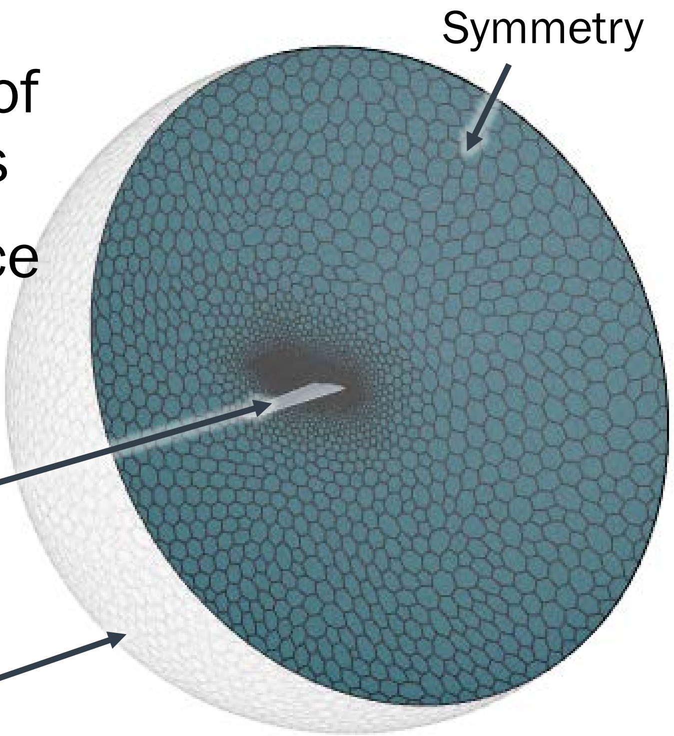
NASTRAN calculates time-accurate structural response on finite element model



Fluid and Solid Models

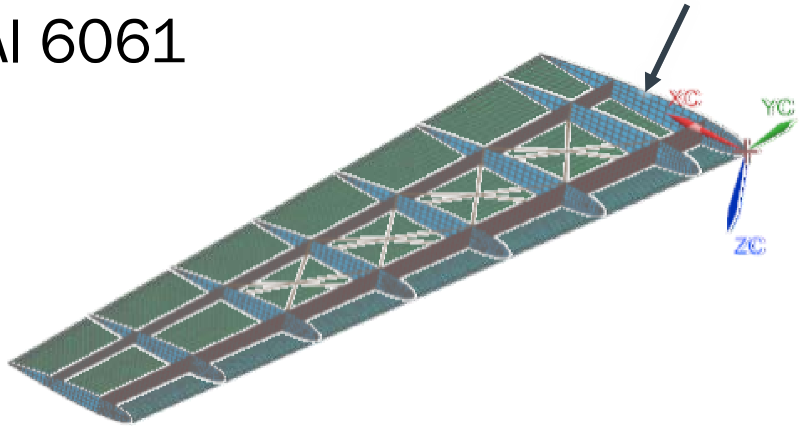
STAR-CCM+ Fluid Model

- Implict unsteady time advancement
- 364k polyhedral and prismatic finite volume cells
- Coupled solver of RANS equations
- $k - \omega$ turbulence model
- Ideal gas



NASTRAN Structural Model

- NASTRAN SOL 401
  - Multi-step non-linear structural dynamics
- Skin: 8190 PSHELL elements
- Spars: 936 PSHELL elements
- Ribs: 1133 PSHELL elements
- Material: Al 6061



Capability Chart 2-Way FSI

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Ingenuity for life

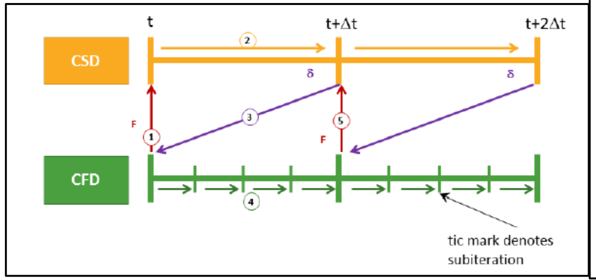
Last updated for: 2021.1	Single Simulation	Co-Simulation	Co-Simulation
Structure Model	Simcenter STAR-CCM+	Simcenter Nastran	Abaqus
Coupling	Implicit	Explicit	Explicit & implicit
Solution Stabilization	Preconditioner, relaxation of applied displacement	None	Relaxation of applied displacement
Coupled physics	Weak, strong, very strong	Weak only	Weak & strong
Save and restart	Fully supported	Not supported	Partially supported
Elements	3D continuum	3D continuum, shells, beams*	3D continuum, shells, beams*
Additional Licenses	None	Simcenter Nastran	Abaqus
Comments	Hyperelasticity, limited mechanical contact	No hyperelasticity, mechanical contact	Hyperelasticity, mechanical contact
Advantage	One license & tool, ease of use, tight coupling	Possible to couple to an existing structure model	

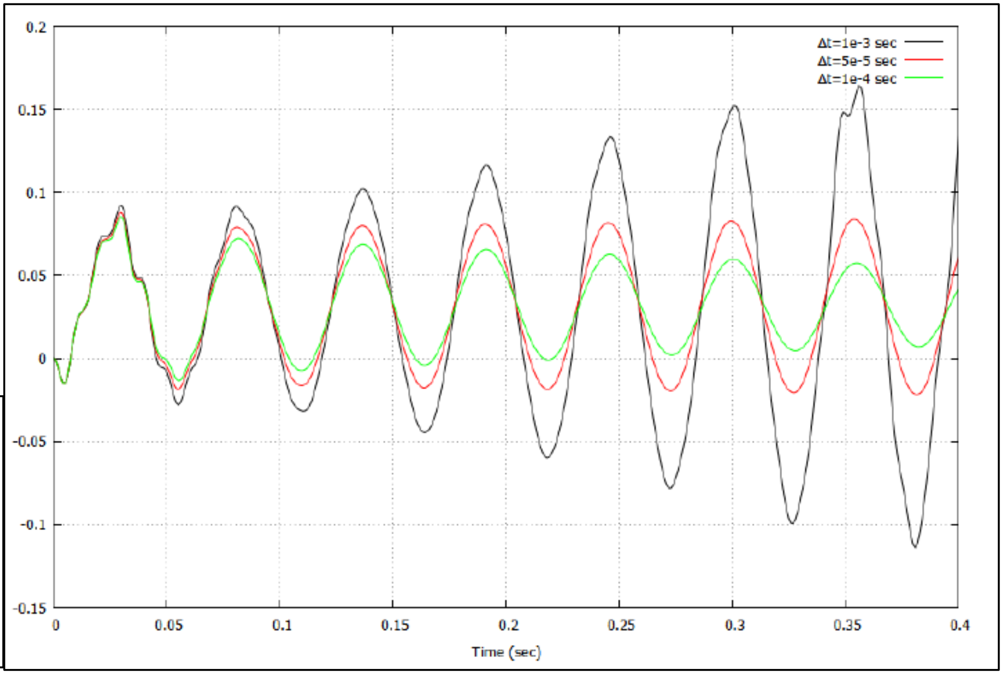
Weak vs. Strong Coupling

- Weak coupling: data exchange happens once per timestep
- Strong coupling: data exchange happens at subiterations
- ATA paper* found that weak coupling was slow to converge [$\mathcal{O}(\Delta t)$] and falsely predicted instability at large timesteps

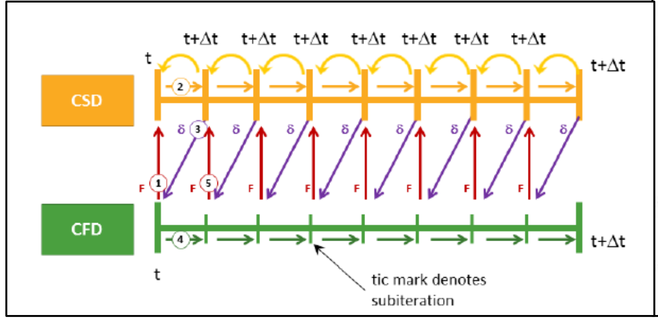
*Development, Verification, and Validation of a Fluid-Structure Interaction Capability and Evaluation of Temporal Coupling Strategies (Blades, E.L., and Cornish., A., AIAA-2017-0870)

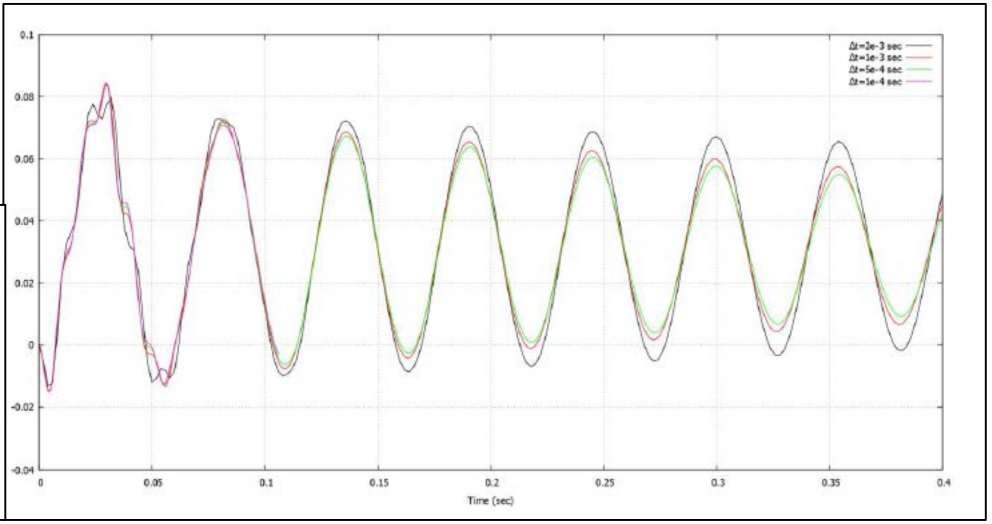
Weak Coupling





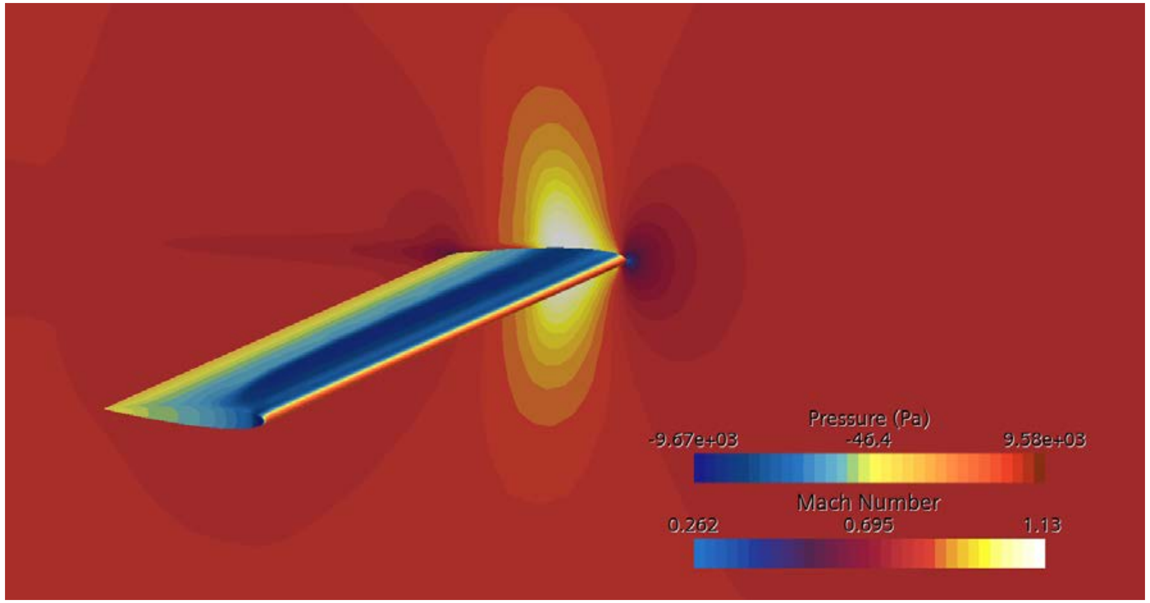
Strong Coupling

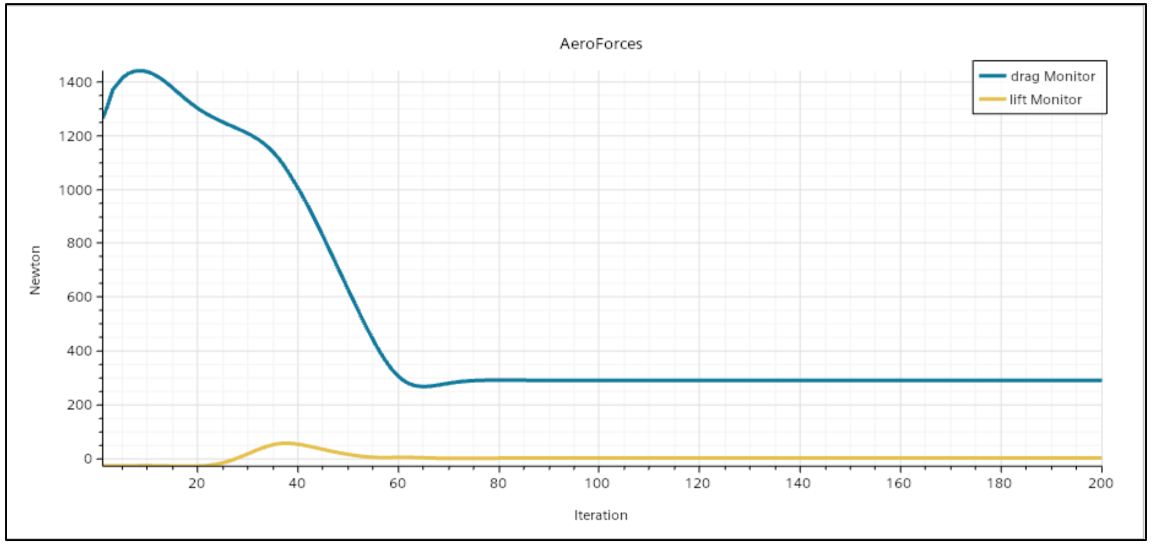




FSI Simulation Step 1: Generate Initial Condition

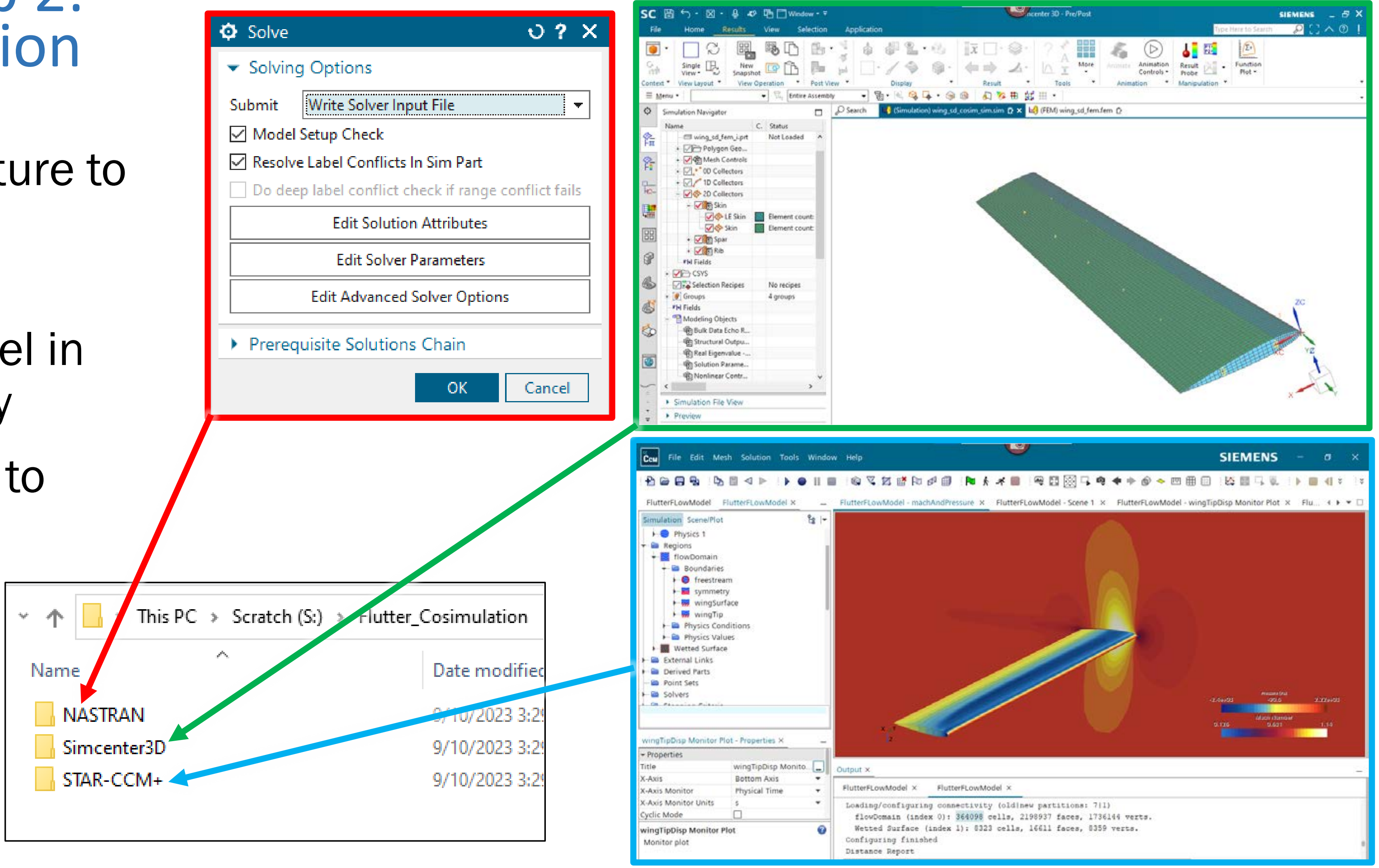
- In reality, wing would respond to flow speed ramp as the vehicle accelerated to cruise
- Simulation of ramp process time-cosuming and not important to current effort
    - Start simulation mid-flight
- Options for fluid initial condition
    1. Guess at cruise flow field and implement through field function
    2. Generate accurate flow field in steady-state STAR-CCM+ simulation over rigid wing geometry and export to table
- Steady-state simulation run until drag and lift converged



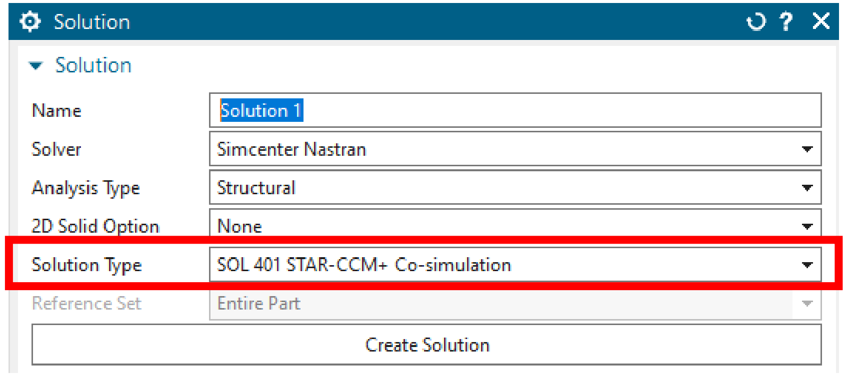


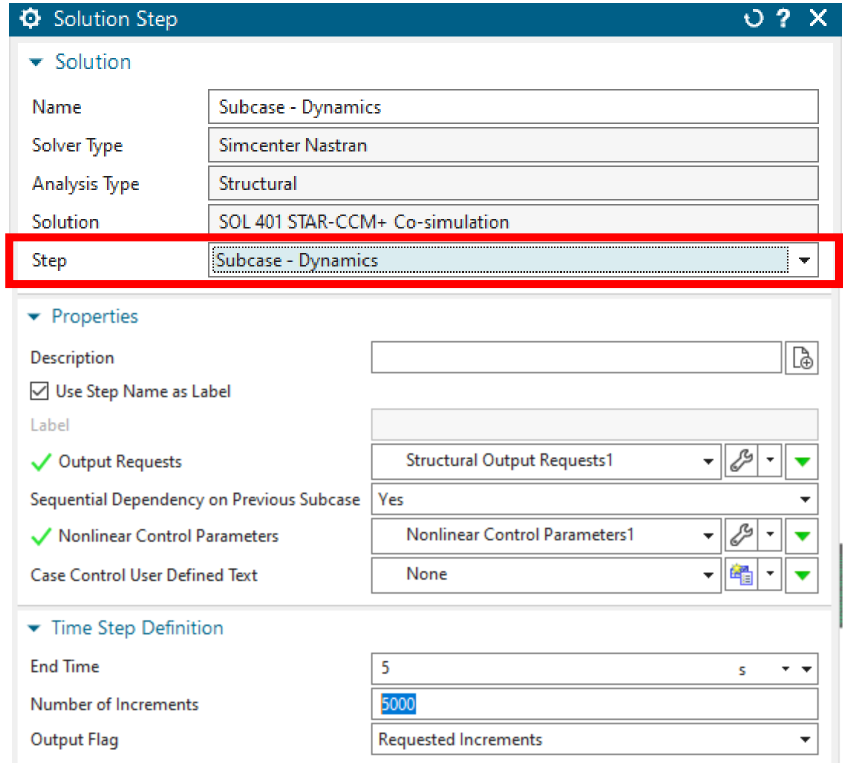
FSI Simulation Step 2: Prepare Cosimulation Input Files

- Create directory structure to keep simulation files organized
- Create structural model in *Simcenter3D* directory
- Export input file (.dat) to NASTRAN director
- Create flow model and run co-simulation from STAR-CCM+ directory



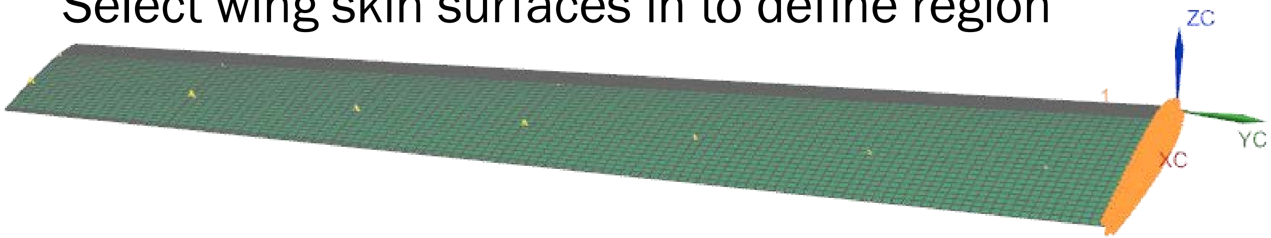
Step 3: Prepare FEM for Co-Simulation





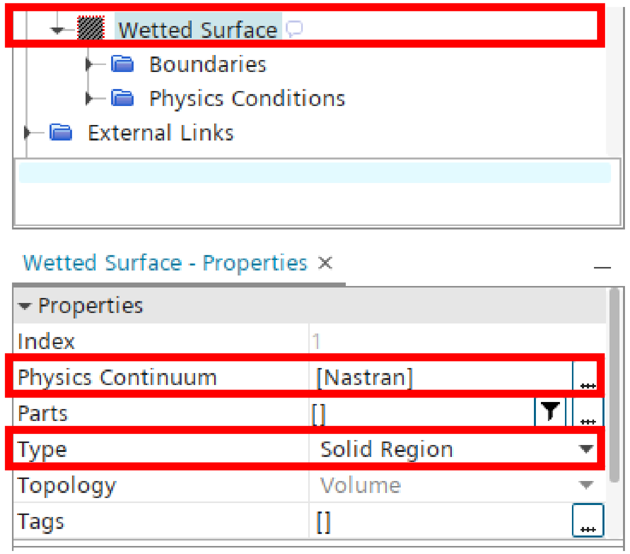
<u>After creation of FEM…</u>

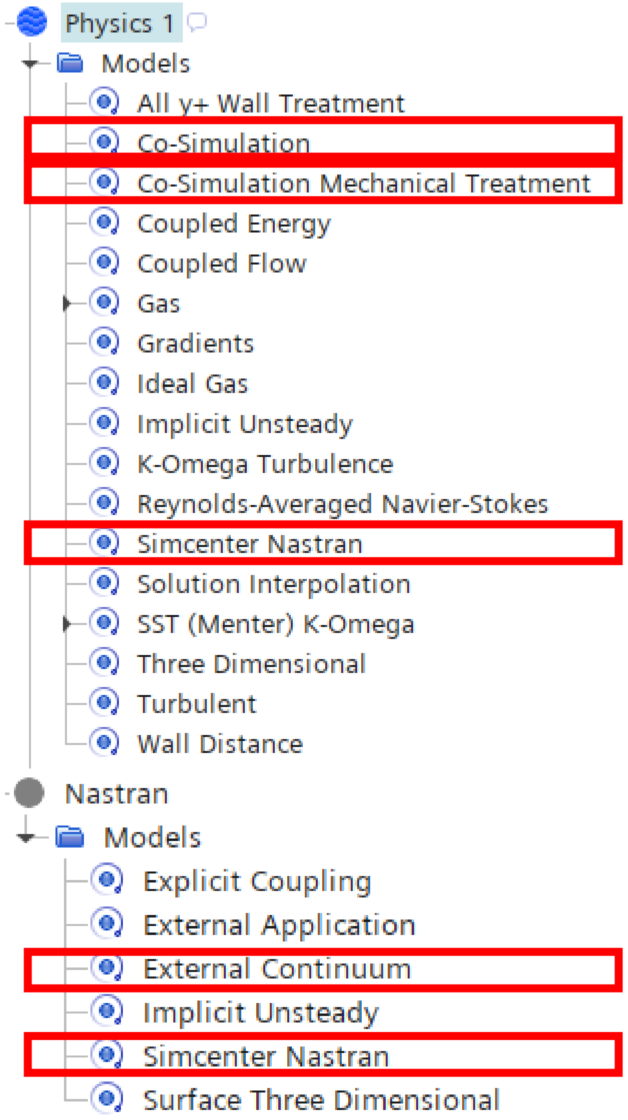
1. Create a new solution
   - Select SOL 401 STAR-CCM+ Co-simulation
2. Specify a Dynamic Solution Step
   - Create Output Request to extract displacement data
3. Specify time discretization
   - End time = 5 s with 5000 increments → dt=1 ms
   - Note: this must be consistent with fluid timestep
4. Create Co-simulation Region simulation object
   - Select wing skin surfaces in to define region



Step 4: Model Selection in STAR-CCM+ for Co-Simulation

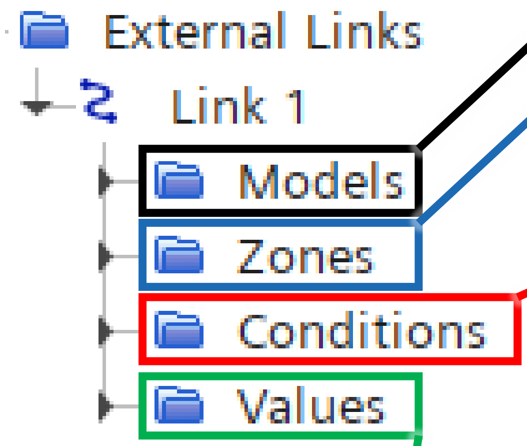
1. In fluid physics continuum, enable NASTRAN Co-Simulation
    - Select Co-Simulation, Simcenter Nastran, and Co-Simulation Mechanical Treatment
2. Create separate External Continuum physics model and select Simcenter Nastran
    - All other required models are autoselected
3. Create additional solid region to represent NASTRAN solution
    - Select the External Continuum physics model and specify type as Solid Region





Step 5: Create External Link to NASTRAN in STAR-CCM+

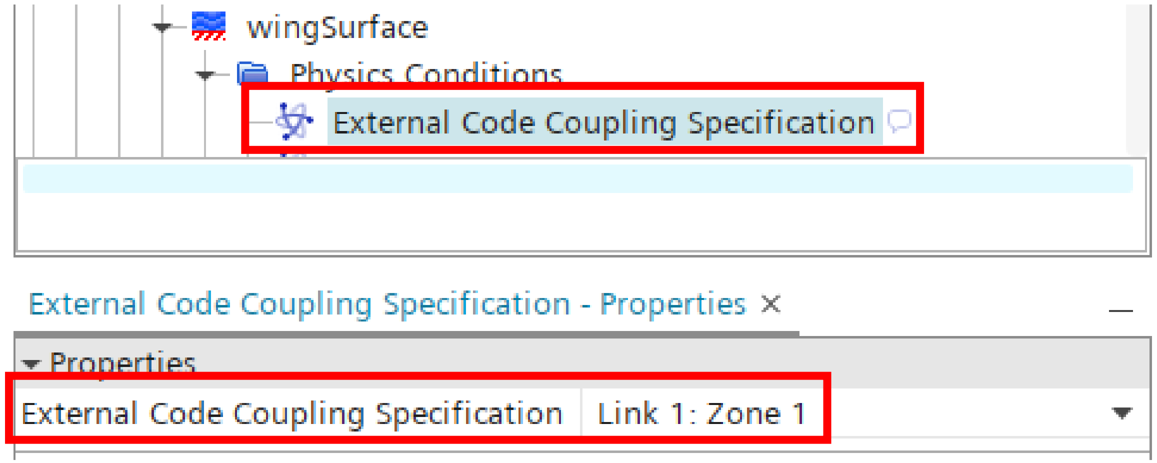
- When Co-simulation models selected, External Links node added to tree
- External Links specifies connection to NASTRAN Model
- Any interacting fluid boundaries need to point to Link 1: Zone 1



Keep defaults

Specify data transter
- Outgoing: Pressure, Shear
- Incoming: Displacement

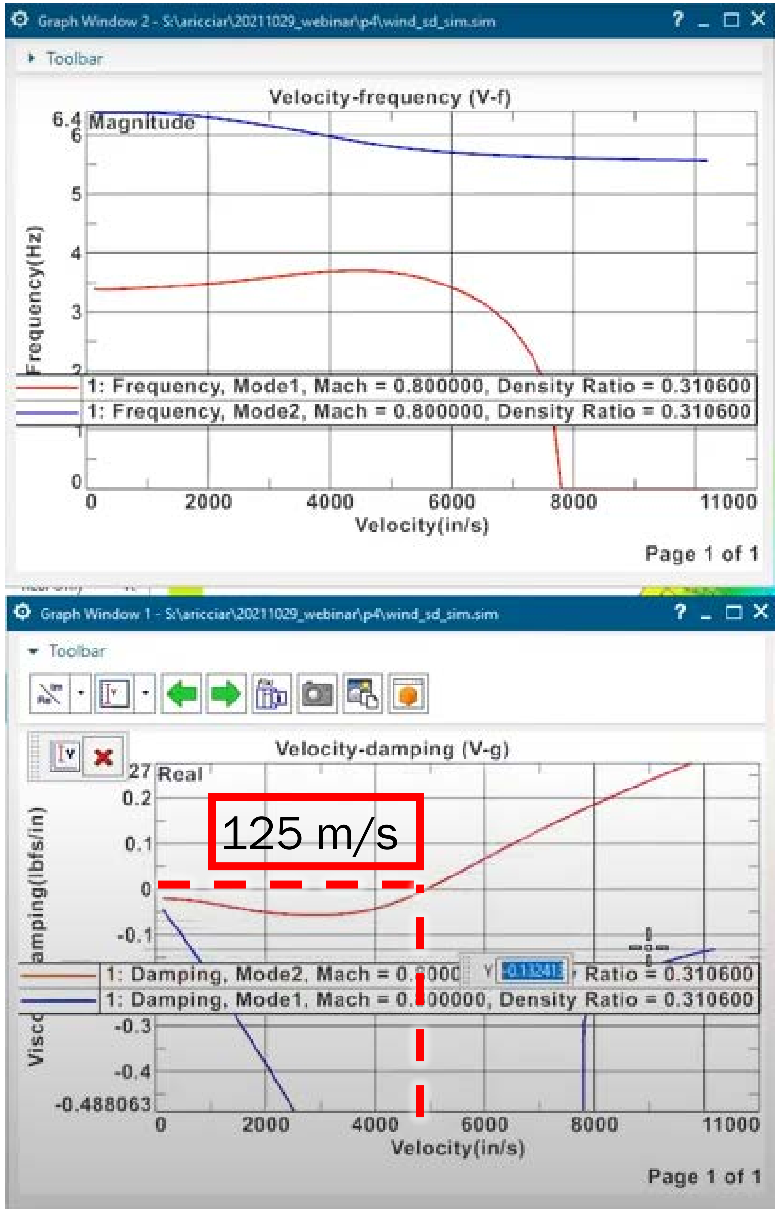
- Launch Partner Option: Launch Application
- Concurrency: Lag (NASTRAN leads)
- Mapping Option: Map Both Directions (STAR does interpolation)



- SimcenterMP Option: --wallshear on
- Simcenter Nastran Executable: path to nastran.exe
- Simcenter Nastran Input File: path to .dat file (../NASTRAN/[filename].dat)

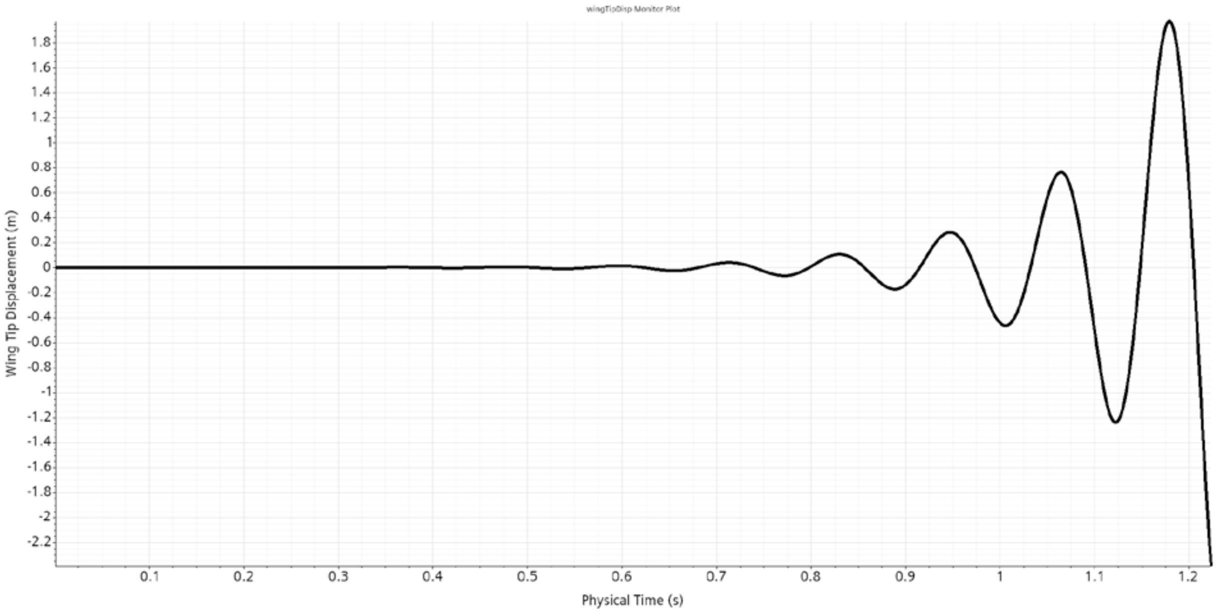
STAR-CCM+/NASTRAN Co-Simulation of Flutter Onset

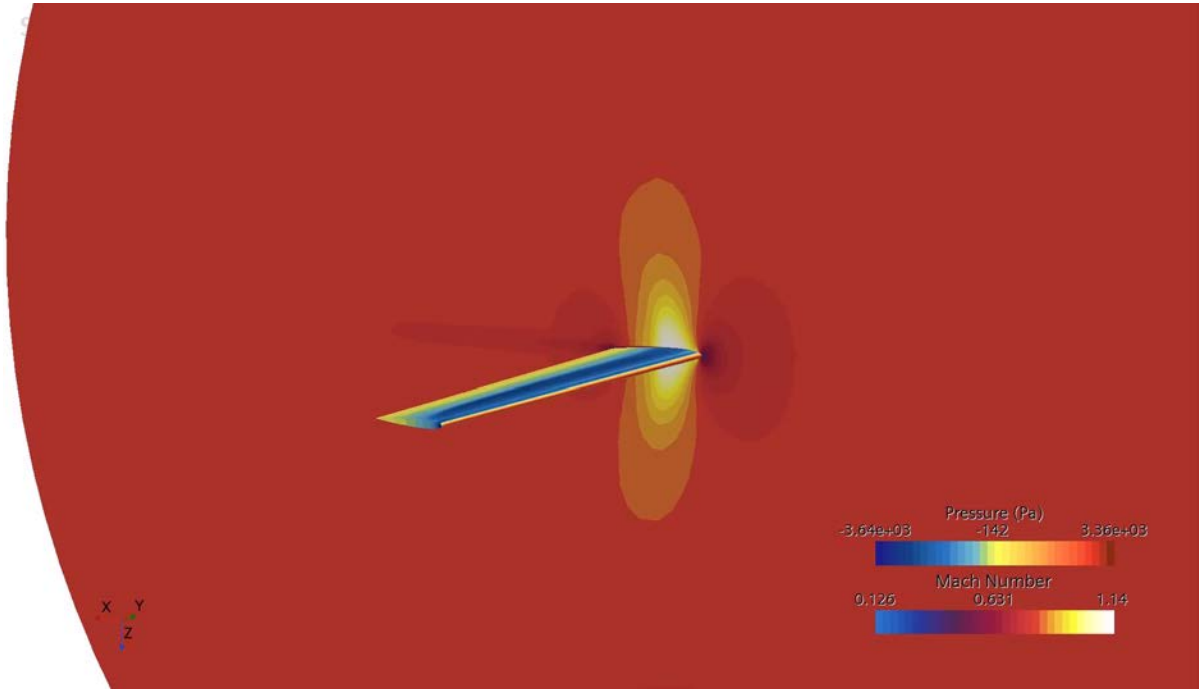
- Previous aeroelastic study suggested following inputs slightly unstable
    - Mach = 0.8
    - Density = 0.38 kg/m^3
    - Velocity = 124 m/s
    - Note that these are not realistic parameters and were contrived for demonstration
- Monitor set up to report wing tip displacement
    - Displacement growth → Unstable
    - Displacement decay → Stable
- Scenes created to visualize Mach number, wing pressure, mesh deformation, and vortex shedding



Wing Flutters as Expected

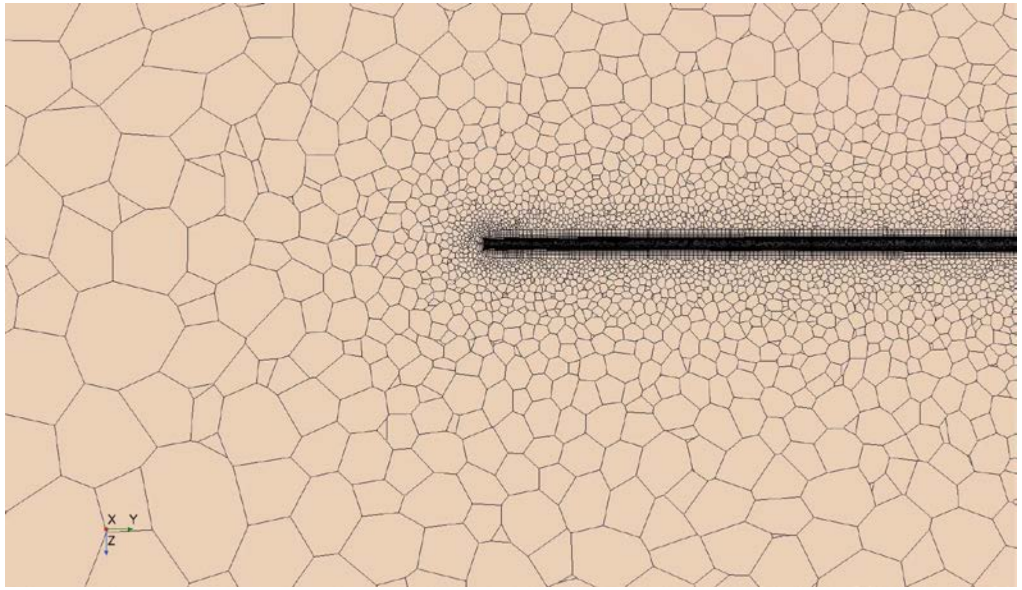
- Wing tip oscillates at ~ 8.5 Hz
- Wing tip displacement growth over time indicates instability
- Coupling between wing motion and flow field evident in symmetry plane Mach number
- Transonic shock oscillates fore and aft on fluttering wing

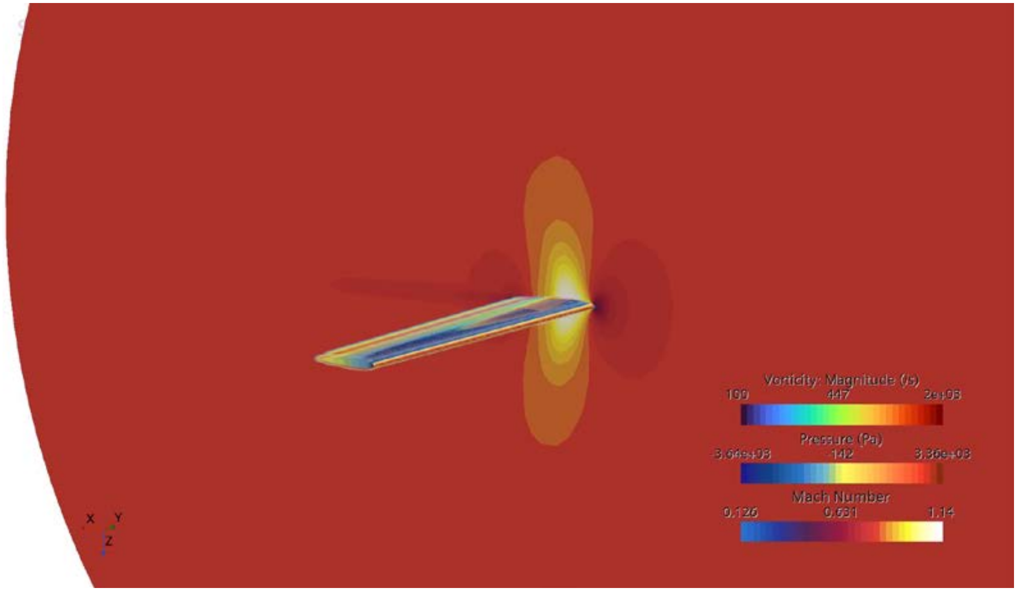


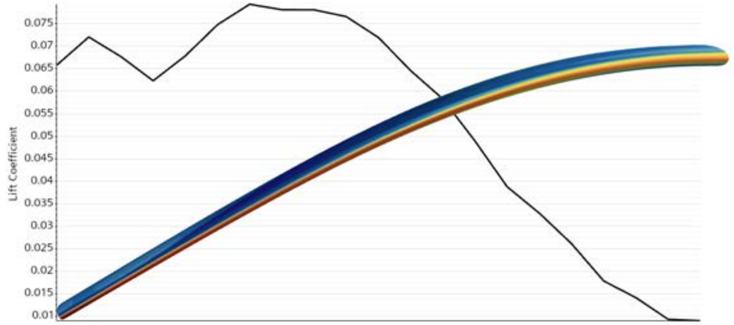


STAR-CCM+ is a Powerful Mesher, Physics Engine, and Post Processor All in One

- Automated mesher generates high-quality computational grids with minimal user input
- Mesh morpher handles large deformations resulting from moving boundaries in FSI applications
- Comprehensive post processing capabilities allow analysts to deeply interrogate complex flow solutions







Summary

- STAR-CCM+ and NASTRAN can operate in a Co-simulation to predict the FSI between a fluid and non-linear structural models
- While FSI can be done completely within STAR-CCM+, NASTRAN structural models allow use of advanced finite element analysis approaches
- STAR-CCM+/NASTRAN Co-simulations currently have only weak coupling available and therefore may not be the recommended choice for highly-coupled problems like wing flutter
- Strong coupling is provided in STAR-CCM+ FSI simulations, but can only use 3D continuum finite elements

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