Aero-Thermo-Servo-Elastic Analysis and Optimization for High-Speed Vehicles

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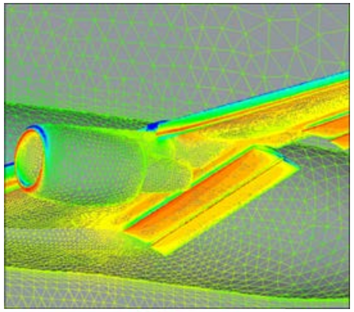
Objectives

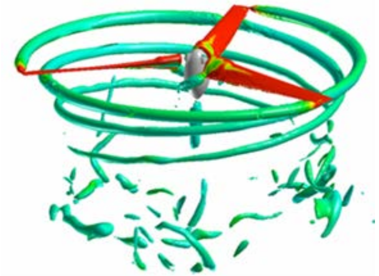
- Develop and demonstrate techniques for accurate numerical simulation and optimization of high speed vehicles
- Include all important disciplines at high fidelity in tightly coupled fashion
  - Aerodynamics
  - Structural dynamics
  - Thermal effects
  - Control system
  - Interaction between all disciplines
- Analysis
  - Non-linear multidisciplinary coupled solvers
- Sensitivity Analysis/Optimization/UQ
  - Corresponding fully coupled multidisciplinary discrete adjoint solver
- Steady-state and time-dependent

Previous Work

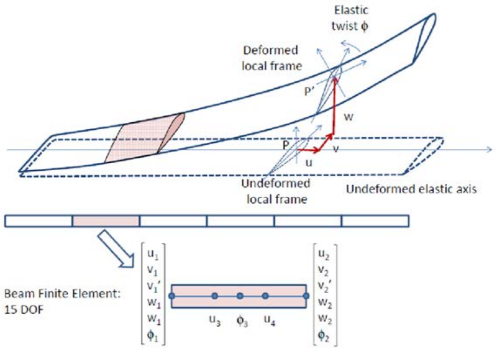
- Time-dependent coupled aero-structural solver
- Corresponding time-dependent aero-structural discrete adjoint
- Includes prescribed motion (flight-control system)
- Optimization of helicopter flexible rotor in forward flight

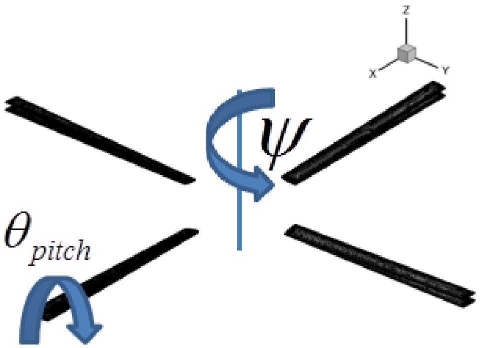
Previous Work

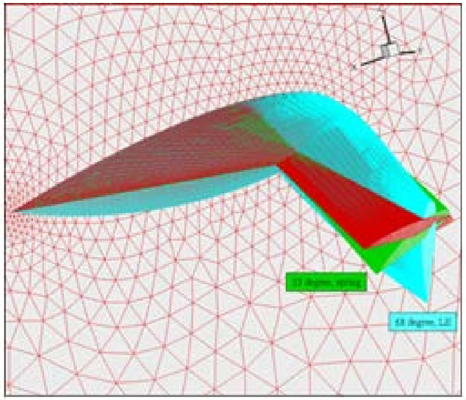




- Aerodynamic Solver: NSU3D
  - 2nd order unstructured mesh FV RANS solver
  - Exact discrete adjoint (steady/time-dependent)
- Structural Model: Beamer
  - Hodges-Dowell FEM beam model
    - Appropriate for slender blades
  - Exact discrete adjoint (steady/time-dependent)
- Cyclic pitch control
- Mesh deformation
  - Linear elastic analogy





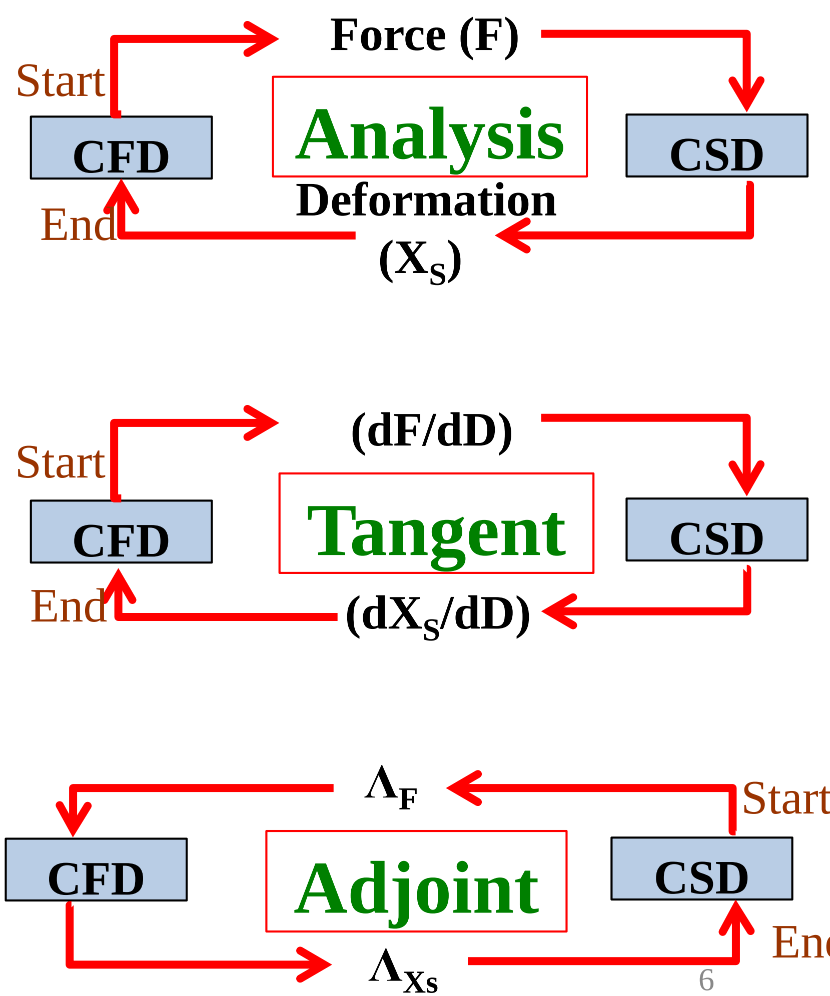


CFD/CSD Coupling Time Integration Methodology

- **Outer loop over physical time steps**
  - **Coupling iterations per time step :**
    - Mesh:
      - Line implicit multigrid
    - Flow:
      - Implicit BDF2 Newton iterations (GMRES)
      - Linear agglomeration multi-grid
    - FSI (Fluid to structure)
      - Explicit assignment
    - Structure:
      - Implicit BDF2 newton iteration (direct inversion)
    - FSI (Structure to fluid)
      - Explicit assignment

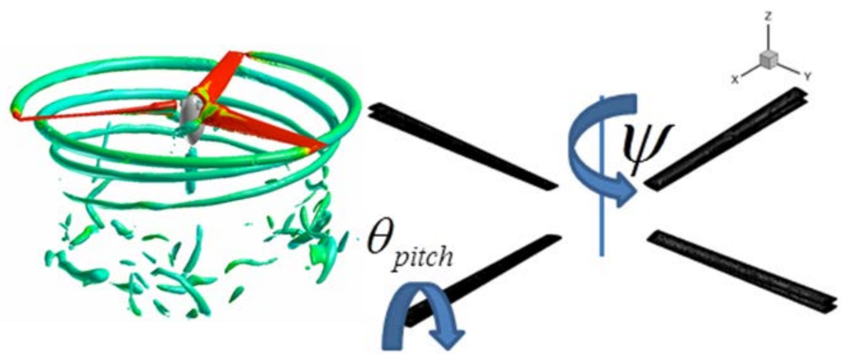
Coupling Schematic

- Analysis solver transfers forces and displacements
- Forward sensitivity problem analogous (transfers force and displacement sensitivities)
- Adjoint problem solved as analogue of analysis or tangent problem in reverse order



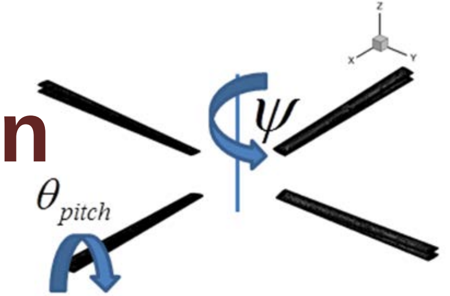
Verification of Strongly Coupled CFD/CSD Adjoint Formulation

- Verified to 10 significant digits
- Verified over multiple time steps
- Accuracy preserved over entire time-history of design cycle (1 rev or 180 time steps)

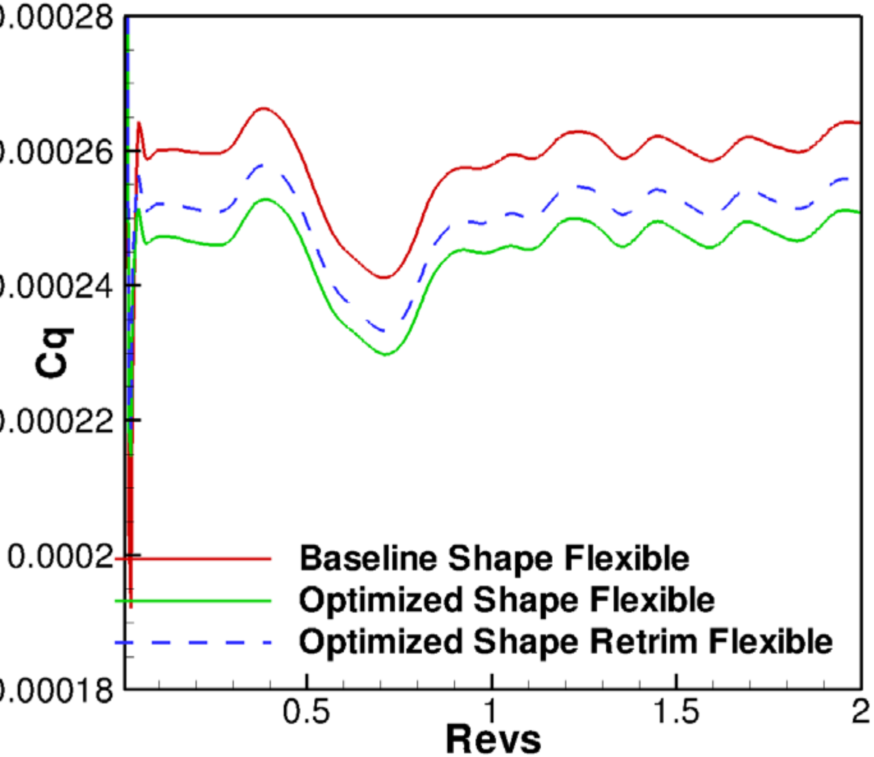


Time step	Method	$\frac{\partial L^n}{\partial D}$
1	Complex	7.569817143673**123**E-005
	Tangent	7.569817143673**061**E-005
	Adjoint	7.569817143672**761**E-005
2	Complex	6.040142774935**852**E-005
	Tangent	6.040142774935**835**E-005
	Adjoint	6.040142774935**570**E-005
3	Complex	-4.959909870786**381**E-006
	Tangent	-4.959909870787**765**E-006
	Adjoint	-4.959909870785**228**E-006
5	Complex	-1.142069116982**308**E-004
	Tangent	-1.142069116982**308**E-004
	Adjoint	-1.142069116982**432**E-004
180	Complex	-5.176189427439**016**E-003
	Tangent	-5.176189427439**005**E-003
	Adjoint	-5.176189427434**507**E-003

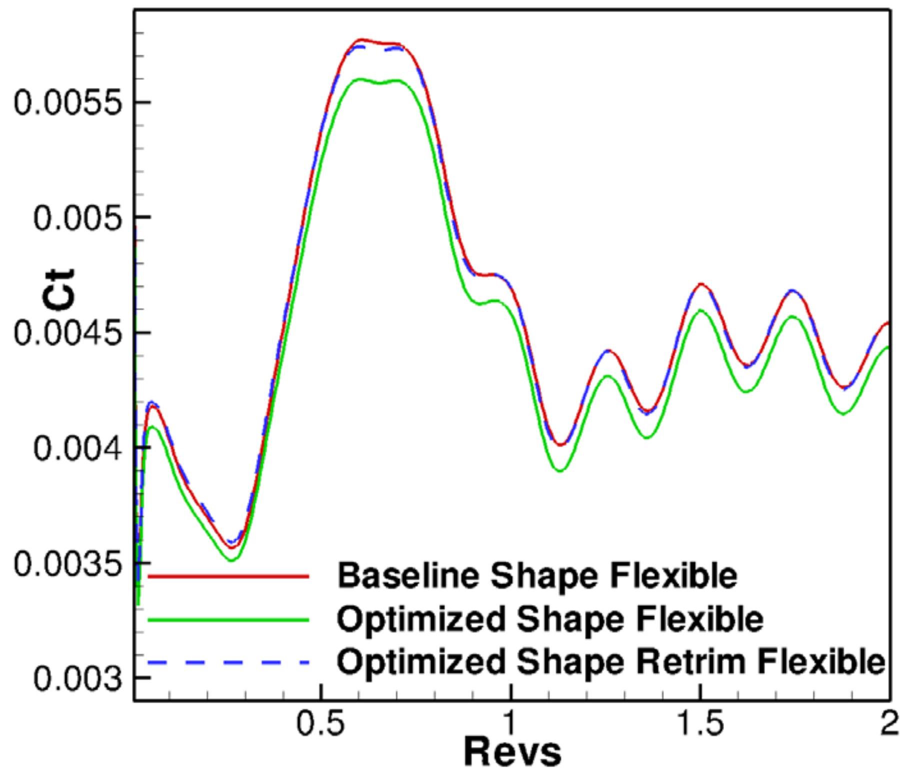
Flexible Hart-II Shape Optimization
(AIAA-2015-1130)



Power vs time



Thrust vs time



- Trimmed to target mean thrust (Ct=4.4e-3), zero moments (~1e-5)
- Overall ~**3.1**% power reduction w/ shape optimization after retrim

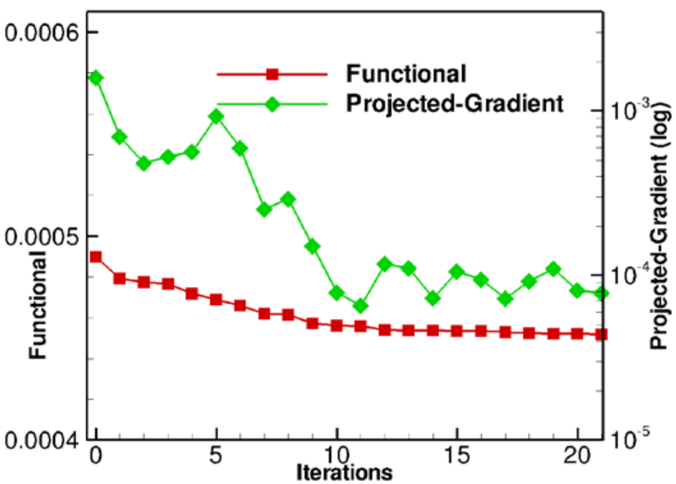
Flexible Optimized Blade Shape

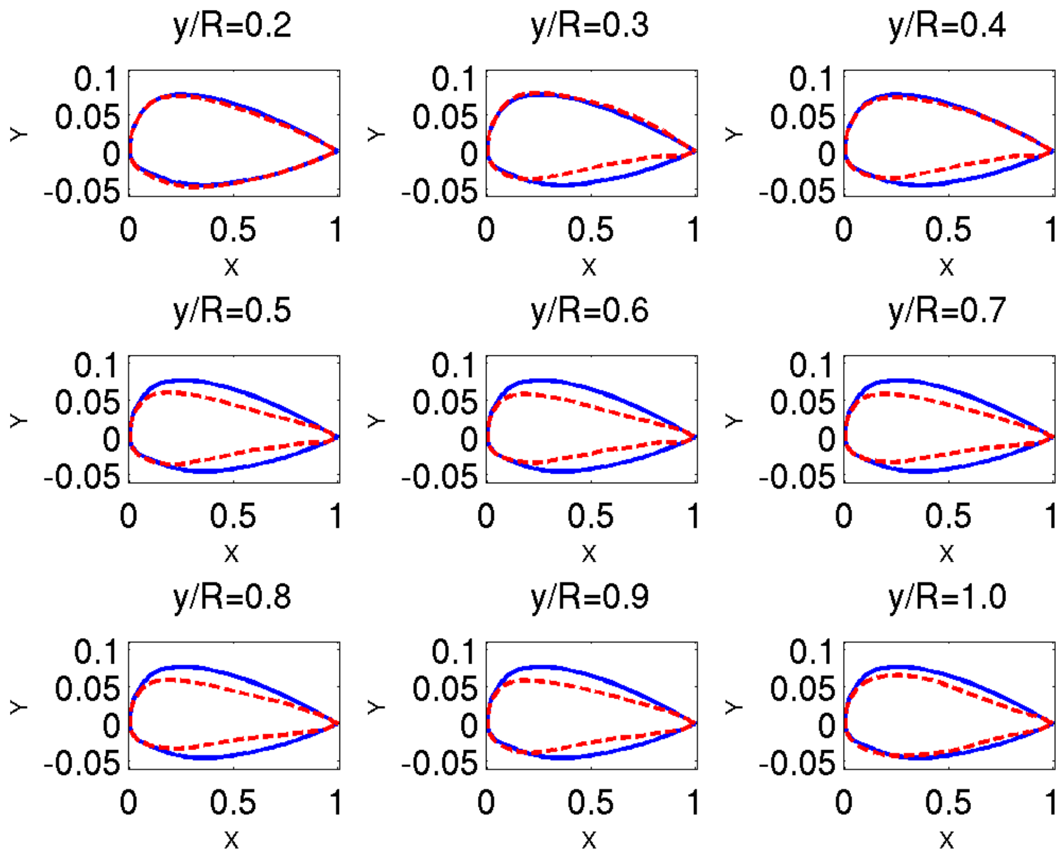
(AIAA-2015-1130)

Baseline

Optimized

Thicker inboard and thinner outboard sections



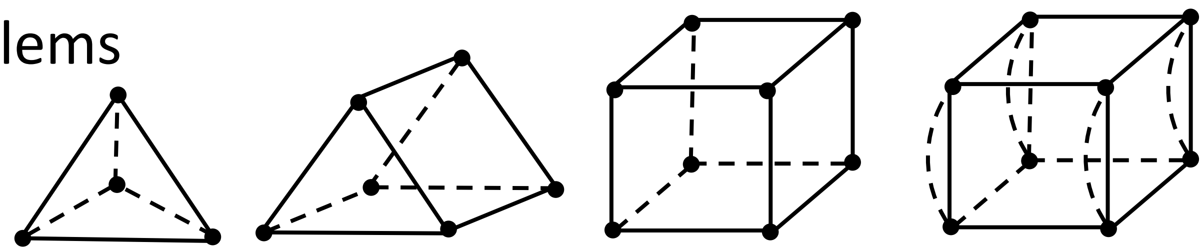


- 1 and ½ order gradient drop, objective converges

Structural Model Development

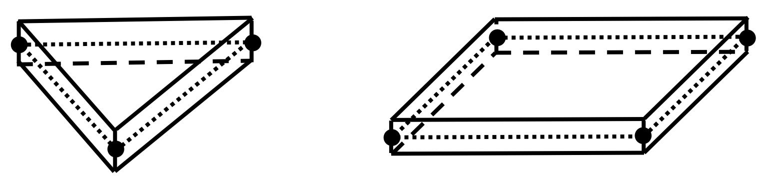
- Higher fidelity replacement for Beam Model
- Open source code is compatible with Abaqus input and output files
- Static, dynamic, and thermal solution capabilities
- Multiple solvers, both on-board and external
- Element library development tailored to aeroelastic problems

Solid Elements:



(Incompatible modes)

Shell Elements:

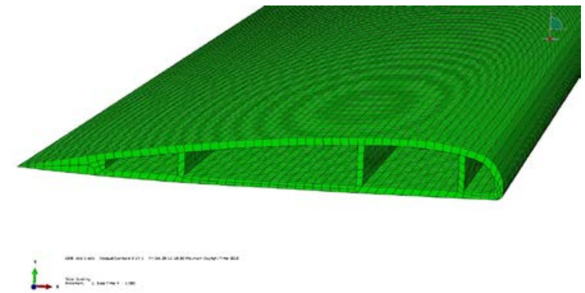


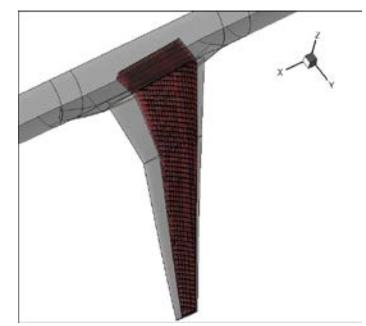
Structural Dynamic Solvers

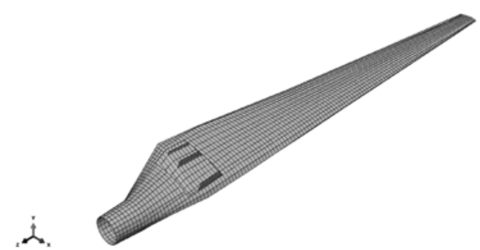
Several methods available for solving structural dynamic response:

- On-board solvers
  - Direct $[L][D][L]^T$ factorization
  - Conjugate gradient, with optional preconditioning
  - Q-iteration
- MUMPS (product of INRIA*) parallel direct solver library

Numerous structural models tested



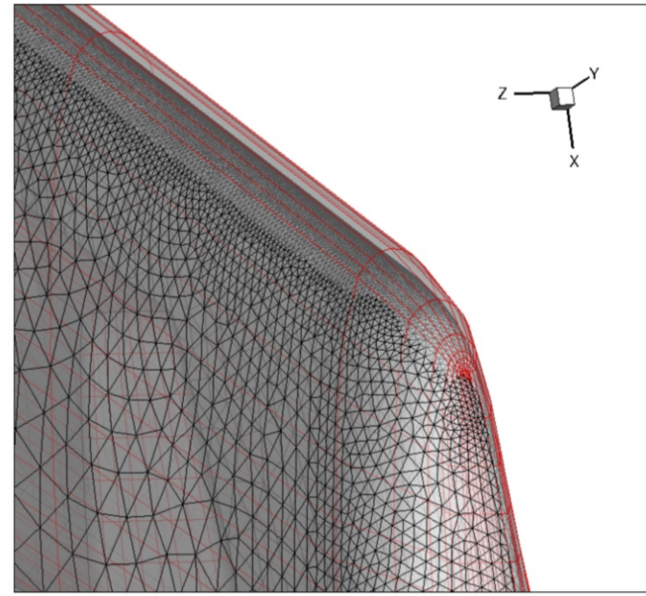


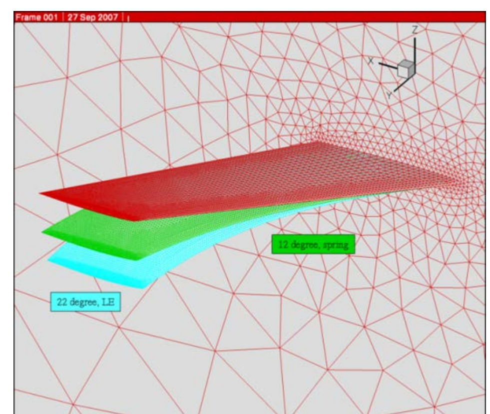


*www.inria.fr

Fluid-Structure Interface (FSI)

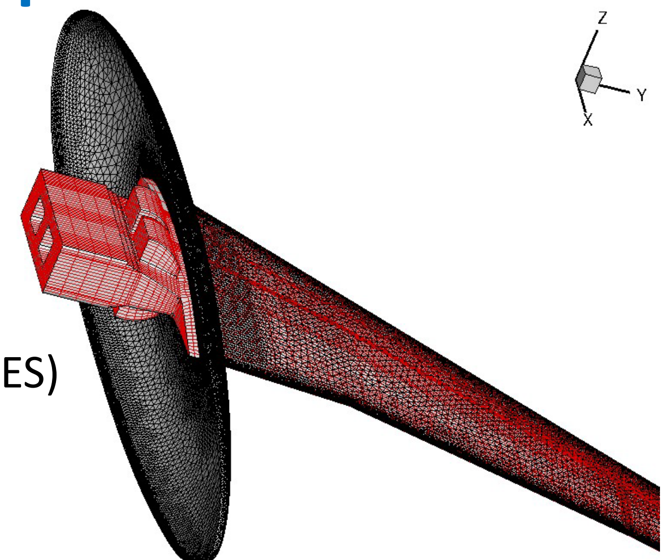
- Mesh generation for structural model and aerodynamic model segregated.
- FSI capable of non-point matched mapping between fluid and structural grids. Search algorithm locates nearest projected point from CFD grid point to structural mesh surface.
- Forces and displacements transferred between flow solver and structural solver in iterative process.
- Fluid mesh deformation via linear elastic analogy.





CFD/CSD Coupling Time Integration Methodology

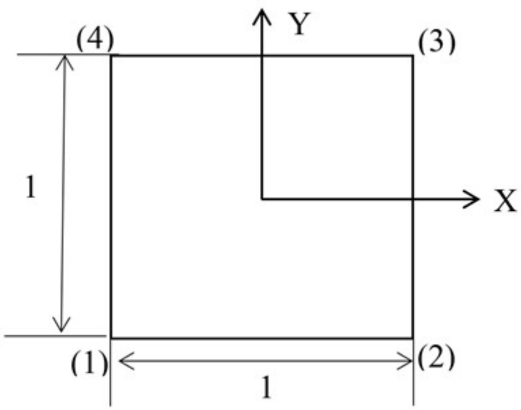
- **Outer loop over physical time steps**
  - **Coupling iterations per time step :**
    - Fluid Mesh:
      - Line implicit multigrid
    - Flow:
      - Implicit BDF2 Newton iterations (GMRES)
      - Linear agglomeration multi-grid
    - FSI (Fluid to structure)
      - Explicit assignment $\{F\}_{CSD} = [T]\{F\}_{CFD}$
    - Structure:
      - Solve via designated method (direct, iterative, MUMPS, etc.)
    - FSI (Structure to fluid)
      - Explicit assignment $\{U\}_{CFD} = [T]^T\{U\}_{CSD}$



Examples of Structural Model Validation

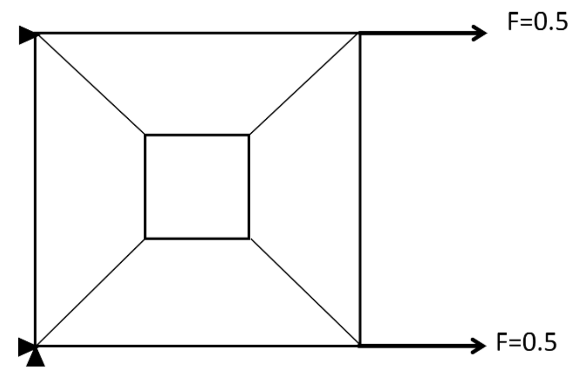
Validation of FEA results through comparison with Abaqus/analytical solutions.

Single element test: 4-node shell subject to bending about Y-axis



Node	θ_1 (Current)	θ_1 (Abaqus)	θ_2 (Current)	θ_2 (Abaqus)
1	1.20000004	1.20000001	0.00000000	0.00000000
2	1.20000004	1.20000001	-12.00000004	-12.00000001
3	-1.20000004	-1.20000001	-12.00000004	-12.00000001
4	-1.20000004	-1.20000001	0.00000000	0.00000000

Patch test for shells, incompatible modes

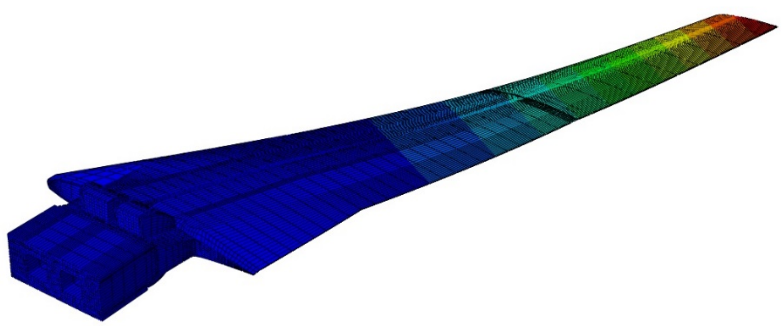


Stress Component	Applied Stress	Standard Deviation From Applied Value
S11	1	$4.497e^{-16}$
S22	0	$1.498e^{-16}$
S12	0	$1.111e^{-16}$

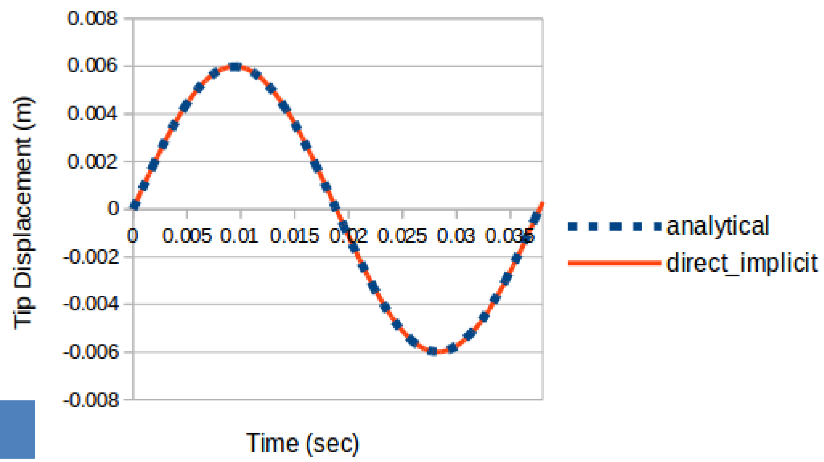
Structural Dynamics Modeling

- 1st mode free vibration test of HIRENASD* wing
- Fixed at the root with initial velocity corresponding to first mode vibration
- Response computed with direct implicit solver of in-house code

First mode vibration displacement contour on deformed HIRENASD wing



Tip displacement history of HIRENASD wing in free vibration



	Current Model	Published
Natural Frequency	26.55	26.53

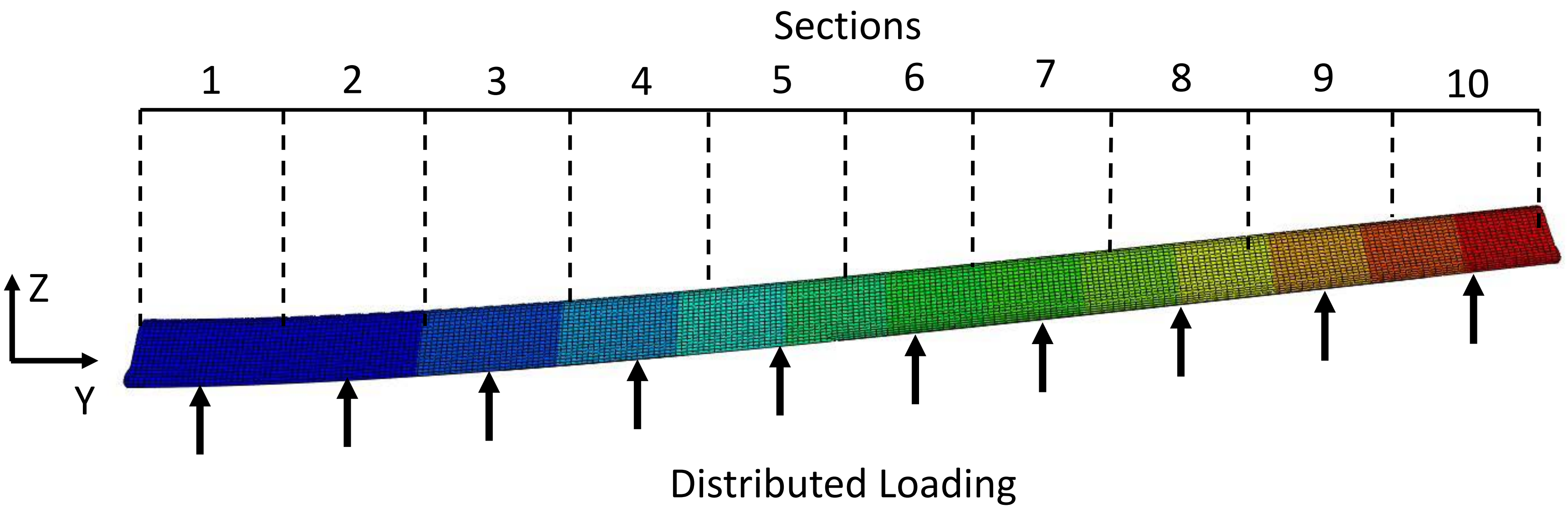
*Reimer, Lars, Boucke, Alexander, Ballmann, Josef, and Behr, Marek, "Computational Analysis of High Reynolds Number Aero-Structural Dynamics (HIRENASD) Experiments," Proc. of the International Forum on Aeroelasticity and Structural Dynamics (IFASD) 2009, Paper IFASD-2009-130.

Structural Optimization Using Adjoint-Based Sensitivities

- Optimization of Hart-2 rotor blade deflection
- Conjugate gradient optimization algorithm

$$Objective = \sum_{i=1}^{n}\left(w_i - w_{target}(y)\right)^2 \quad n = number\ of\ nodes, w = vertical\ (z)\ deflection$$

$$Design\ variables\ D_i = Stiffness\ of\ section\ i$$

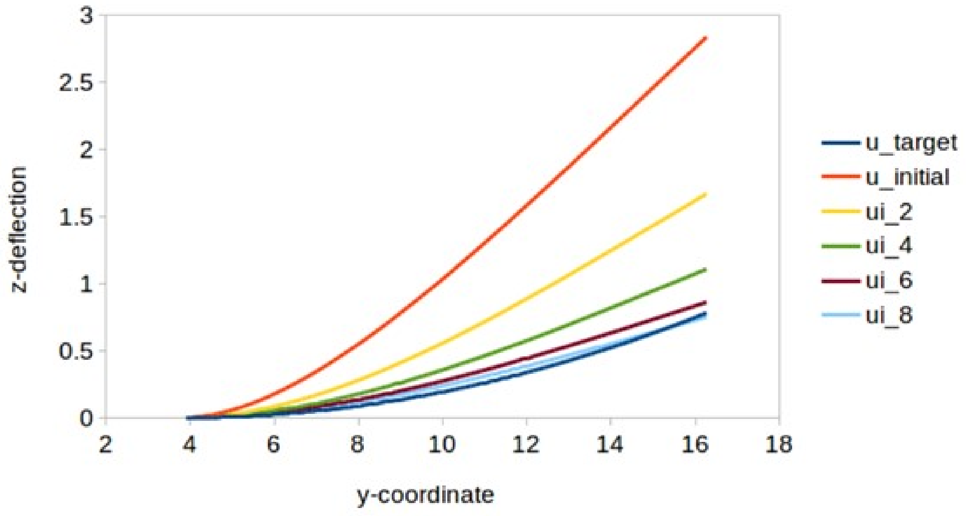


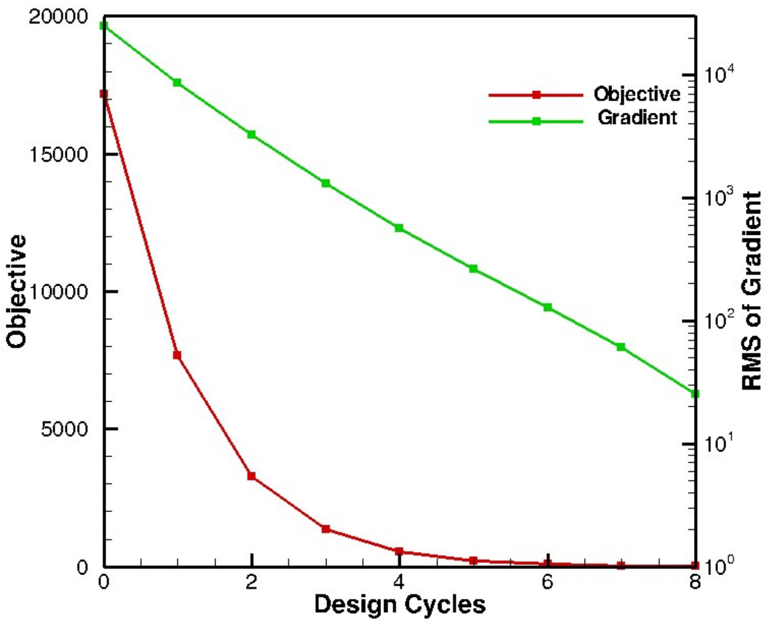
Hart-2 Blade Optimization Results

- Monotonic convergence to target deformed shape
- Objective minimized to near zero in 8 design cycles

Convergence of objective function residual and RMS of objective function gradient

Convergence of vertical deflection of rotor blade

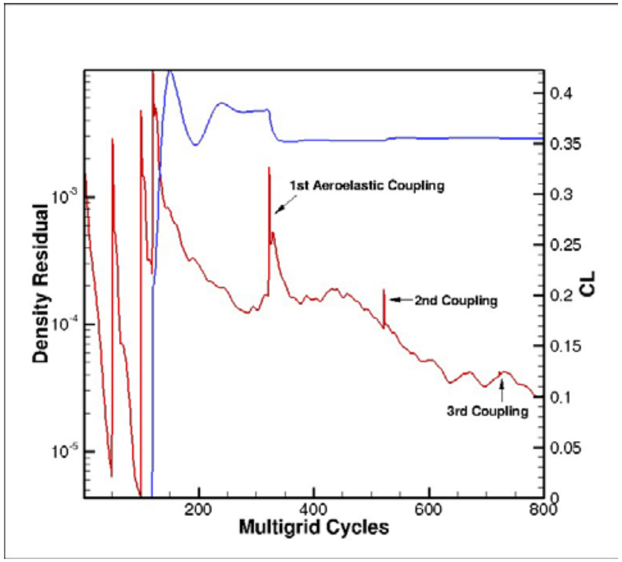




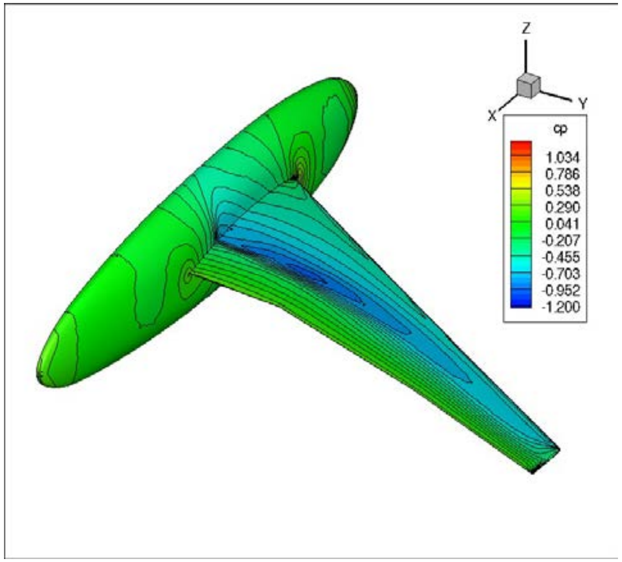
Aero-Structural Results

- Fully-coupled steady-state analysis of HIRENASD wing
  - Mach=0.8, α=1.5°, Re=7M
  - CFD Mesh: 6.5 M points, CSD Mesh: 42K C3D8I elements
- 3 fluid-structure coupling iterations
- Lift coefficient compares to reported value, 0.3304

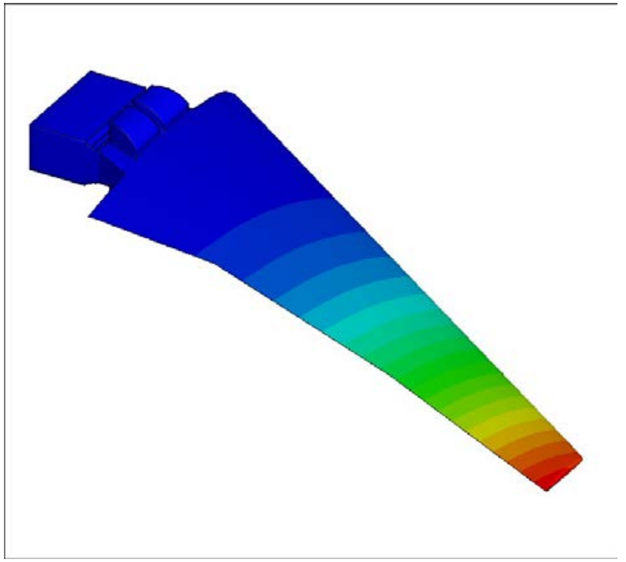
Convergence history of static case



Surface pressure coefficient contours

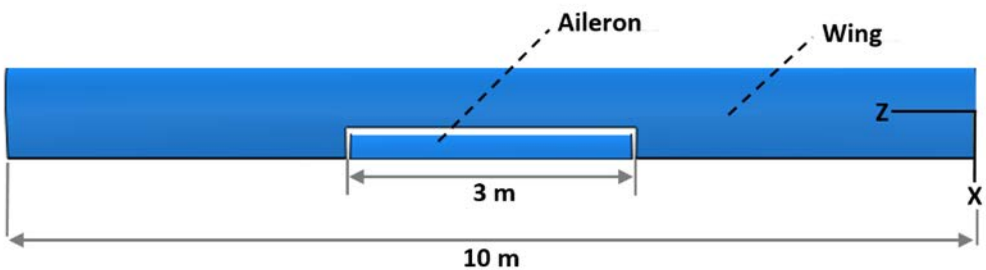


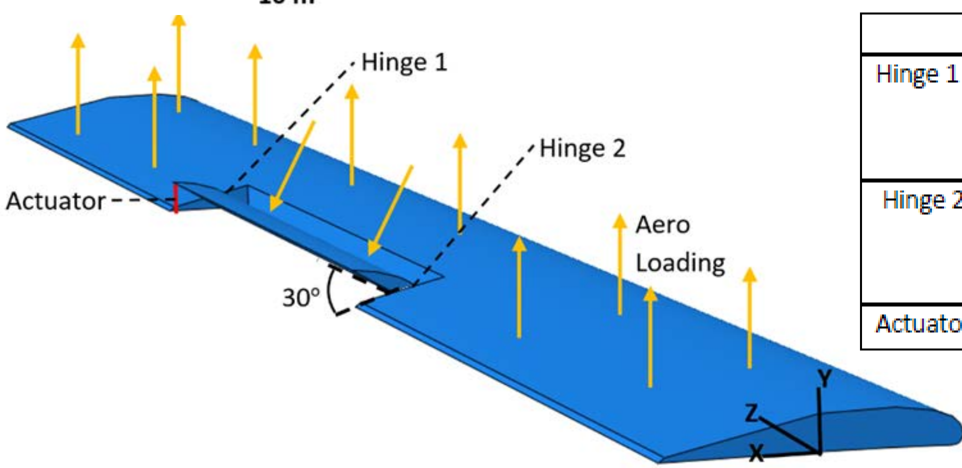
Displacement field



Current Work
Hinge Joint for Control Surfaces

- Implementation of multi-point nodal displacement constraints in FEM model to simulate hinge joints
- Implementation of geometrically non-linear structural dynamics (large displacements): Green-Lagrange strain tensor



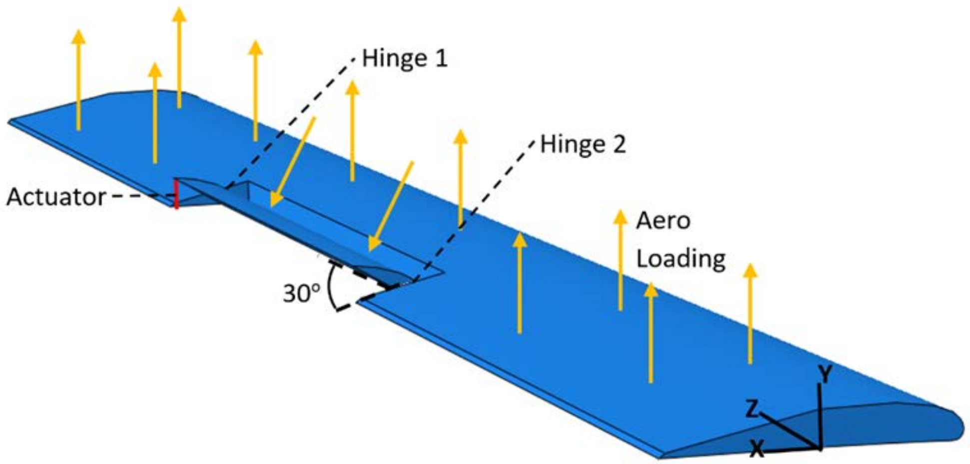


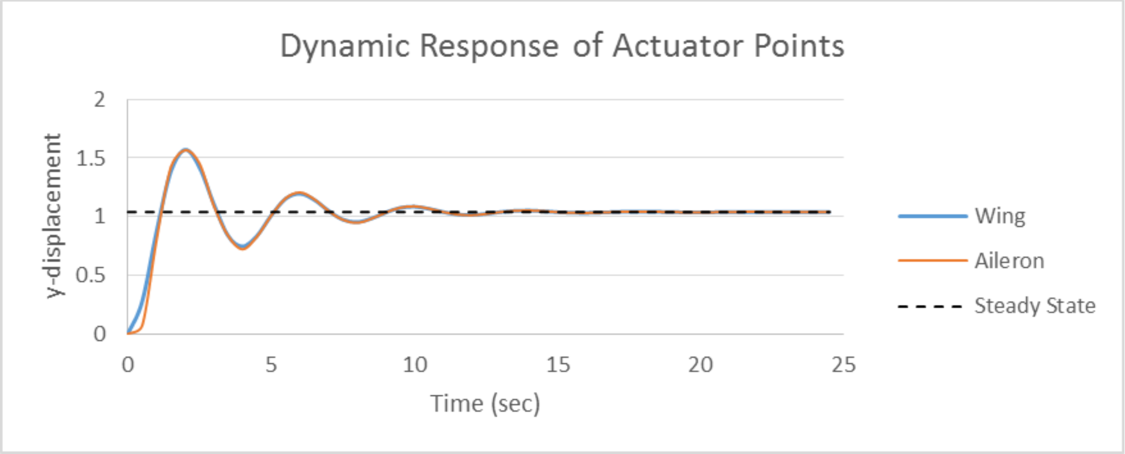
Steady-state solution with prescribed actuator displacement

		Wing	Aileron
Hinge 1	U1	3.5956712019126E-02	3.5956712019126E-02
	U2	1.0389342958601E+00	1.0389342958601E+00
	U3	-1.0831638284435E-01	-1.0831638284436E-01
Hinge 2	U1	1.3521822240126E-02	1.3521822240126E-02
	U2	3.6038955728938E-01	3.6038955728938E-01
	U3	-2.8279196022693E-02	-2.8279196022684E-02
Actuator	U2	1.0391984874015E+00	1.0391984874015E+00

Hinge Joint for Control Surfaces

- Time-dependent simulation starting with undeflected aileron using actuator force from steady-state solution
  - Recovers steady-state configuration



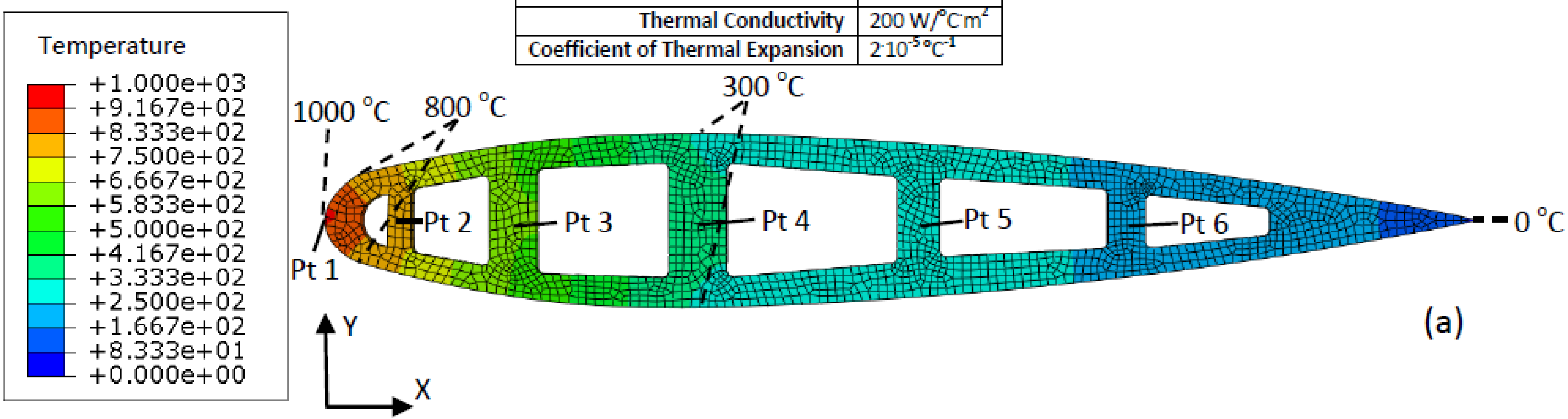


Current Work
Thermo-Elastic Model Development

- Thermo-elastic analysis capability implemented in FEM code
  - Material properties assumed independent of temperature
- Simulated aeroheating test case compares well with Abaqus

Point	AStrO	Abaqus
1	1.00000E+03	1.00000E+03
2	7.61624E+02	7.61624E+02
3	5.85357E+02	5.85357E+02
4	3.38382E+02	3.38382E+02
5	2.82028E+02	2.82028E+02
6	2.36751E+02	2.36751E+02

Young's Modulus	70 GPa
Poisson's Ratio	0.33
Thermal Conductivity	200 W/°C·m²
Coefficient of Thermal Expansion	$2 \cdot 10^{-5}$ °C^{-1}



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Point	AStrO	Abaqus
1	6.93302E-03	6.93340E-03
2	6.01970E-03	6.02108E-03
3	4.75171E-03	4.75326E-03
4	3.31698E-03	3.31857E-03
5	2.11210E-03	2.11353E-03
6	1.15342E-03	1.15489E-03

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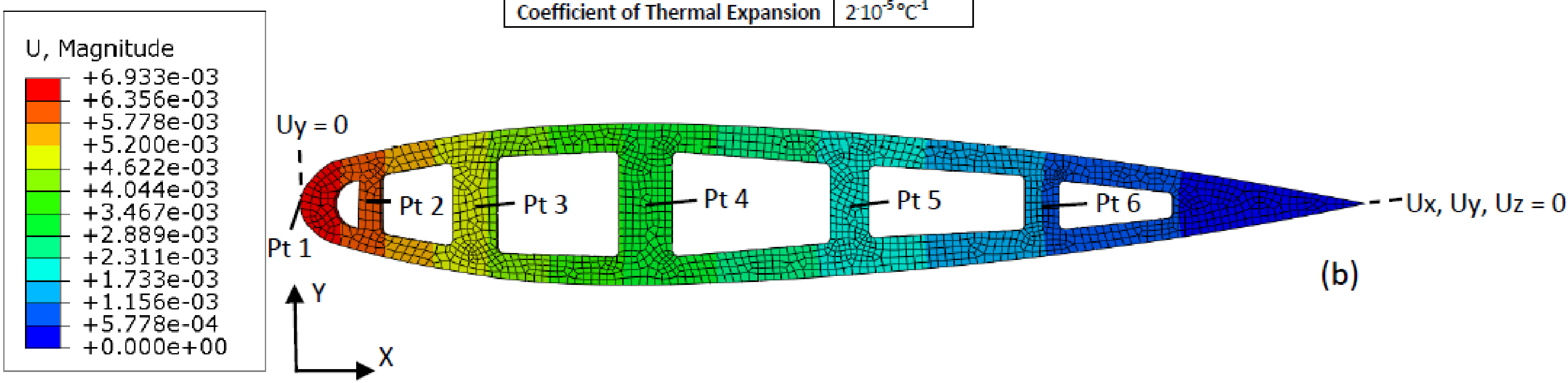

Future Work

- Perform analysis coupling of disciplines
  - Conjugate heat transfer
  - Aeroelastic
  - Aerothermoelastic
  - Aerothermoservoelastic
- Develop disciplinary adjoint capabilities
  - Thermal, thermoelastic
- Develop coupled multidisciplinary adjoint capabilities
  - Conjugate heat transfer
  - Aeroelastic
  - Aerothermoelastic
  - Aerothermoservoelastic
- Perform analysis and optimization of multidisciplinary problems
  - High speed
  - Perfect gas only

Milestones

Task	Milestone	Year 1	Year 2	Year 3
1	Thermo-Elastic Analysis			
	Conjugate Heat Transfer Analysis			
2	Incorporation of Control Inputs			
3	Conjugate Heat Transfer Adjoint			
	Thermo-Elastic Adjoint			
	Adjoint for Control Inputs			
4	Multidisciplinary Analysis/Optimization			

- Implementation of single disciplines
  - Analysis
  - Adjoint
- Extension to coupled multidisciplinary cases

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- University of Wyoming
  - Evan Anderson, PhD student
  - Zhi Yang, Postdoctoral Researcher
  - UW Advanced Research Computing Center (ARCC)
- NCAR-Wyoming Supercomputer NWSC