



Fundamental Aeronautics Program

Subsonic Rotary Wing Project

Overview of Recent FUN3D Code Developments and Applications for the Subsonic Rotary Wing Project

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Motivation



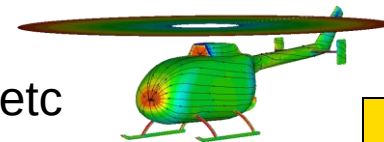
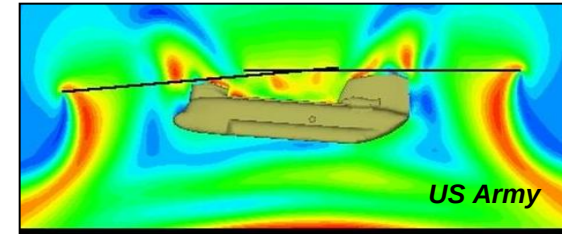
- Helicopters/Tiltrotor aircraft provide many crucial services (civilian and military)
- Challenging phenomena associated with rotorcraft simulations
 - Vortex wakes and blade vortex interaction (BVI)
 - Dynamic stall on retreating blade
 - Transonic shocks on advancing blade
 - Moving components with rotor blade flexibility
 - Multidisciplinary (aerodynamics, structural dynamics, and trim/controls)
 - Aerodynamic performance and noise prediction
- Interactions of these phenomena are difficult to model and accurately predict
 - Several rotorcraft-specific computational structural dynamics (CSD) codes (“comprehensive codes”) have been developed for MD analysis of complete rotorcraft systems but typically have lower-fidelity aerodynamic models
 - An objective of NASA’s Subsonic Rotary Wing (SRW) Project is to develop physics-based computational tools to improve aerodynamic modeling
 - Structured-grid Computational Fluid Dynamics (CFD) code – OVERFLOW
 - Unstructured-grid CFD code – FUN3D
 - Use loose-coupling (periodic) and tight-coupling (every time step) interfaces from CFD to CSD codes to model structures/trim



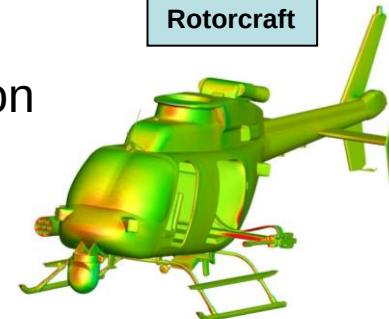
FUN3D Core Capabilities (<http://fun3d.larc.nasa.gov>)



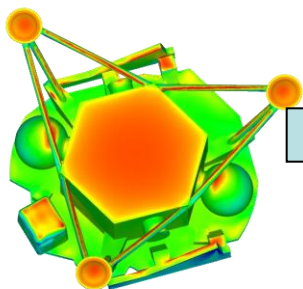
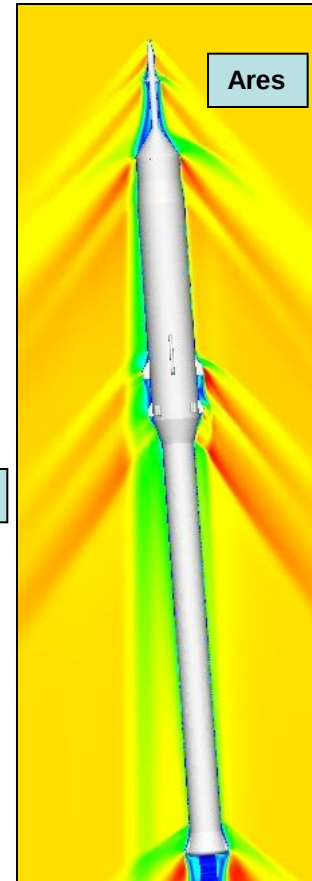
- Solves 2D/3D steady and unsteady Euler and RANS equations on node-based mixed element
- Used for numerous projects internal and external to NASA across the speed range
- General dynamic mesh capability: any combination of rigid/overset/morphing grids, including 6-DOF effects
- Aeroelastic modeling w/ mode shapes, full FEM, CC, etc
- Adjoint solver
 - Efficient design sensitivities for optimization
 - Error estimation and error-based mesh adaption
- Software maintained with revision control and continuous build and testing environment



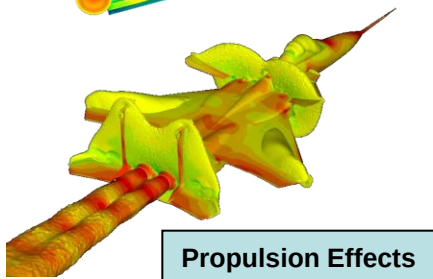
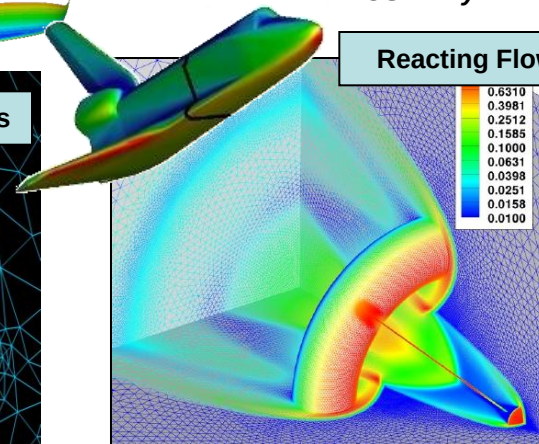
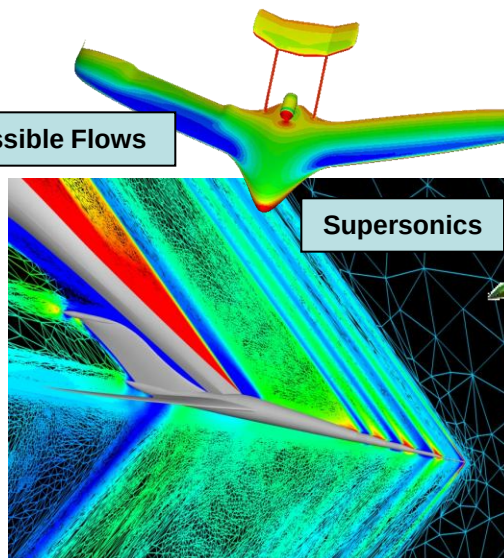
Rotorcraft



US Army



Incompressible Flows



Outline



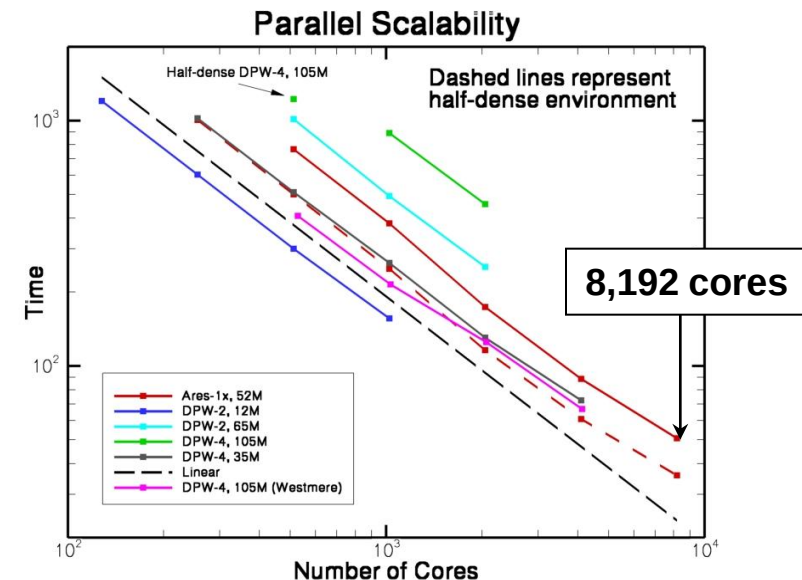
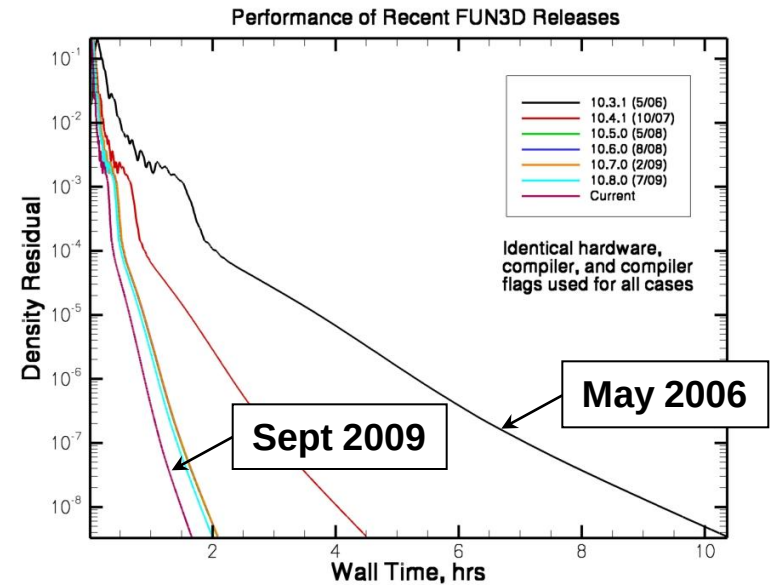
- FUN3D code developments for SRW
 - Improved time to solution
 - Periodic grid adaption for time-dependent flows on overset meshes
 - Implementation of unsteady adjoint for overset meshes
- FUN3D validation cases for SRW
 - Higher-harmonic Aeroacoustic Rotor Test (HART-II) Wind Tunnel
 - UH-60 NASA/Army Airloads Flight Test Program
- Collaborative NRA
 - Innovative Strategies for Rotary-Wing Coupled Aeroelastic Simulations
 - Georgia Tech (9/2007 – 2/2011)
- Summary
- Future Work

FUN3D Computational Performance



- Flow solver 6.5x speedup via computer science details demonstrated on full Navier-Stokes equations
- Linear scaling demonstrated to 8,192 cores on NAS Pleiades
- New fully distributed-memory grid processing paradigm
- Solution visualization direct from solver using parallel co-processing
- Improved efficiency of deforming mesh algorithm for overset meshes
- Improved optimization and automation of the loose-coupling process

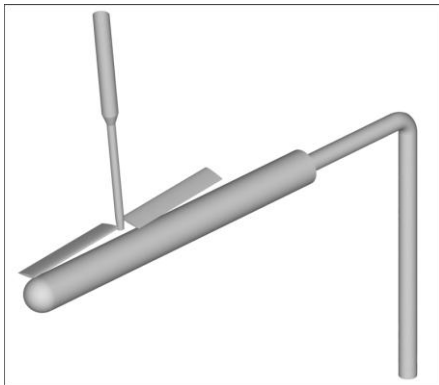
From Sept. 2007 to Feb. 2010 reduced solution turn around time for loosely coupled HART-II computation by 75% for a given accuracy (grid size)



Unstructured Overset Mesh Adaption

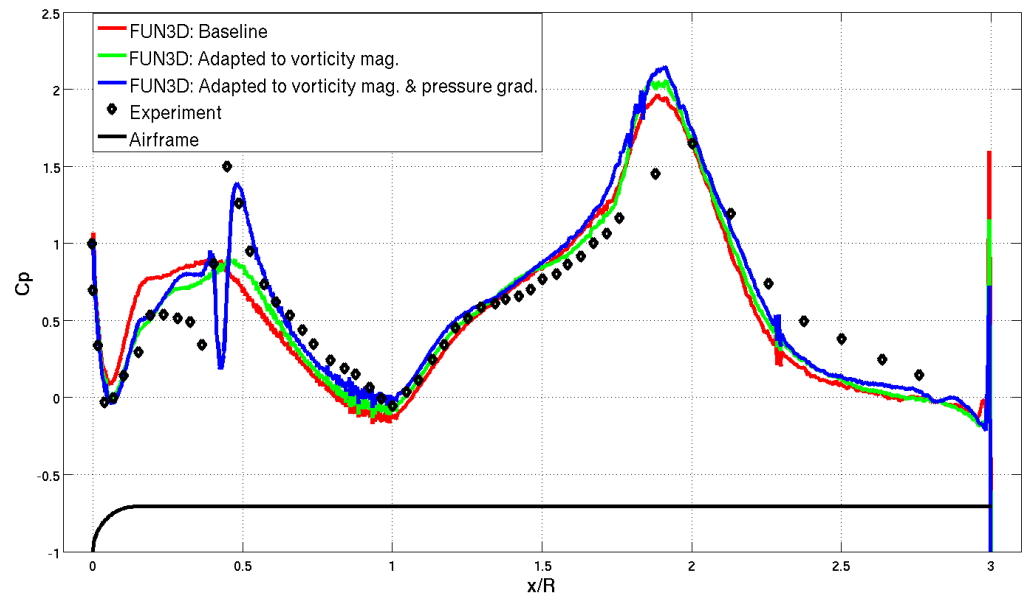
Collaborative with Rajiv Shenoy and Prof. Marilyn Smith, Georgia Tech

- Feature-based anisotropic adaption extended for overset, moving grids demonstrated in FUN3D
- Vorticity magnitude indicator implemented to preserve vortical structures in the rotor wake
- Adaption for periodic flows utilizes minimum spacing requirement over a time-interval



GT Rotor/Fuselage Experiment

GT Rotor/Fuselage Experiment
Average Pressure on Upper Fuselage

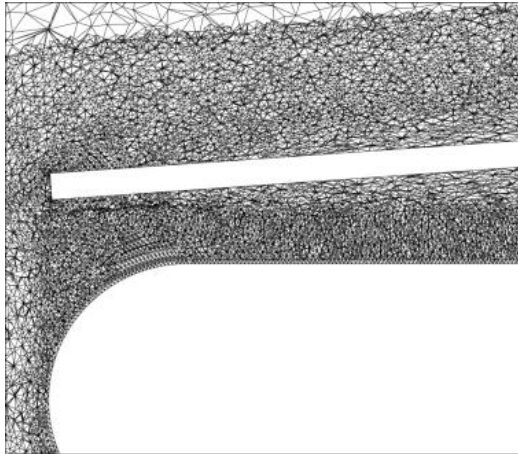


Adaption based on vorticity and pressure gradient improves prediction of tip-vortex impingement on fuselage

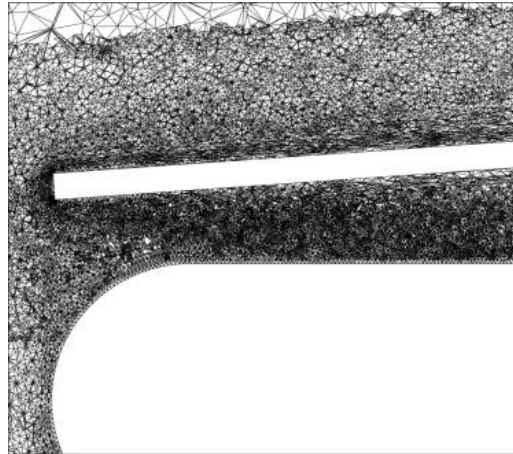
Unstructured Overset Mesh Adaption

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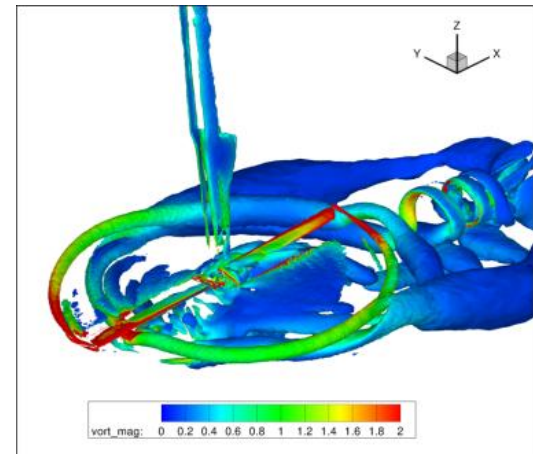
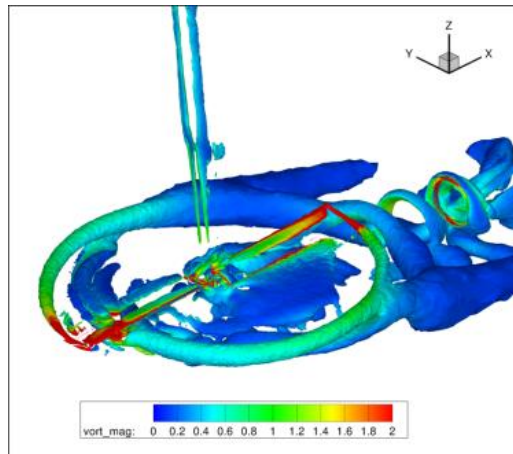
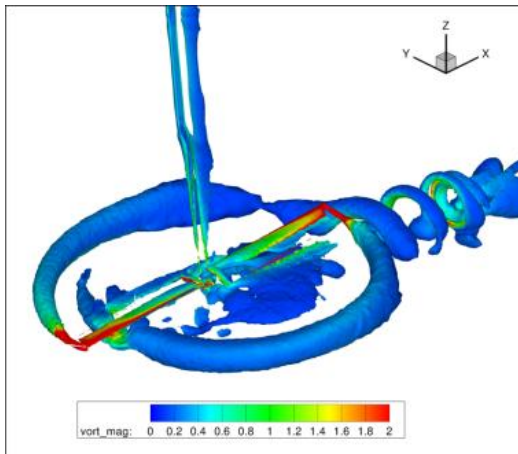
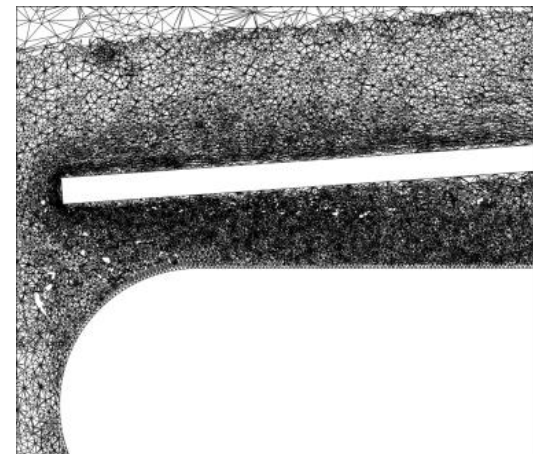
Baseline mesh



Mesh adapted to vorticity magnitude



Mesh adapted to vorticity magnitude and pressure gradient



Isosurface of Q-Criterion colored by vorticity magnitude

Status: Discrete Adjoint for Dynamic Overset Grids

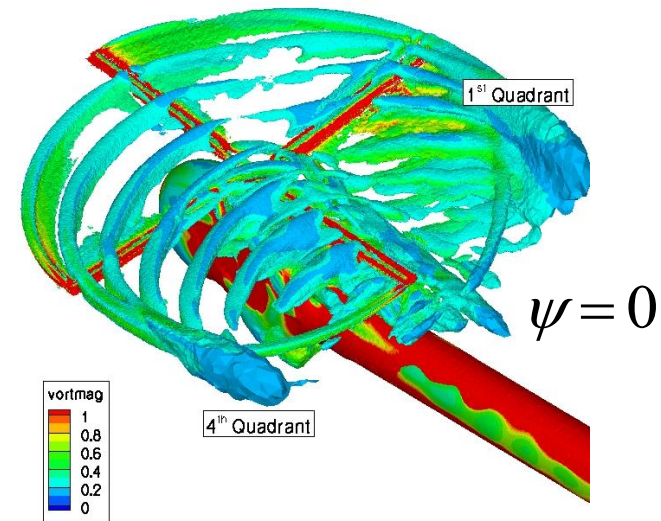
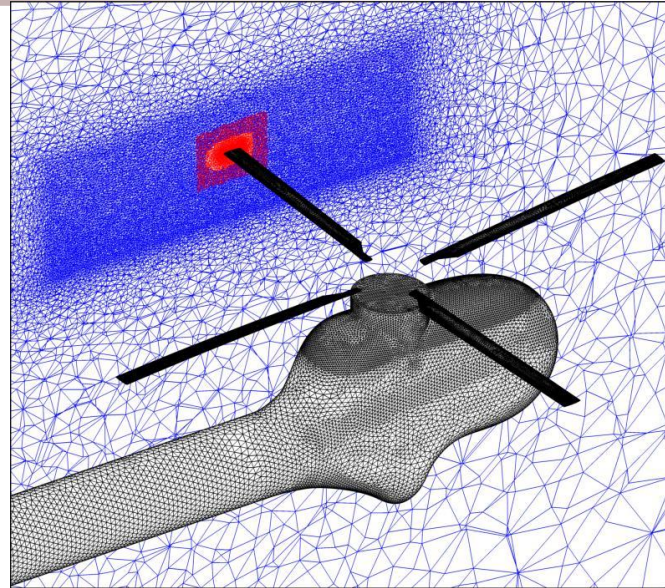


Collaborative with Dr. Boris Diskin, NIA

- A discretely-consistent adjoint implementation for turbulent flows on dynamic unstructured grids was demonstrated for large-scale design cases at the 2009 FAP Annual Forum
- Effort has been underway for ~6 months to extend the formulation and implementation to overset grids
- Implementation complete for steady and unsteady flows on static and rigidly-moving overset grids
 - Asynchronous I/O for massively parallel environments implemented for all information at each time step, including overset domain-connectivity data
 - Discrete consistency demonstrated using complex-variable formulation
- Final step is to accommodate deforming dynamic overset grids; hope to publish results shortly

HART-II Loosely Coupled Computations

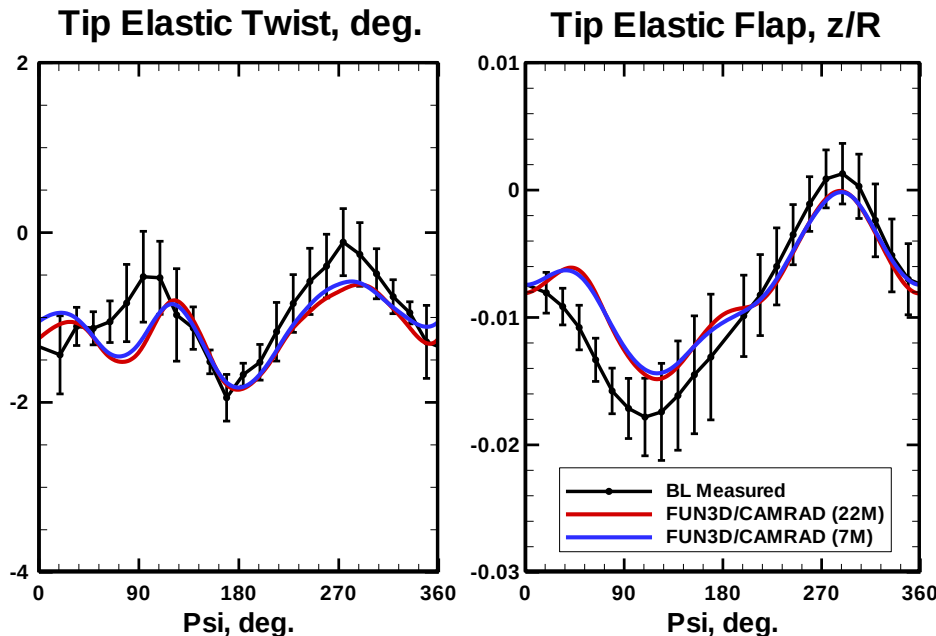
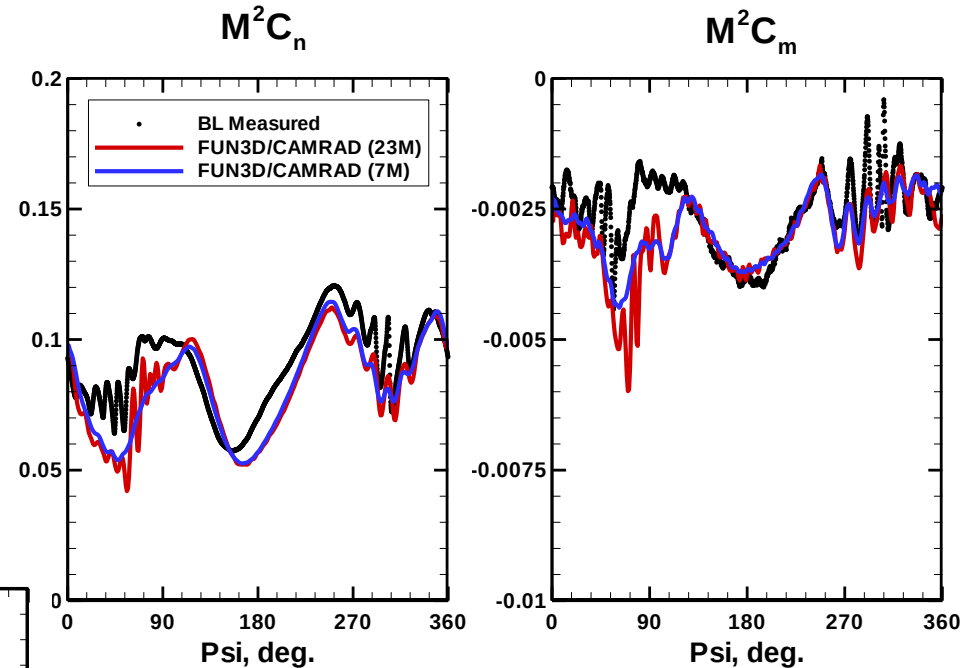
- Higher-harmonic Aeroacoustic Rotor Test HART-II , DNW Tunnel
- Nominal conditions:
Advance Ratio = 0.15,
descending flight with
Blade Vortex Interaction (BVI)
- With and without higher-harmonic pitch control
- Loose-coupling to CAMRADII
- Ongoing workshops for CFD and experiment



HART-II Loosely Coupled Computations



- Study the effects of off-body grid refinement and use of prismatic elements in boundary-layer
- Improved the correlation of BVI in sectional airloads- elastic deformations are not changed

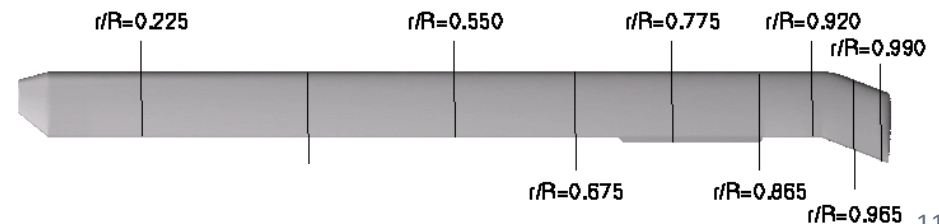
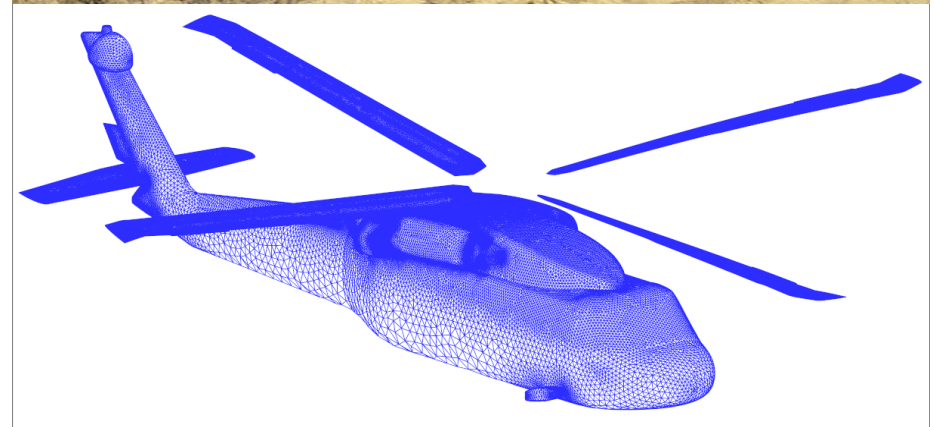


Example without higher harmonic control

UH-60 Loosely Coupled Computations



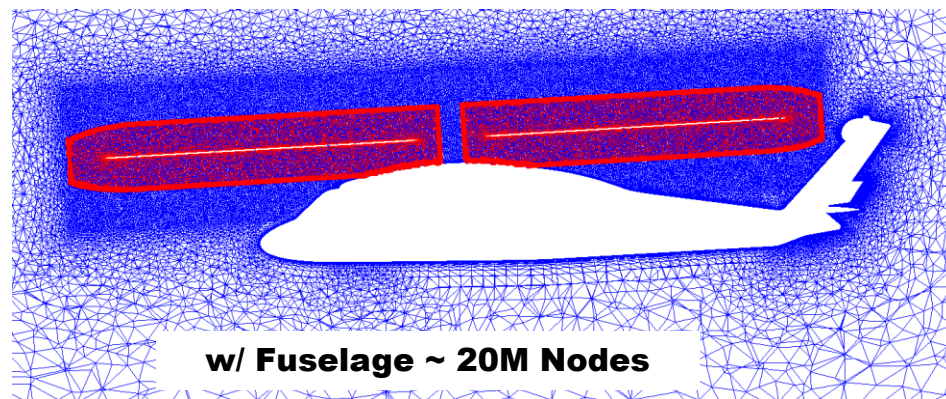
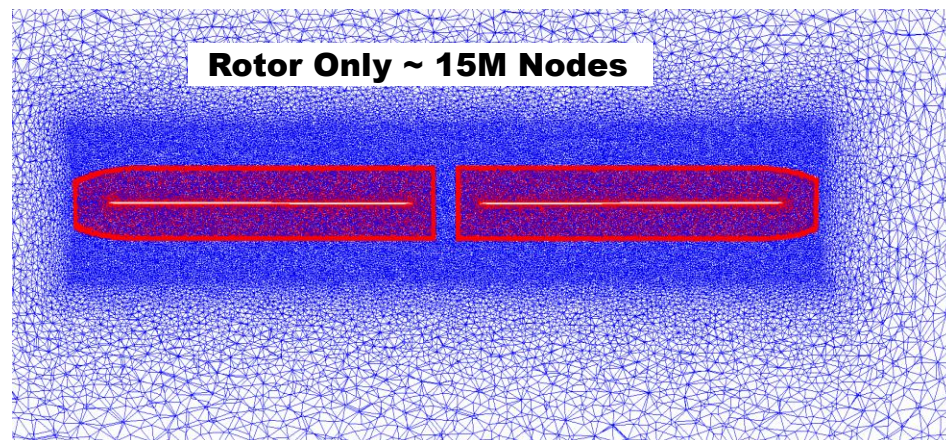
- Joint NASA/Army Flight Test
- Level flight conditions:
 - High-speed
 - High-thrust w/ dynamic stall
 - Low-speed w/ BVI
- Comprehensive flight test measurements including sectional airloads (pressures) at 9 radial locations
- Loose-coupling to CAMRADII
- Ongoing workshops for CFD and experiment
- Recent wind tunnel test in NFAC



UH-60 Loosely Coupled Computations



- Isolated Rotor results:
 - Airloads compare well with other CFD codes: OVERFLOW and Helios(DOD)
 - Comparison to experimental airloads is good for unsteady loads in many locations but the mean levels trends are off-set
 - Studied the effects of grid/temporal refinement and turbulence models
- With fuselage but no hub, propulsion or tail rotor: improved correlation in some inboard areas for high speed
- Use results from recent UH-60 Airloads Wind Tunnel Test to clarify some uncertainty in rotor trim conditions and fuselage interference

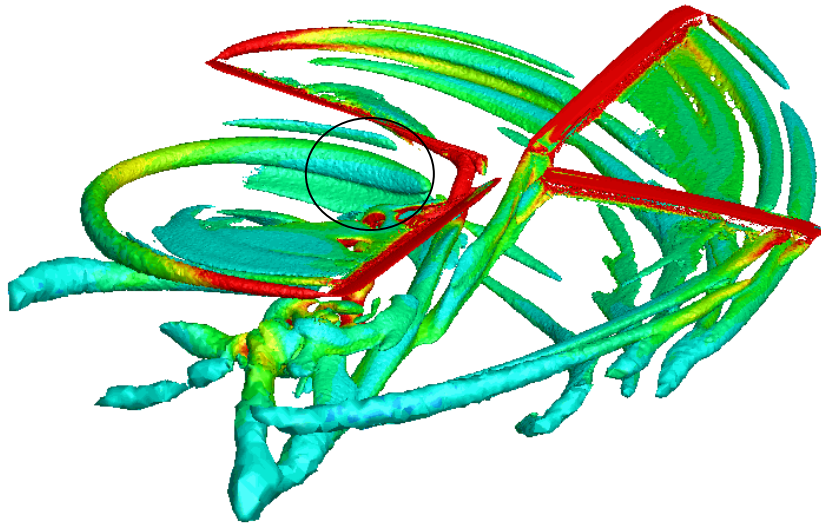


**Complete set of results to be published at
2011 American Helicopter Society Forum**

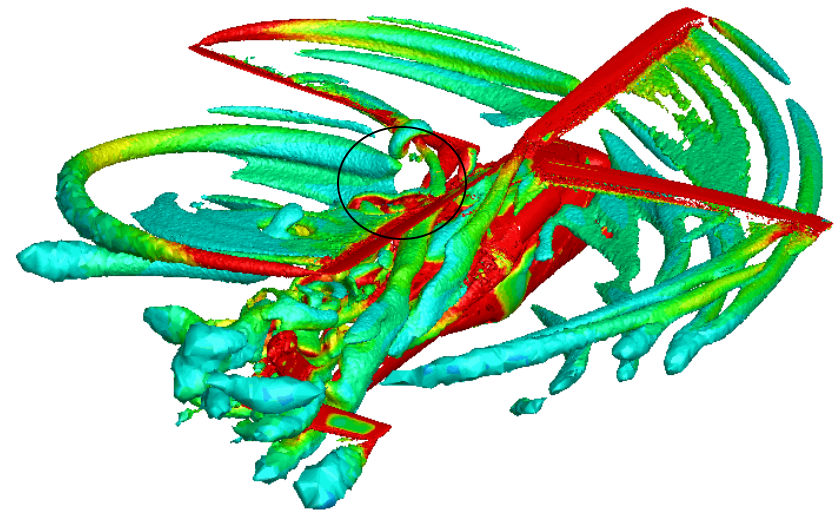
UH-60 Loosely Coupled High Speed Case



Advance Ratio 0.37



Isolated



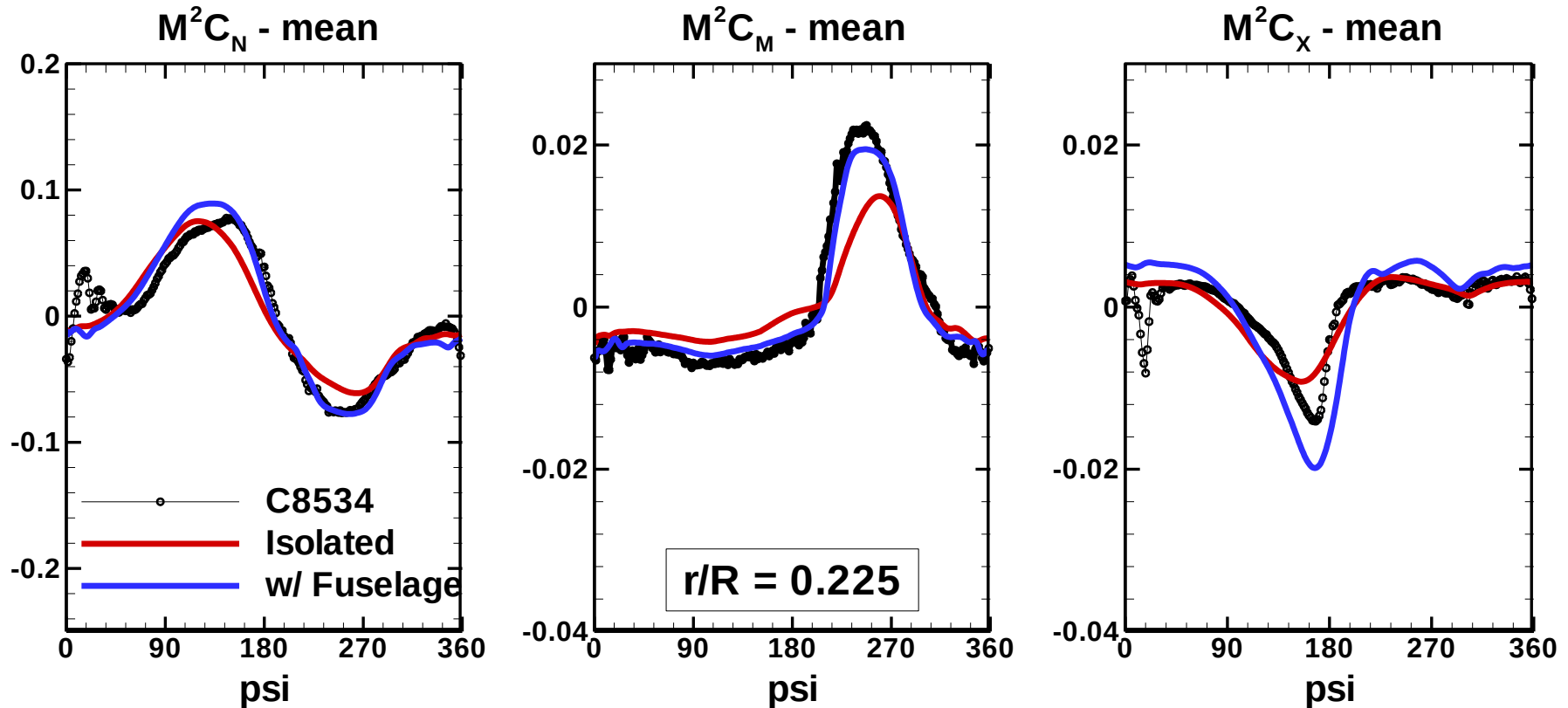
w/ Fuselage

Isosurfaces of Q-Criterion colored by vorticity magnitude
Generated concurrently by the flow solver and animated with Tecplot

UH-60 Loosely Coupled High Speed Case



Advance Ratio 0.37
Unsteady Sectional Airloads



Improved correlation at the retreating azimuthal location

Innovative Strategies For Rotary-Wing Coupled Aeroelastic Simulations (NNX07AP43A)



Nic Reveles, Afifa Zaki, Profs. Marilyn Smith and Olivier Bauchau, Georgia Tech

Technical Objective: Develop framework to couple CFD-CSD-Computational Aeroacoustic codes to replace current ad hoc coupling and trim approaches.

Problem

- CFD/CSD analysis relies on trim inputs from autopilot algorithms that are updated via loose coupling
- Initial trim estimates based on CSD-alone or experiments that are not close to CFD/CSD controls
- Cost of runs increases due to trim constraints

Approach

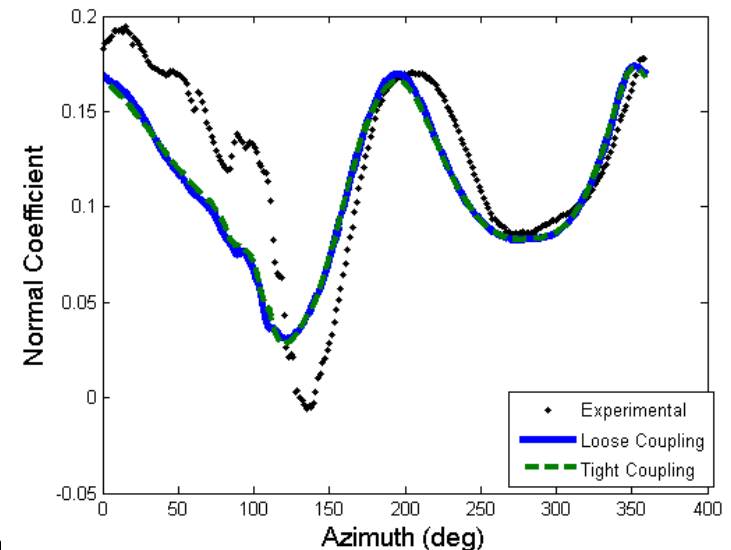
- Systems identification used to construct a reduced-order kriging meta-model to provide initial trim estimates and “on the fly” trimming
- “Plug and Play” implementation via Python or compiling all modules together

Demonstration Codes

- Comprehensive Rotorcraft Code: Dymore4
- CFD Codes: FUN3D (unstructured) and OVERFLOW (structured)



Source: defenseimagery.mil

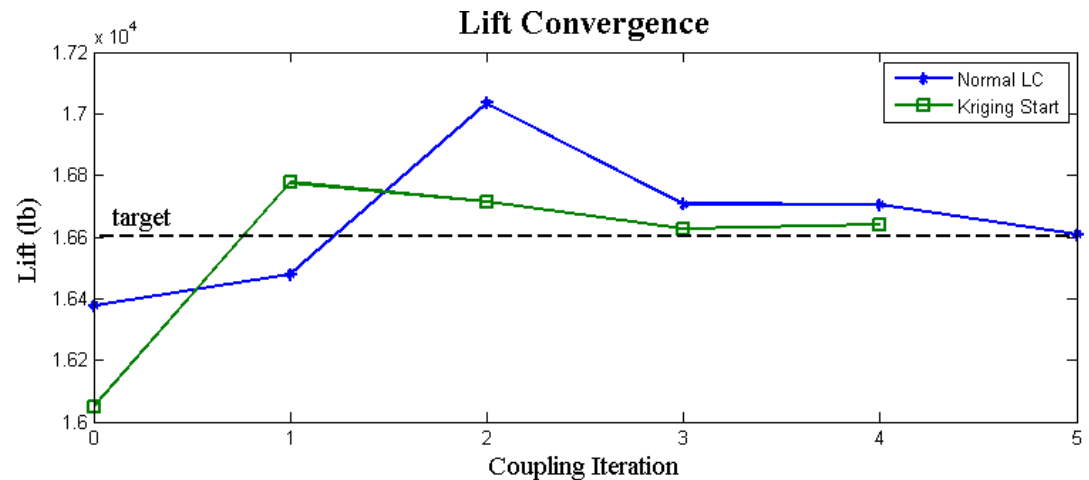


Sample Rotor Loads for the UH60 at 77.5%

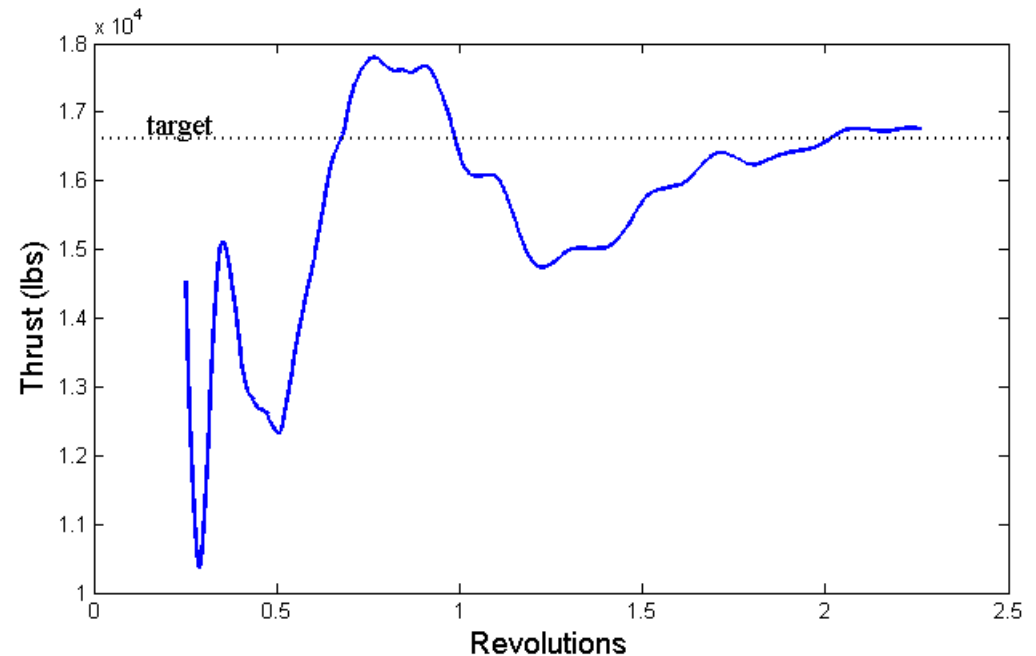
Innovative Strategies For Rotary-Wing Coupled Aeroelastic Simulations



- Use of the kriging meta-model improves loose coupling convergence through the elimination of 2-3 iterations, a savings of 1/2-2 rotor revolutions



- Kriging allows trimming “on the fly” during tight coupling



Summary



- Code developments
 - Reduced solution turn around time for loosely-coupled computation by 75% for a given accuracy (grid size)
 - Demonstrated feature-based grid adaption for time-dependent flow on overset grids
 - Discrete adjoint implementation complete for steady and unsteady flows on static and rigidly-moving overset grids
- Rotorcraft Applications
 - Improved BVI prediction for HART-II with grid refinement and use of prismatic elements in boundary layer
 - UH-60 Airloads Flight Test
 - Isolated rotor airloads compare well with other CFD codes: Overflow and Helios
 - Studied the effects of fuselage, grid/temporal refinement and turbulence models
- Innovative Strategies For Rotary-Wing Coupled Aeroelastic Simulations (NRA)
 - FUN3D and OVERFLOW tightly-coupled interface to Dymore4 comprehensive code
 - New trim algorithm allows “on the fly” trimming during tight coupling and more efficient trim for loose coupling

Future Work



- Code developments
 - Improve time to solution
 - Additional work to parallelize the hole-cutting and domain connectivity
 - Multi-grid acceleration for grid deformation and flow solution
 - Automatic surface mesh generation: spacing based on curvature
 - Concurrent visualization of vortex core location and size
 - Grid adaption: on-surface and time-accurate
 - Unsteady flow adjoint-based error estimation and design
- Applications
 - UH-60 Airloads Wind Tunnel Test
 - Downwash/Outwash Hover Test in LaRC 14'X22'
 - Apache Active-Twist Wing Tunnel Test
 - Adjoint-based aerodynamic design of a tilt-rotor concept

