2017 NRTC Year End Review

- **Project Title:** **Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles**
- **Project Number:** **NRTC-FY15-A-02**
- **Principal Investigator:**

Mr. Ted Meadowcroft
The Boeing Company
610-591-8482
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- **Team Members:** **Boeing, Sikorsky, Georgia Tech, University of Maryland**
- **Agreements Officer Representative (AOR):** Dr. Hyeonsoo Yeo, US Army Aviation Directorate

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Project Description

- TASK ASSIGNMENT TITLE: NRTC-FY15-A-02; Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles
- BASE VLC PROJECT AGREEMENT NO.: 2015-325
- VLC PROJECT TASK ASSIGNMENT NO.: 03
- PARTIES: Advanced Technology International (“VLC CAO”) and The Boeing Company (“Project Agreement Awardee”)

Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

Project Number: NRTC-FY15-A-02

PROJECT MEMBERS

Boeing

Mr. Ted Meadowcroft
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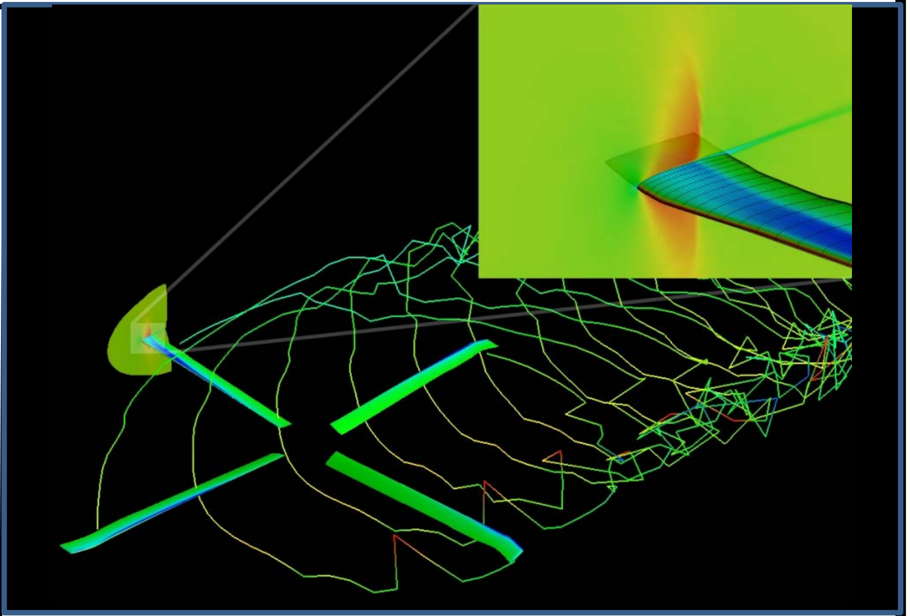
Dr. Ananth Sridharan

2017 NRTC Year End Review

Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles
PI: Ted Meadowcroft
Project Number: NRTC-FY15-A-02

Technical Objectives:

- Joint research initiative to extend aeromechanics analyses to maneuvering flight as well as towards improved accuracy of rotor structural loads and control loads predictions.
- The effort focuses on including additional physics like the drive-train, flexible fuselage, swashplate, variable pitchlink stiffness.



Technical Challenges:

- CFD-coupled CSD has vastly improved our ability to analyze advanced rotor systems at critical flight conditions; however, deficiencies remain.
- The pattern of correlation quality suggests simulation models need improvement with regard to blade root boundary conditions.
- Need better understanding of physics necessary to analyze rotor and hub loads

Deliverables:

- Improve first pass quality for new rotorcraft development programs, such as Future Vertical Lift

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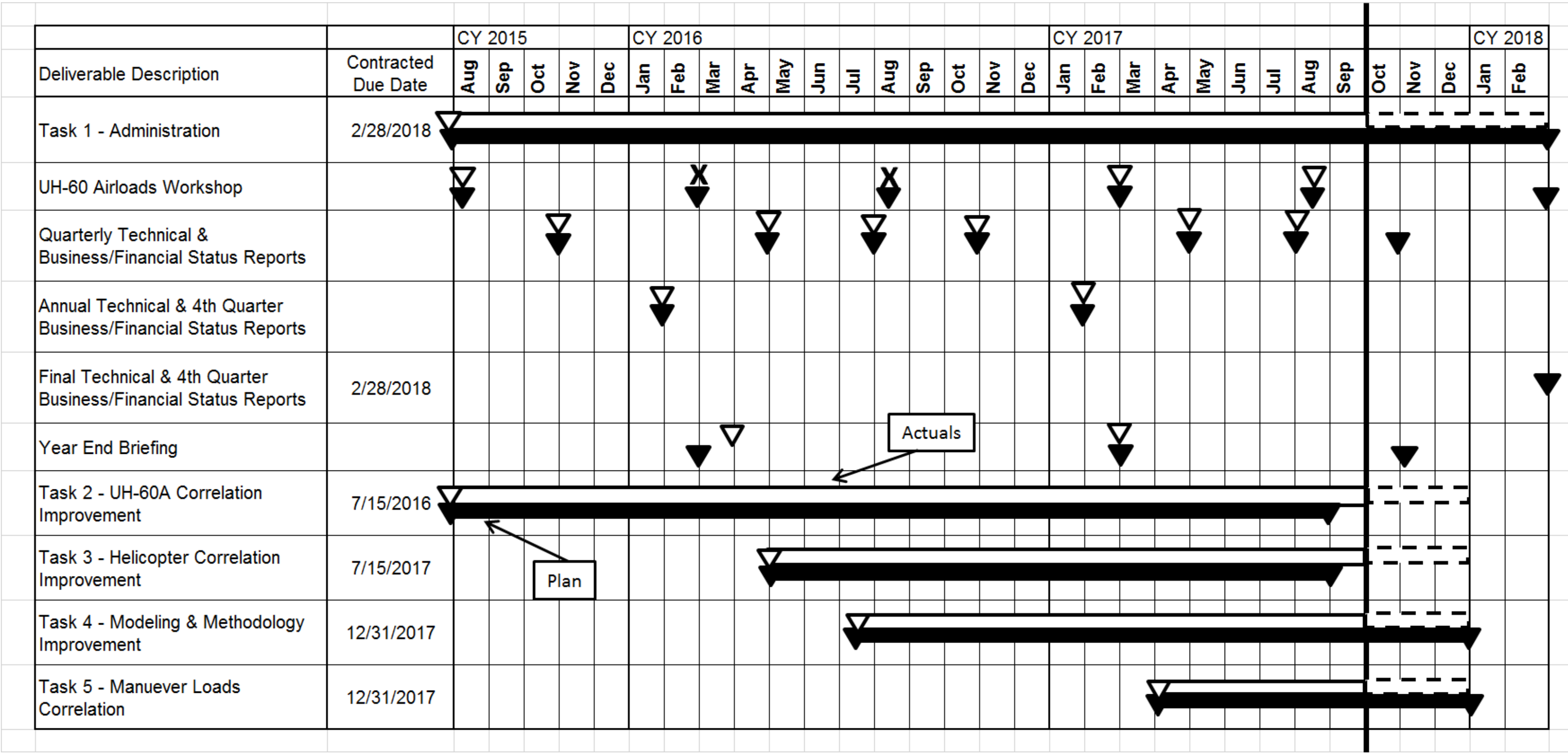


2017 NRTC Year End Review

Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

Project Number: NRTC-FY15-A-02

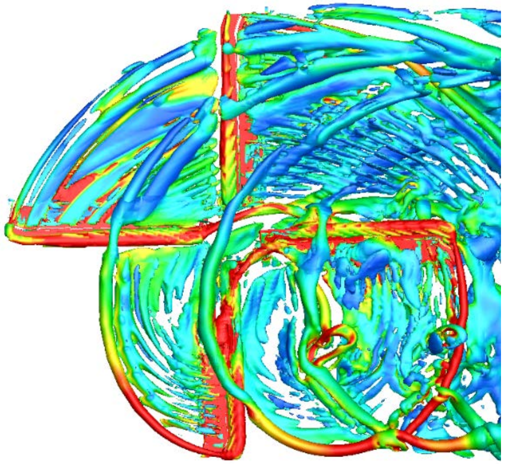
Technical Accomplishments during 2017 Project Year

- Task 2 – UH-60A Correlation
  - Wind tunnel test article:
    - Hub impedance model improves correlation with test case
  - Flight test article:
    - Drive train model shows small benefit to 4p edgewise bending
- Task 3 – Helicopter Correlation
  - Implemented H-47 flexible fuselage model. CFD coupling underway.
  - Fuselage flexibility has minor effect on AH-64 rotor loads
  - Drivetrain model has significant effect on AH-64 rotor loads
  - HELIOS for UH-60M correlation (RCAS w/ OVERFLOW on blades) achieved parity with legacy RCAS-OVERFLOW
  - Revised blade properties for UH-60M improved pitch link load prediction
- Task 4 – Modeling and Methodology Improvements
  - Developed the CFD coupling for PRASAD-UM - HELIOS
  - Developed the hub impedance coupling in PRASAD-UM
  - Vortex particle methodology expands GT-Hybrid code usability
  - Improved the OVERFLOW-CHARM CFD interface

Program Status/Changes

- No changes

Task 2 – UH-60A Correlation



Boeing, Georgia Tech, Sikorsky, University of Maryland

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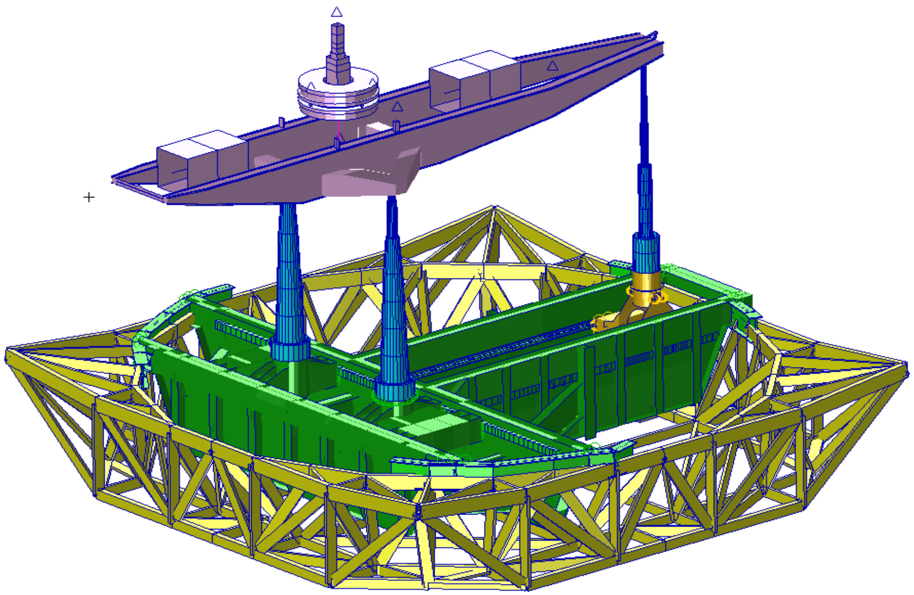
LRTA Test Stand Coupling with UH-60A Rotor



Boeing

DETERMINATION OF HUB IMPEDANCE FOR CFD-CSD ANALYSIS

- Received Government Furnished Information from NASA as starting point:
  - Large Rotor Test Apparatus (LRTA) test stand shake test data
  - LRTA NASTRAN model
- Tuned the NASTRAN model to improve correlation with shake test measurement.
- Computing hub impedance using the tuned model.

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SOFTWARE MATRIX USED FOR UH-60A MODELING

	CSD	CFD	Isolated Rotor or (Rotor + W.T. Installation Effects)
Boeing Phila	RCAS	OVERFLOW	Isolated
Boeing Mesa	CAMRAD II	OVERFLOW	Isolated
Sikorsky	DYMORE	OVERFLOW	Isolated
Georgia Tech	DYMORE	OVERFLOW-CHARM	Isolated
Georgia Tech	DYMORE	OVERFLOW-CHARM	Installed
Georgia Tech	DYMORE	GT-HYBRID	Isolated
UMD	PRASAD-UM	HELIOS (OVERFLOW ON BLADES)	Isolated

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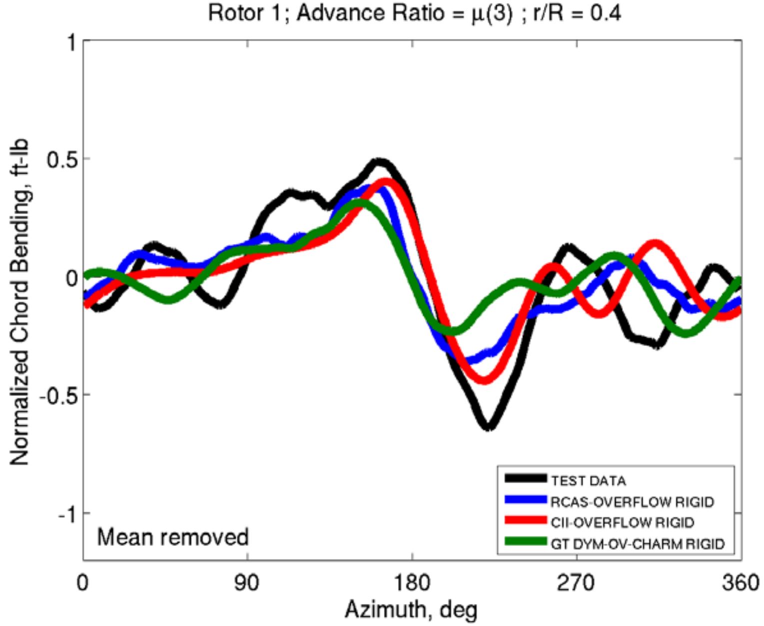
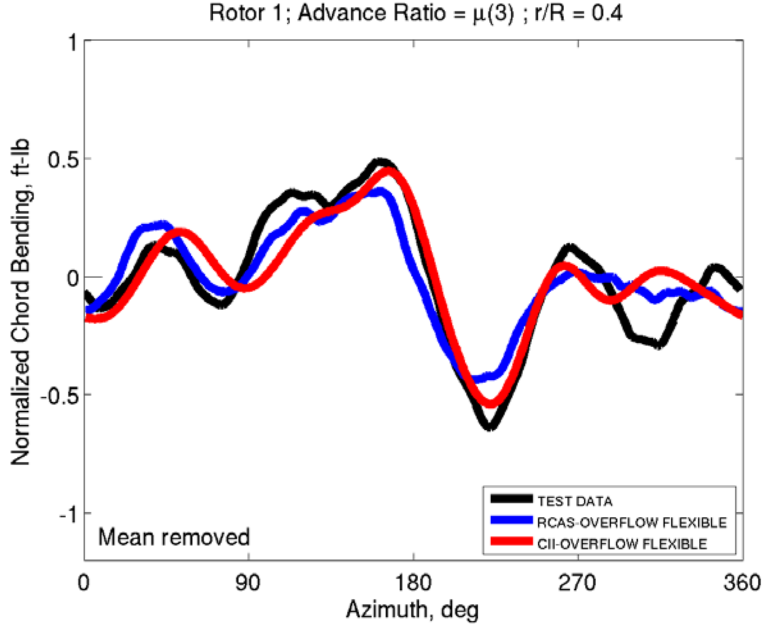
CHORD BENDING AT 40%R VS. AZIMUTH

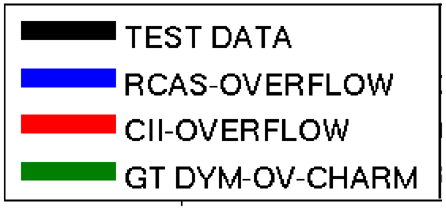
RIGID HUB



FLEXIBLE HUB



- UH-60A NFAC C5240 (High speed)
- Improvement in edgewise bending prediction is expected due to the added flexibility in the in-plane direction



Hub impedance model significantly improves chord bending prediction

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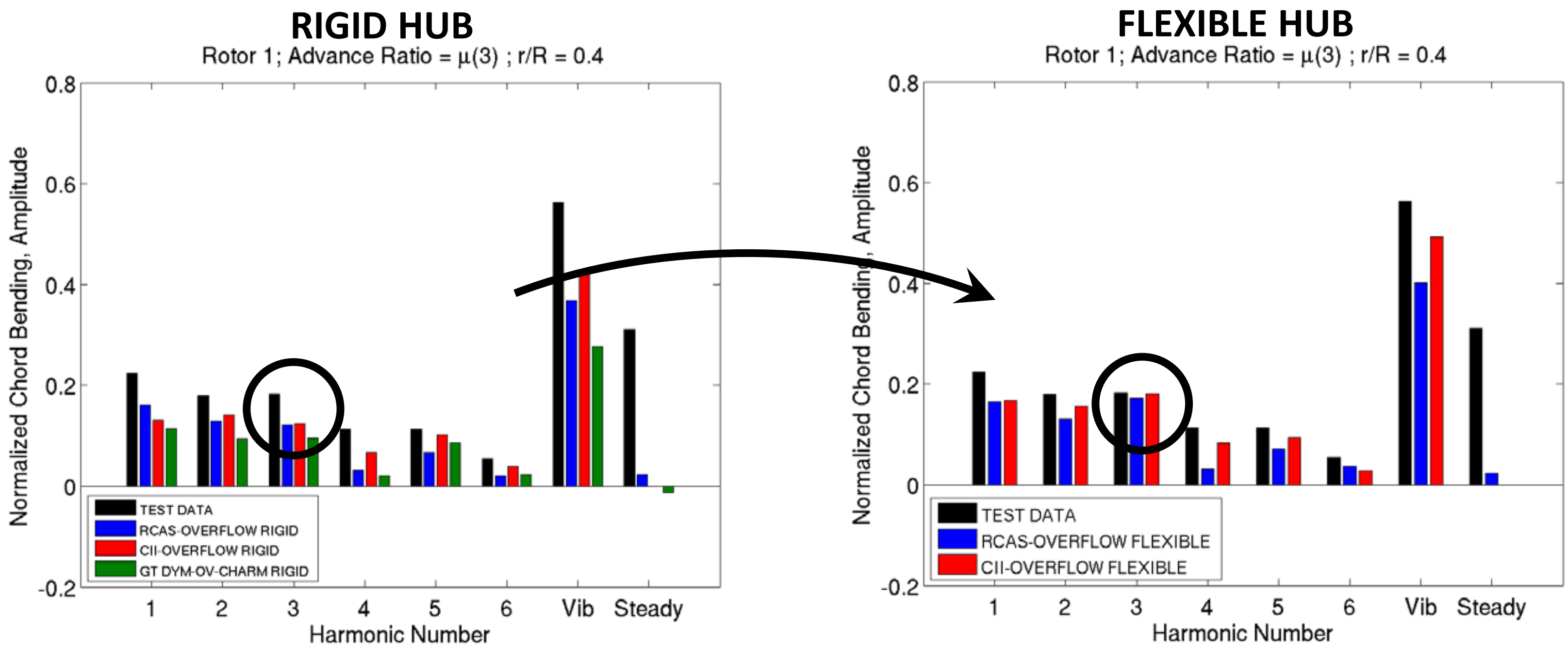
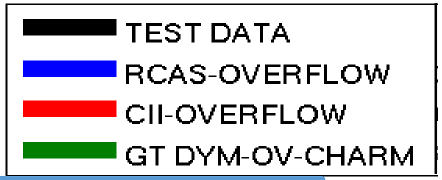
CHORD BENDING AT 40%R VS. AZIMUTH



- UH-60A NFAC C5240 (High speed)
- Other harmonics still under-represented in CFD-CSD
- Results hold along entire blade span



3/rev loads interact with the fixed system in-plane dynamics through the progressing 1st chord bending (1CB) rotor mode

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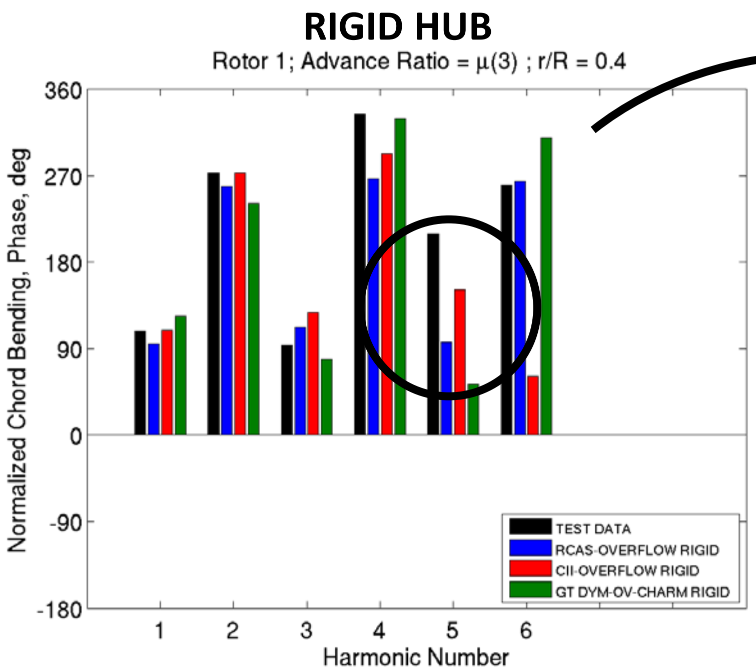
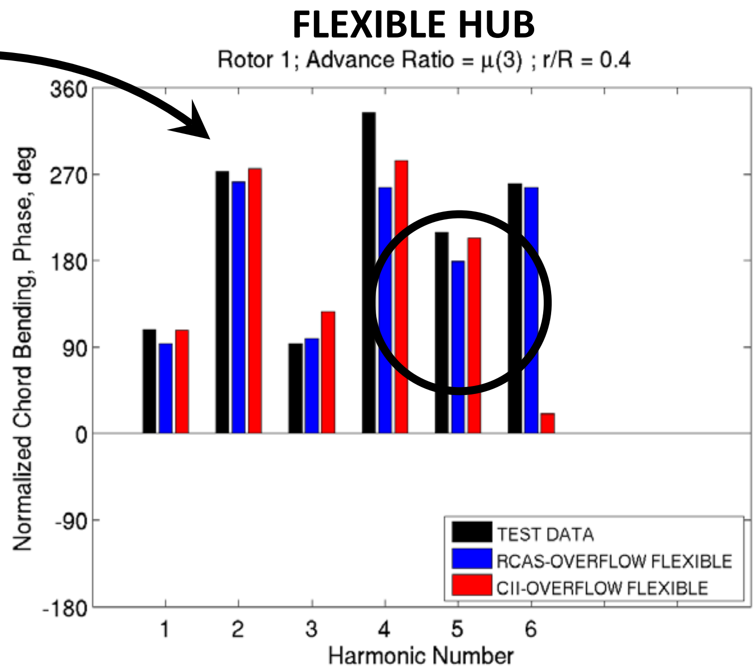
CHORD BENDING PHASE AT 40%R VS. AZIMUTH





- UH-60A NFAC C5240 (High speed)
- Results hold along entire blade span

TEST DATA
RCAS-OVERFLOW
CII-OVERFLOW
GT DYM-OV-CHARM

5/rev loads interact with the fixed system in-plane dynamics through the regressing 1st chord bending (1CB) rotor mode

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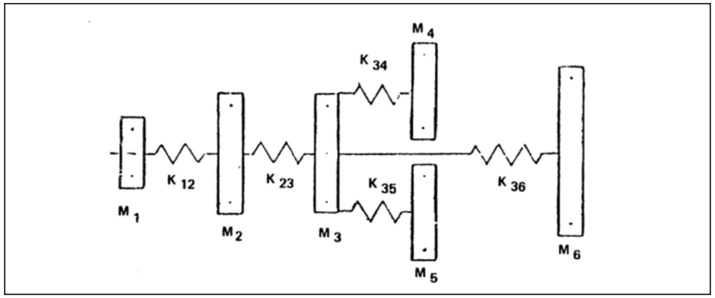
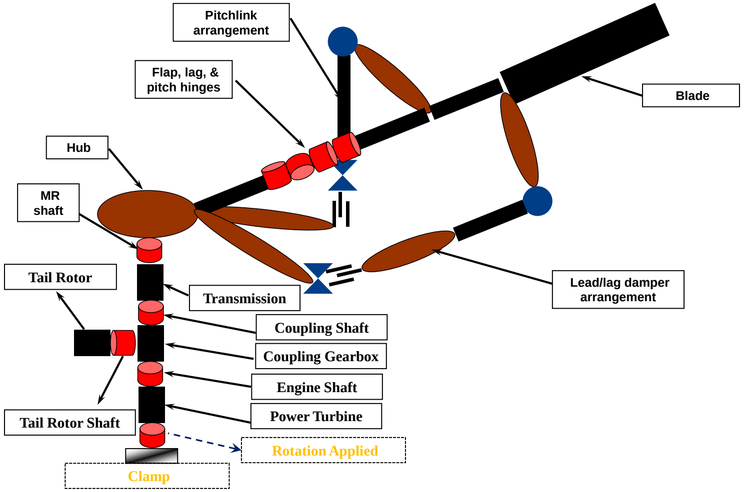
Rotor/Drivetrain Coupling Effects





Sikorsky

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Project Number: NRTC-FY15-A-02

OVERVIEW

- Rotor/Drivetrain coupling effects on rotor loading response
  - Expected to affect vibratory edgewise bending response
- UH-60A drivetrain / UH-60A rotor coupled system
  - Proprietary drivetrain attributes preclude project collaboration
  - Sikorsky/Government collaboration is possible
- Rotor Systems Research Aircraft (RSRA)
  - Publically available drivetrain model (NASA-CR-166155)
  - Former intention to fly the RSRA with UH-60A blades (and others) (UH-60A blades and drivetrain are notionally compatible)
- RSRA drivetrain / UH-60A rotor coupled system
  - Representative effects verified on UH-60A rotor modes
  - Results presented below

Evaluating the influence of a representative aircraft drive train on UH-60A rotor edgewise bending

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Correlation with UH-60M Drivetrain modes

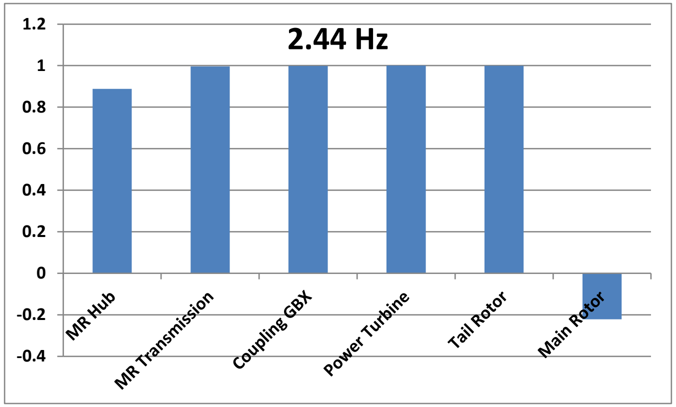
- **RSRA DT model Includes UH-60A Main rotor inertia & centrifugal stiffness**

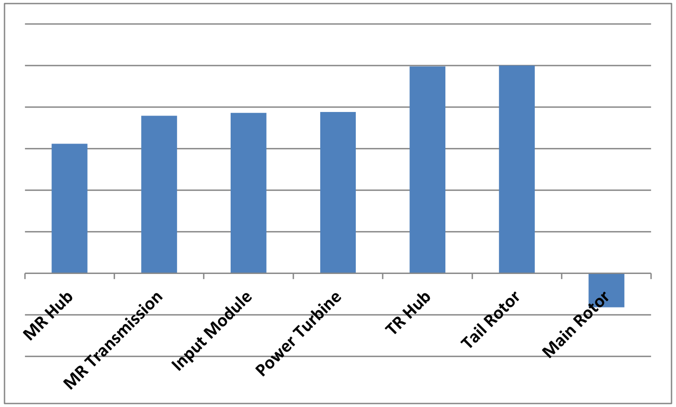
- Collective rigid lag mode
- Comparable mode shape and frequency

RSRA

UH-60M

MR against rest





Response of RSRA and UH-60M drivetrain components for rotor rigid collective mode are comparable

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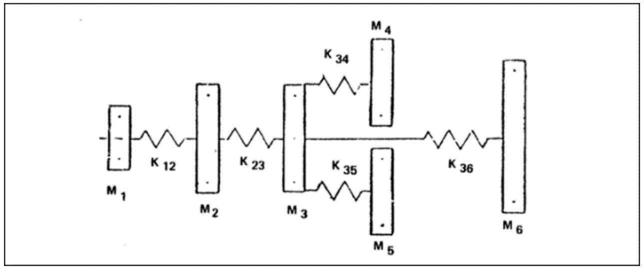
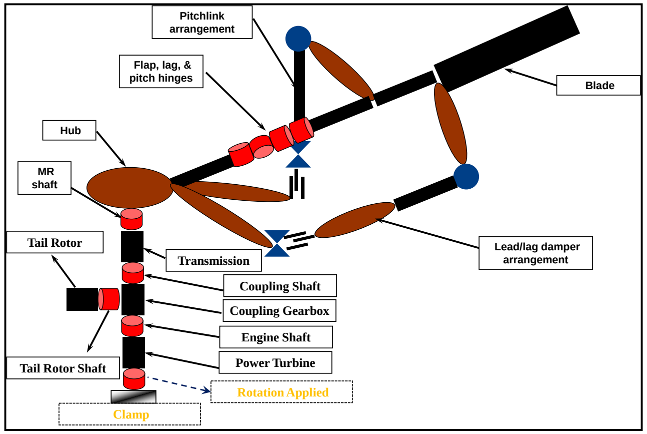
Rotor/Drivetrain Model



- RSRA drivetrain model (NASA-CR-166155) (shown right)
- Open-loop: free boundary condition at engine mass
- Closed-loop (ideal engine): prescribed engine mass motion



- Verification that ideal engine is sufficient for vibratory rotor load predictions: realistic fuel controller (finite control stiffness, etc.) is not necessary if changes to elastic lag modes are equal for open and ideal engine closed-loop systems

Ideal engine is sufficient for vibratory rotor loads predictions

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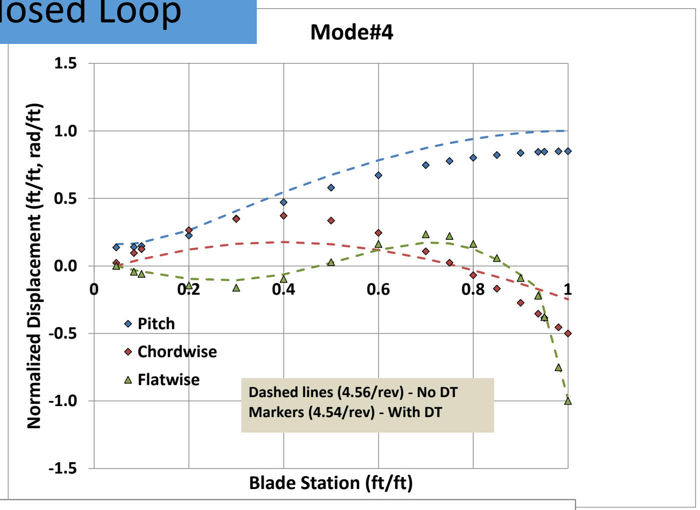
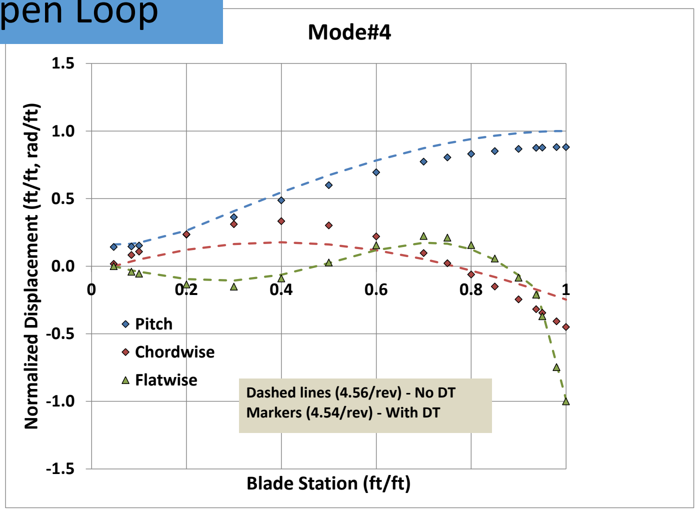
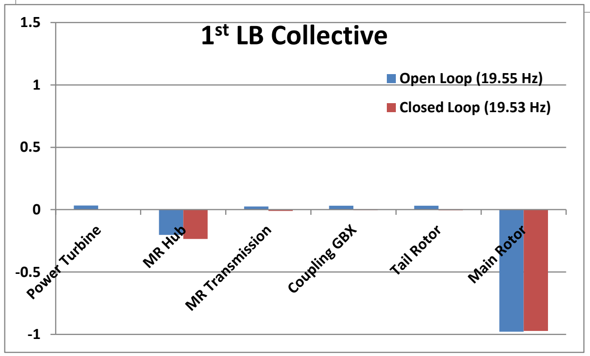
Blade Mode Shapes
Mode 4: Flap-Lag-Torsion Mode

Closed Loop



Open Loop





Drivetrain coupling

- Reduces pitch component
- Increases chordwise component

Equivalent effect for open & closed-loop drivetrain models

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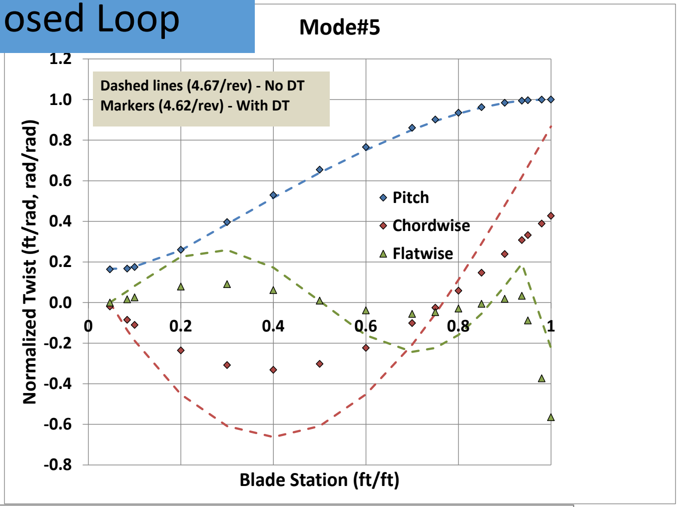
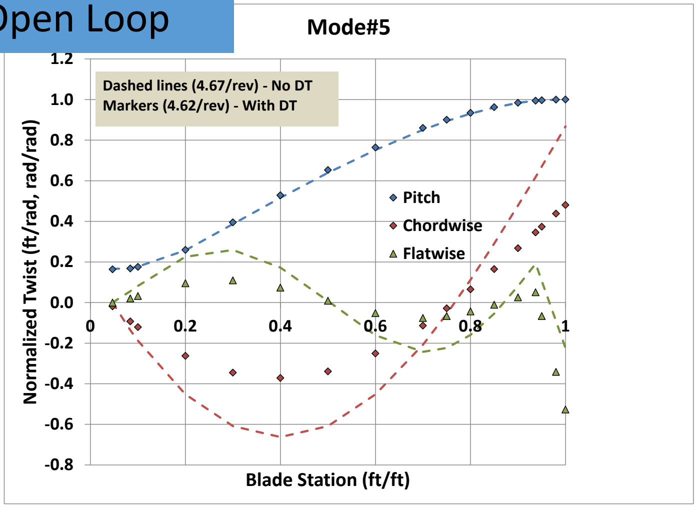
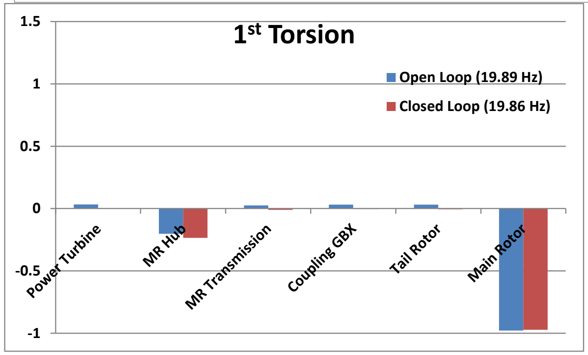
Blade Mode Shapes
Mode 5: Flap-Lag-Torsion Mode

Closed Loop



Open Loop





Drivetrain coupling

- Reduces chordwise participation
- Reduces flatwise participation

Equivalent effect for open & closed-loop drivetrain models

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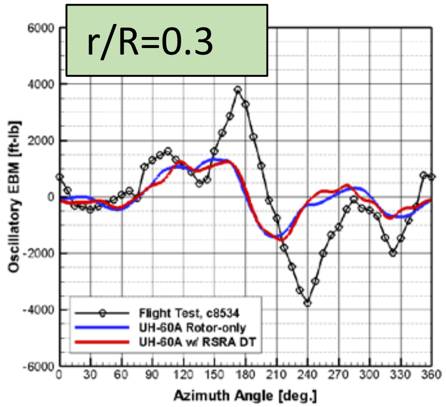
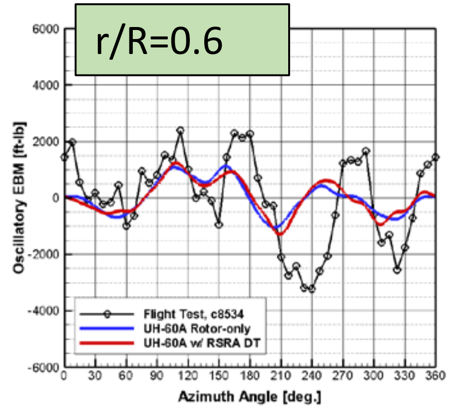
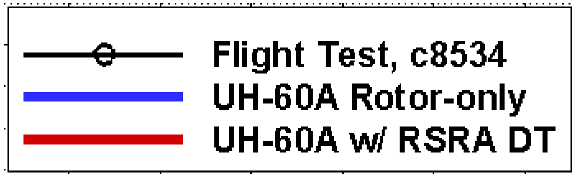
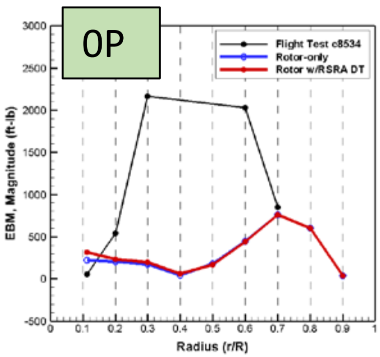
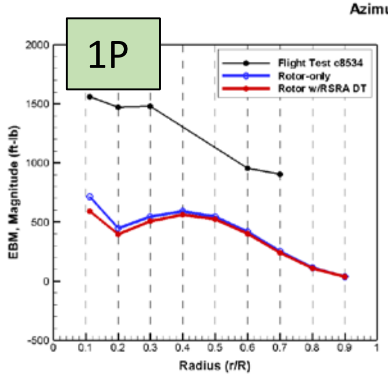
EFFECT OF RSRA DRIVETRAIN ON UH-60A CHORD BENDING

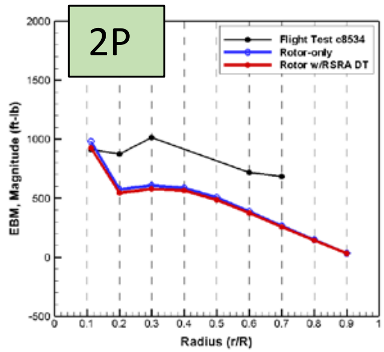


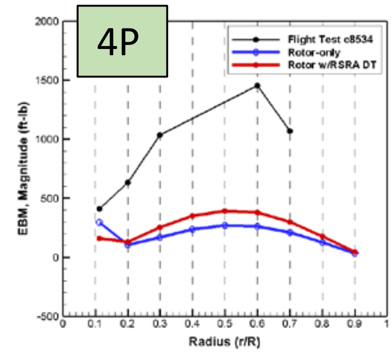












- UH-60A Flight Test Counter 8534 (High speed)
- Small improvement to 4/rev rotor loads

Drive train has minor effect on UH-60A rotor loads

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Task 3 - Helicopter Correlation

Objective

- Evaluate fuselage dynamics and drivetrain modeling on industry helicopter platforms

Boeing CH-47F

Sikorsky UH-60M

Boeing Apache Block III

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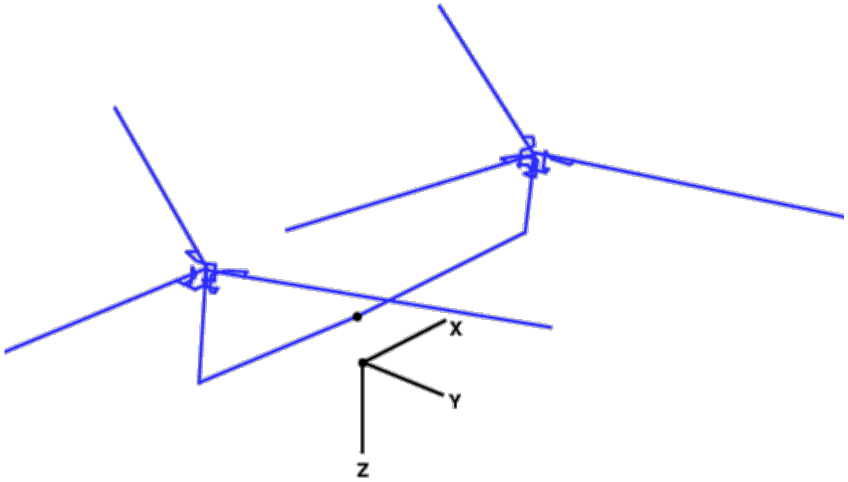
Project Number: NRTC-FY15-A-02

Flexible Fuselage Model for H-47 Rotor Loads Analysis



Boeing

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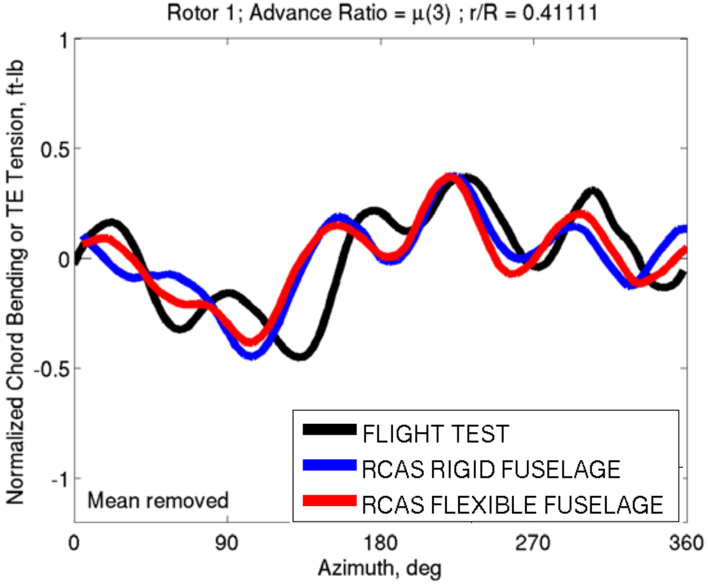
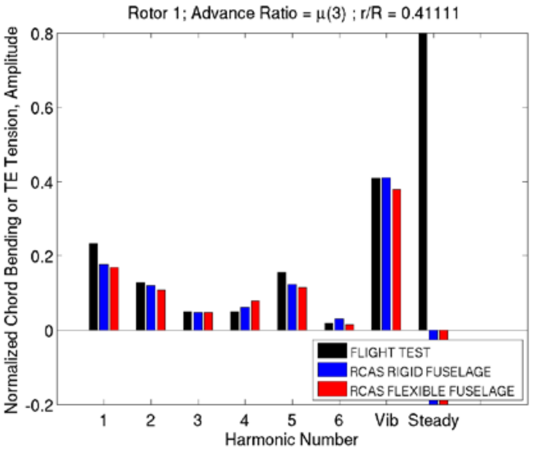
FRONT ROTOR IN-PLANE BENDING AT 0.41R VS. AZIMUTH

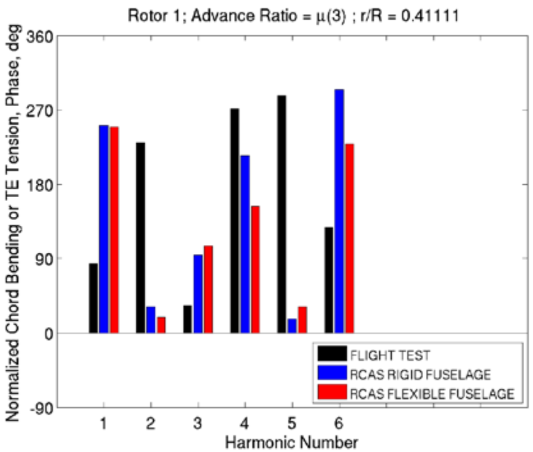
FRONT ROTOR - TIME HISTORY



HARMONIC AMPLITUDE



HARMONIC PHASE



- H-47 High Speed Case
- Lifting Line Aerodynamics
- Correlation of rigid hub model is good
  - Minor changes due to flexible hub
  - Rigid hub improves 4p phase
  - Flexible hub has better 6p phase

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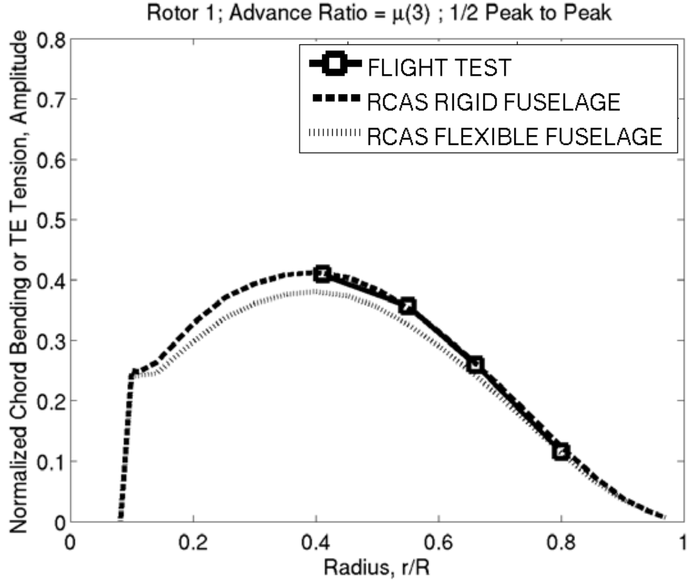
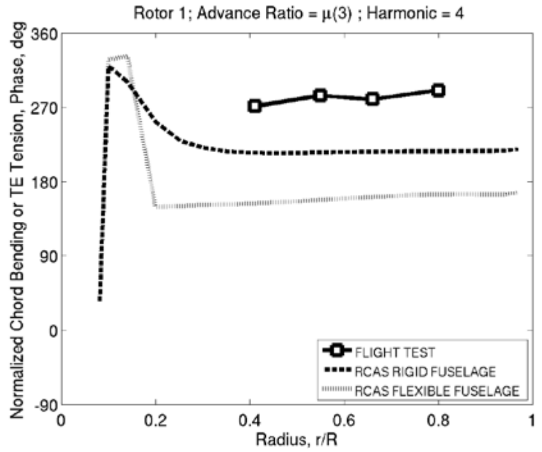
FRONT ROTOR IN-PLANE BENDING VS. RADIUS

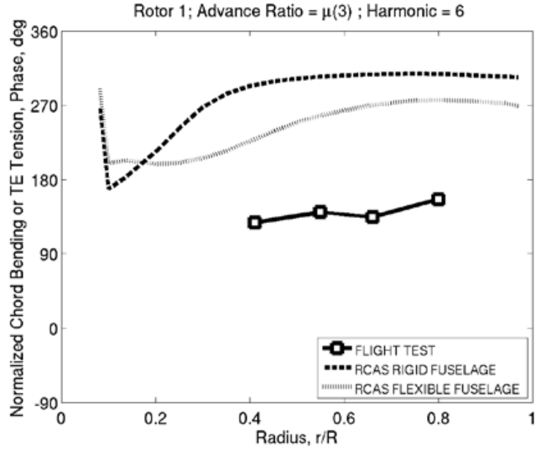
FRONT ROTOR - VIBRATORY LOAD



4P HARMONIC PHASE



6P HARMONIC PHASE



- Results at 41%R are consistent at other radii
  - Rigid hub has better vibratory amplitude
  - Rigid hub improves 4p phase
  - Flexible hub has better 6p phase

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CONCLUSIONS FOR H-47 CORRELATION

- Flexible fuselage model shows some sensitivity
  - At the high speed flight condition
    - Changes to 4p, 6p and 7p edgewise bending, due to the in-plane coupling between rotor and fixed frame hub
    - Change to vibratory torsion and pitch link load – possibly due to aircraft trim change
  - Minor or no changes observed in damper loads and flap bending
- Based on these results, there remains an opportunity to improve in-plane bending predictions
- It is recommended to run the flexible fuselage with the CFD aerodynamics
- CFD may benefit front rotor phase and aft rotor amplitude and phase

Implemented flexible fuselage model. CFD coupling underway

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Apache Block III Correlation

Boeing Apache Block III

Boeing

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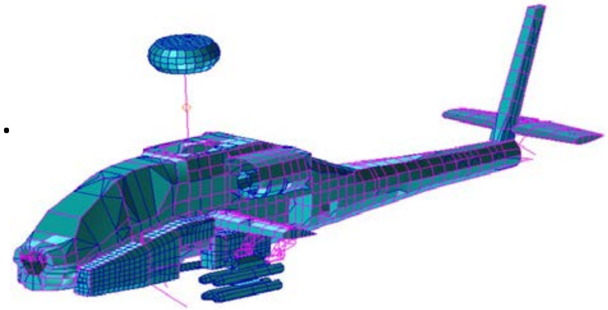
Project Number: NRTC-FY15-A-02

DETERMINATION OF HUB IMPEDANCE FOR APACHE



- Use existing Apache NASTRAN model for the configuration utilized in CFD/CSD analyses.
- Model contains about 5900 nodes and 11000 elements. *(1D elements for frames and stringers, 2D for external skins and floors, no 3D elements)*
- Use modes with frequencies below 50 Hz (*twice the 5/rev frequency*) to get adequate response up to 4/rev in the fixed system.
- Model yields 169 modes below 50 Hz (*163 elastic modes + 6 rigid body modes*).
- Only 38 elastic modes that contribute significantly to hub motion are included in hub impedance computations.
- Correlation against measured shake test data is considered to be good for major modes up to about 25HZ

Transformed NASTRAN modes and frequencies into CAMRAD II flexible hub model

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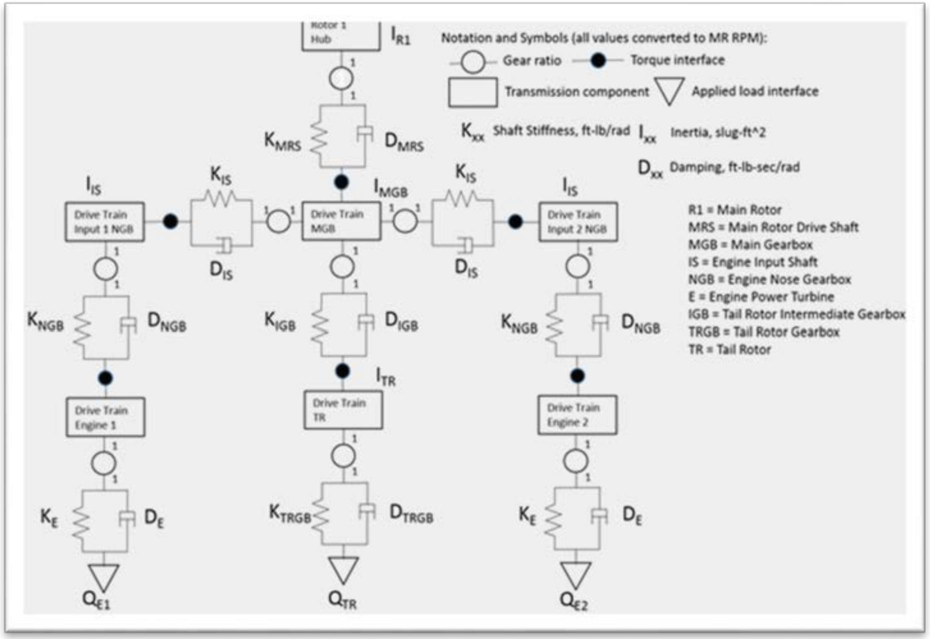
THREE BRANCH DRIVE TRAIN MODEL

- Three-branch drivetrain model
  - Developed a core model in CII for three-branch drivetrain model (main rotor gearbox connected to two engine inputs and tail rotor output).
  - Main gearbox connected to three torsional branches, consisting of two engine branches and a tail rotor branch by spring, damper and inertia elements.



Developed a three branch drive train model in CAMRAD II

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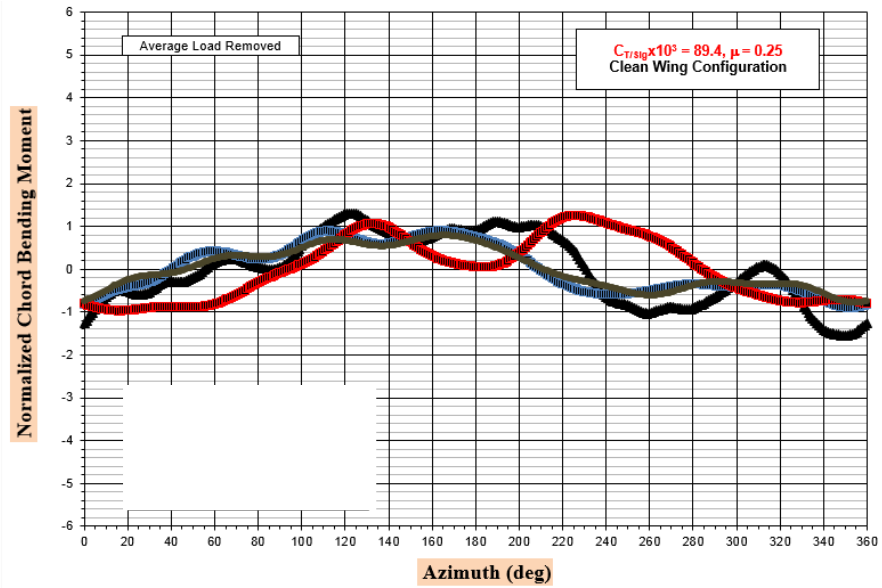
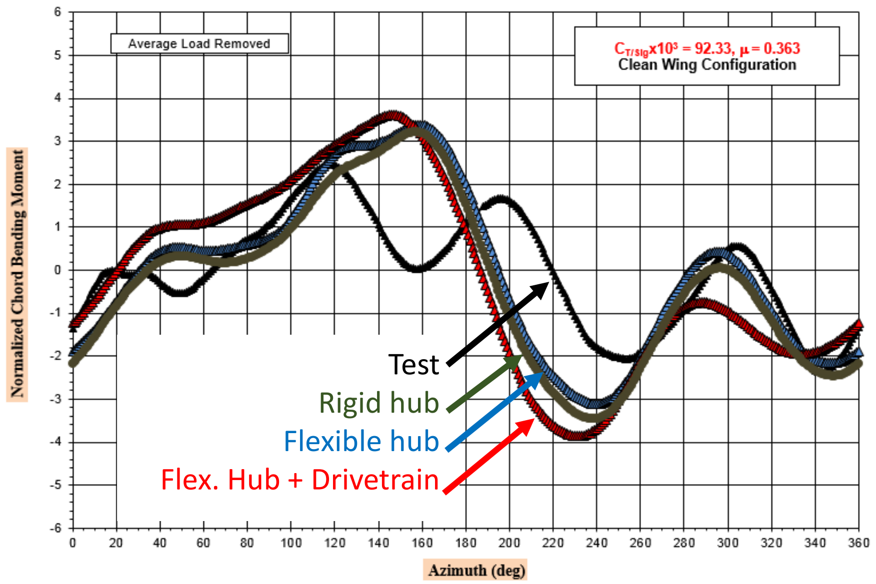
CHORD BENDING AT 22.1% RADIUS

0.25 ADVANCE RATIO



0.36 ADVANCE RATIO



Fuselage flexibility has minor effect on AH-64 rotor loads
Drivetrain model has significant effect on AH-64 rotor loads

UH-60M Correlation

Sikorsky UH-60M

Sikorsky

UH-60M CORRELATION IMPROVEMENTS

- HELIOS for UH-60M correlation (RCAS w/ OVERFLOW on blades) achieved parity with legacy RCAS-OVERFLOW
- Revised blade properties for UH-60M improved pitch link load prediction

Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

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IMPROVEMENTS TO EDGEWISE BENDING CORRELATION

	UH-60A Wind Tunnel Article	UH-60A Flight Test Article	H-47	AH-64
Hub impedance	Significant improvement	Not evaluated	In work	Minor effect
Drivetrain	Not evaluated	Minor improvement	Not evaluated	Significant effect

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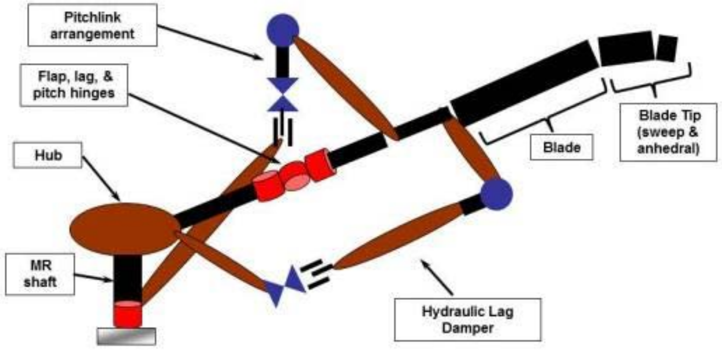
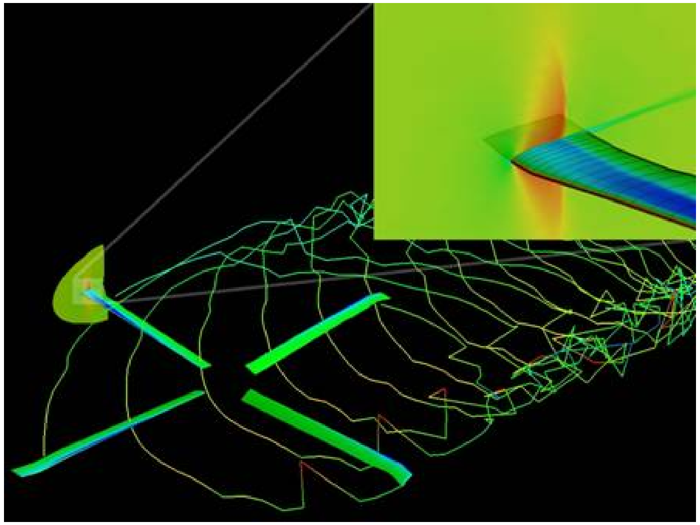
Task 4 – Modeling and Methodology Improvements



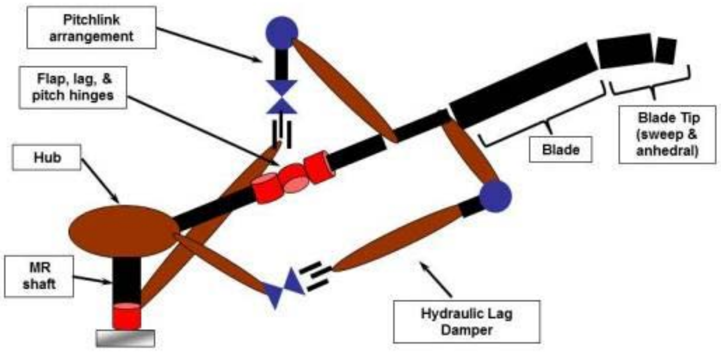


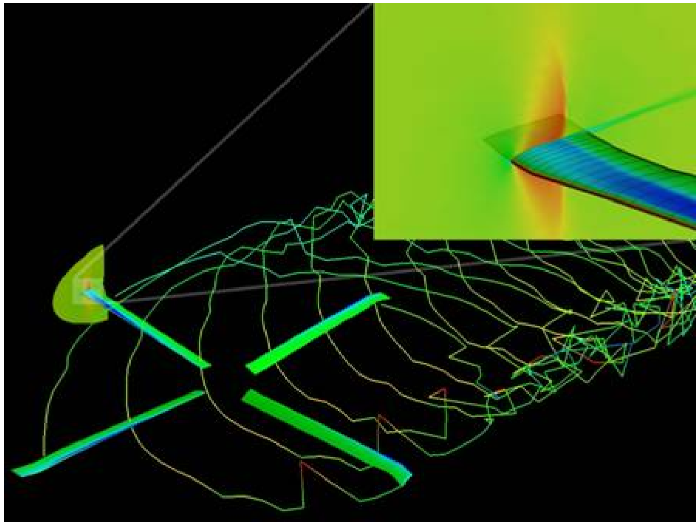
Georgia Tech, University of Maryland

Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

Project Number: NRTC-FY15-A-02

Task 4 – GT-Hybrid Improvements





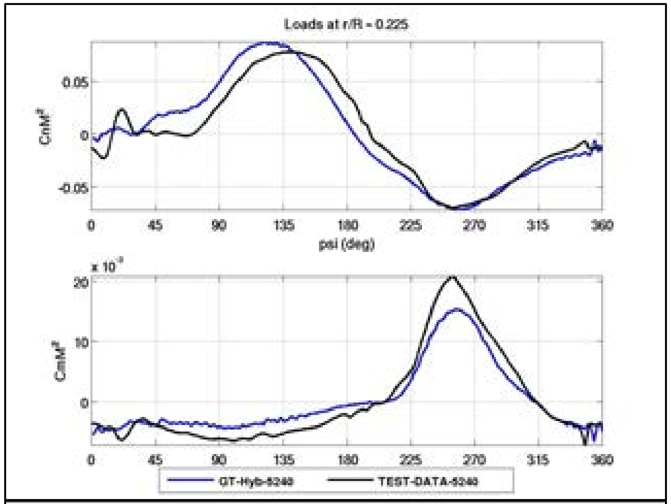
Georgia Tech

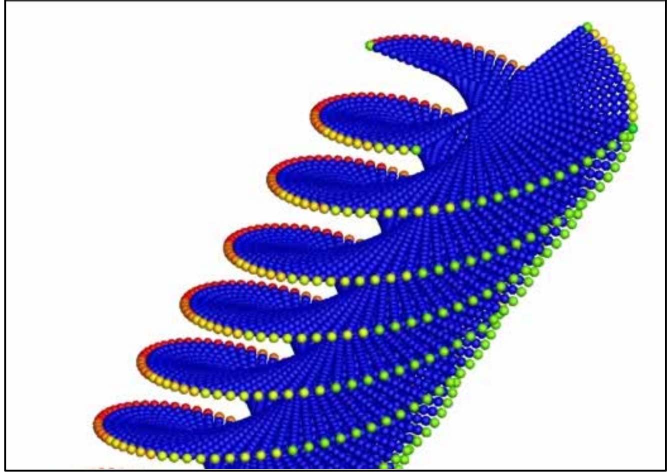
Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

Project Number: NRTC-FY15-A-02

GT-Hybrid Improvements

- A vortex particle method has been added to GT-Hybrid in place of a lattice wake.
- Two forward flight cases were conducted (C8534 & C5240) to evaluate its capabilities.
- The solutions were coupled between GT-Hybrid and DYMORE for 15 CFD/CSD iterations.
- C_nM^2 & C_mM^2 is shown at 0.225 r/R from C5240 as an example of the modified code's accuracy.
- Good correlations were seen with respect to experimental data and the lattice solution.
- Future work entails evaluating 3 maneuver cases: C11679 & C11780 (Dive-turns) and C11029 (Pull-up)





Vortex particle methodology expands code usability

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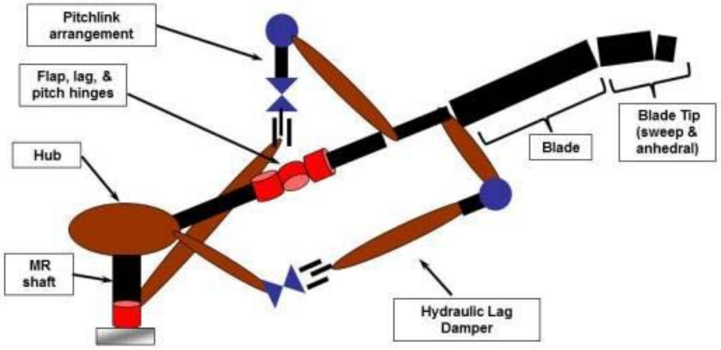
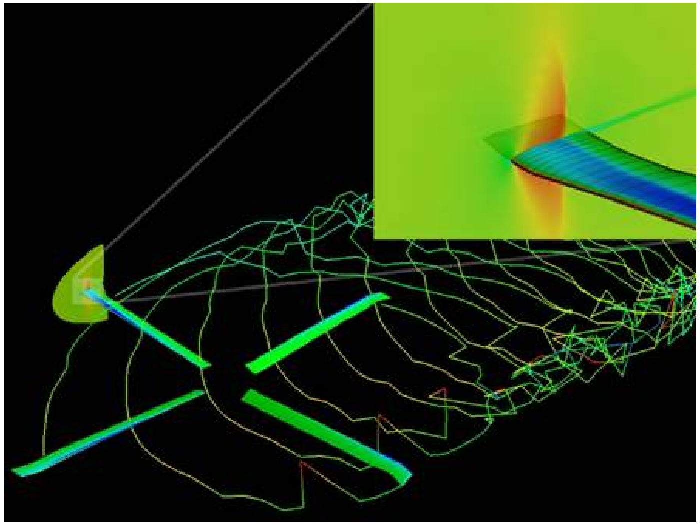
Task 4 – OVERFLOW-CHARM Improvements





Georgia Tech

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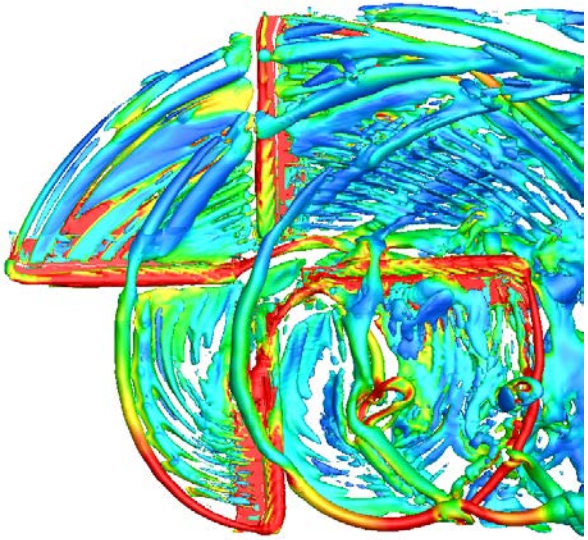
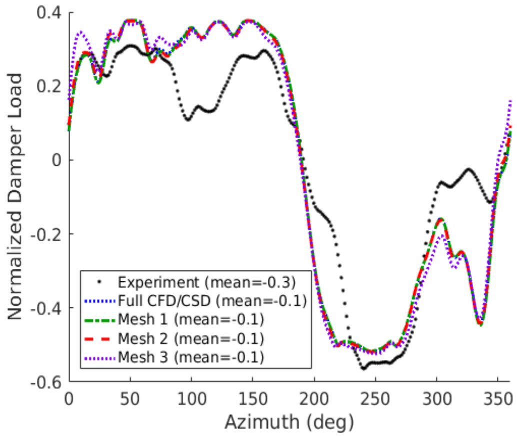
Project Number: NRTC-FY15-A-02

OVERFLOW-CHARM Hybrid Solver

- OF-Charm hybrid approach predicts comparable results to OF alone for most evaluations
  - Need to optimize initialization to save revolutions
- Background meshes can be reduced in number and in extents without loss of predictive accuracy
  - Savings of 60% in background and ~40% total mesh
  - Background mesh coarsening shows ability to capture most salient features and magnitudes
  - Charm appears to capture these features; sometimes more accurately than CFD
- Thin layer SA not as accurate as Menter kω-SST model
- Extensive results available in the August 2017 Airloads Workshop





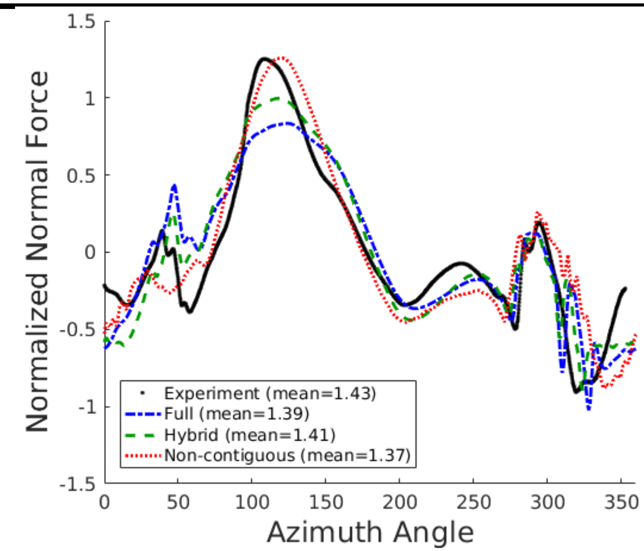
Improved the OVERFLOW-CHARM CFD interface

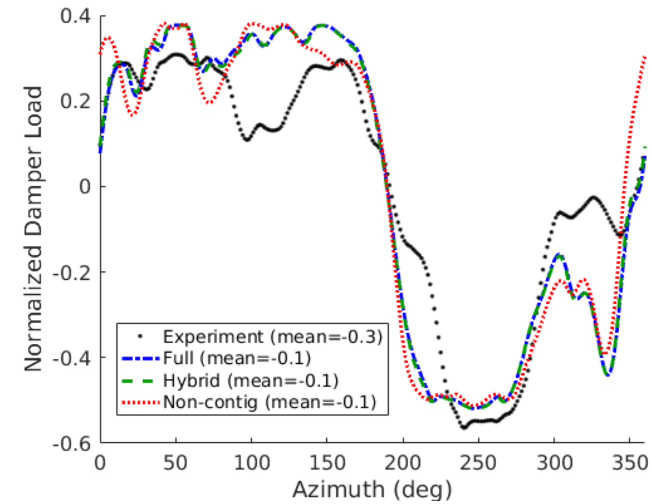
Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

Project Number: NRTC-FY15-A-02

OVERFLOW-CHARM Hybrid Solver

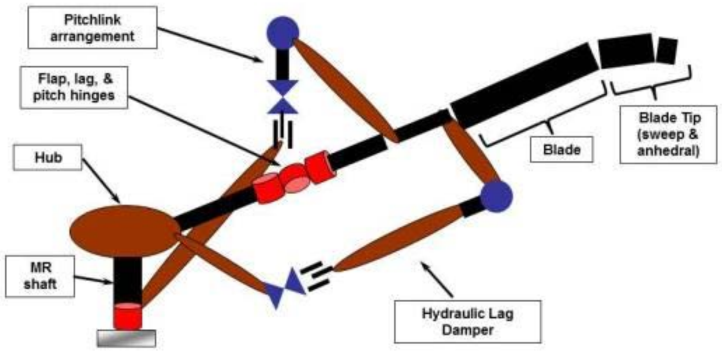
- Non-contiguous mesh development
- Velocity updates from Charm cause oscillations – removed with interpolation
- Can capture most features as fully contiguous hybrid and CFD-alone
- ~65% savings in mesh (prior to optimization)
- No savings on rate of convergence
- Optimization and best practices underway
- Extensive results available in the August 2017 Airloads Workshop

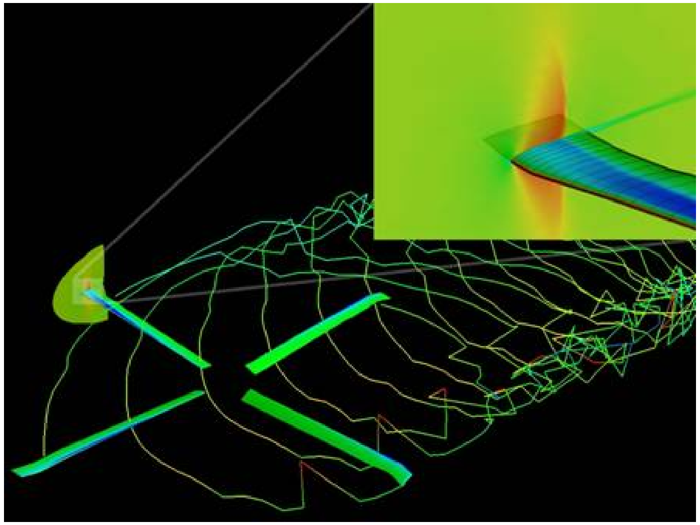




Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles | **Project Number: NRTC-FY15-A-02**

Task 4 – PRASAD-UM-HELIOS Coupling Improvements





University of Maryland

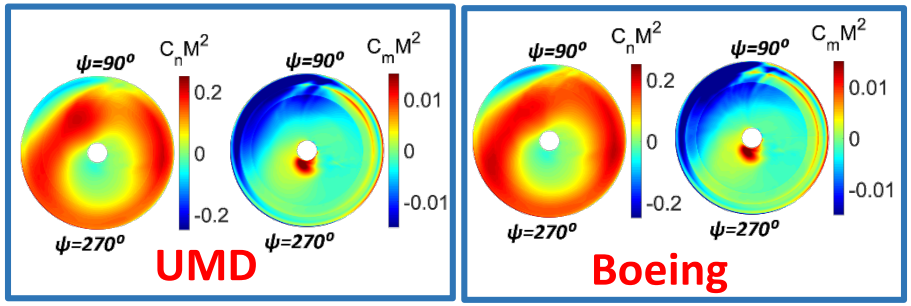
2017 NRTC Year End Review

Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

Project Number: NRTC-FY15-A-02

- Loose coupled **CFD/CSD** runs for **high-thrust** case and **high-speed** case with **rigid hub** were performed with **PRASAD-UM-Helios/Overflow**
  - Compared UMD predicted airloads, Boeing's airloads and wind tunnel tests data

High- Speed



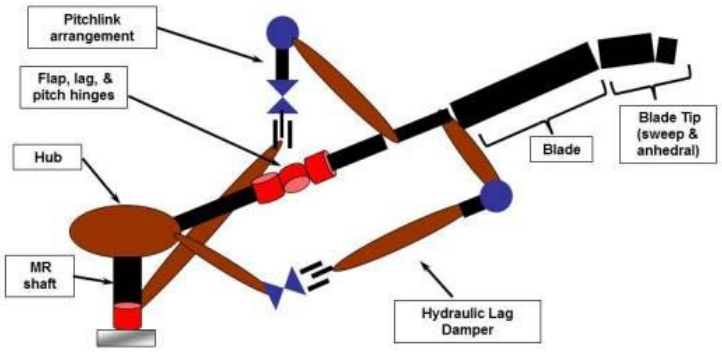
- Improvement to PRASAD-UM-Helios coupling process focused on two areas
- **Interpolation of deflections** from quadrature nodes to user-specified nodes
  - It was observed that if deflections are specified at fine azimuthal resolution, then CFD airloads exhibit oscillatory behavior
    - Old interpolation routine used linear interpolation in both azimuth and span
      - Smooth deflections but stair-stepping in time-derivative of deflections
      - Replaced with cubic spline interpolation in azimuth, resolved oscillations
- **Interpolation and filtering of CFD airloads** directly to quadrature points using trigonometric interpolation and FFT, did not have significant effect on coupling process
- Started to perform coupled CFD/CSD (high-speed case) with hub motions

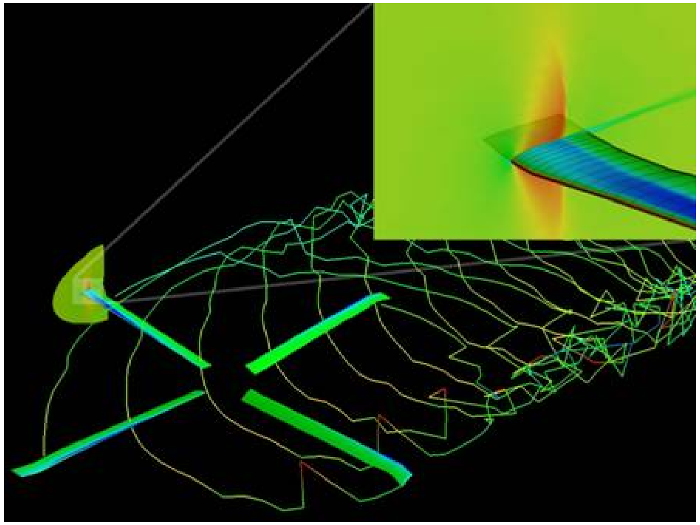
Developed the CFD coupling for PRASAD-UM - HELIOS

Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

Project Number: NRTC-FY15-A-02

Task 4 – LRTA Modeling in PRASAD-UM





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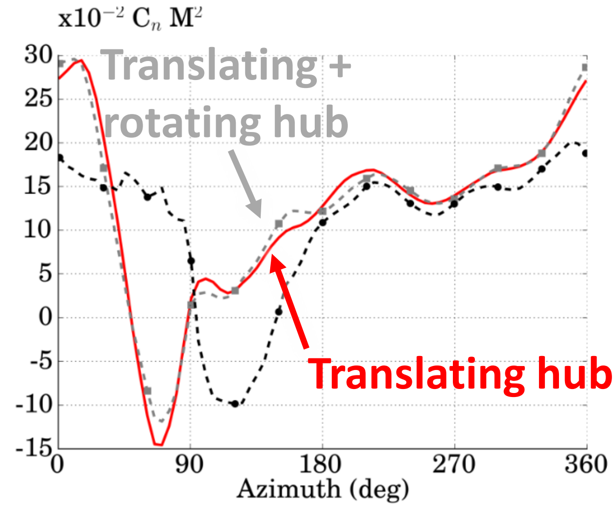
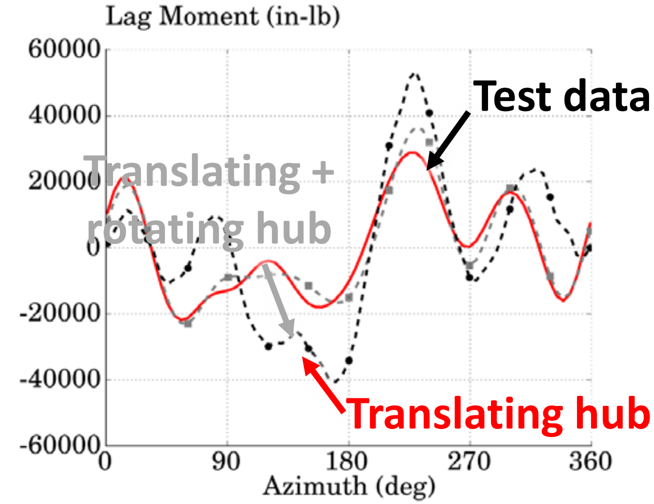
Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

Project Number: NRTC-FY15-A-02

UMD Milestones

- CSD analysis (PRASAD-UM)
  - Adapted rotor-body interface to include rotor/test stand coupling
  - Expanded CFD interface for precessing hub transform
  - Compared trim to time integration results – no difference
  - Expanded rotor trim process to include support structure DOF
    - Hub translation affects lag bending
    - Hub rotation effects are minor
  - Hub motion affects elastic twist through coupled lag-torsion modes (driven by blade CG offset)





Developed the hub impedance coupling in PRASAD-UM

Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

Project Number: NRTC-FY15-A-02

SUMMARY FOR PROJECT

- Task 2 – UH-60A Correlation
  - Wind tunnel test article:
    - Hub impedance model improves correlation with test case
  - Flight test article:
    - Drive train model shows small benefit to 4p edgewise bending
- Task 3 – Helicopter Correlation
  - Implemented H-47 flexible fuselage model. CFD coupling underway.
  - Fuselage flexibility has minor effect on AH-64 rotor loads
  - Drivetrain model has significant effect on AH-64 rotor loads
  - HELIOS for UH-60M correlation (RCAS w/ OVERFLOW on blades) achieved parity with legacy RCAS-OVERFLOW
  - Revised blade properties for UH-60M improved pitch link load prediction
- Task 4 – Modeling and Methodology Improvements
  - Developed the CFD coupling for PRASAD-UM - HELIOS
  - Developed the hub impedance coupling in PRASAD-UM
  - Vortex particle methodology expands GT-Hybrid code usability
  - Improved the OVERFLOW-CHARM CFD interface

Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

Project Number: NRTC-FY15-A-02

PROJECT LOOK-AHEAD

- Task 2 – UH-60A Correlation
  - Wind tunnel test article:
    - Hub impedance modeling with DYMORE and PRASAD-UM
  - Flight test article:
    - Drivetrain modeling with RCAS
  - Swashplate modeling with DYMORE
  - Study with refined OVERFLOW grid for stall boundary prediction
- Task 3 – Helicopter Correlation Improvement
  - CFD coupling for H-47 full aircraft model
  - UH-60M with drivetrain
- Task 4 – Modeling and Methodology Improvements
  - Evaluate whether OVERFLOW-CHARM can produce higher accuracy for less cost than wake capturing methods
  - NASA NFAC tunnel installation effects on UH-60A loads
  - UH-60A Airloads Program instrumentation effects on loads
  - PRASAD-UM-HELIOS coupling improvements continuing
- Task 5 – Maneuver Loads Correlation
  - UH-60A modeling by all team members
  - AH-64, H-47, and UH-60M

Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

Project Number: NRTC-FY15-A-02

Papers and Presentations:

- March 2017 Airloads Workshop
- August 2017 Airloads Workshop

Auxiliary Data Delivered

- None

Patents Disclosed

- None

Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

Project Number: NRTC-FY15-A-02

Questions?

Thank you

Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

Project Number: NRTC-FY15-A-02

Thank You's

- NRTC Agreements Officer Representative
  - Dr. Hyeonsoo Yeo
- US Army
  - Mr. Rohit Jain
  - Mr. Tom Maier
  - Dr. Roger Strawn
- NASA
  - Dr. Wayne Johnson
  - Mr. Robert Kufeld
  - Mr. Thomas Norman
  - Mr. Carl Russell
- Advanced Rotorcraft Technology
  - Dr. Hossein Saberi

Project Title: Advanced Aeromechanics Prediction Methods for Rotorcraft Flight Vehicles

PI: Ted Meadowcroft, ted.meadowcroft@boeing.com

Project Number: NRTC-FY15-A-02

Technical Objectives:

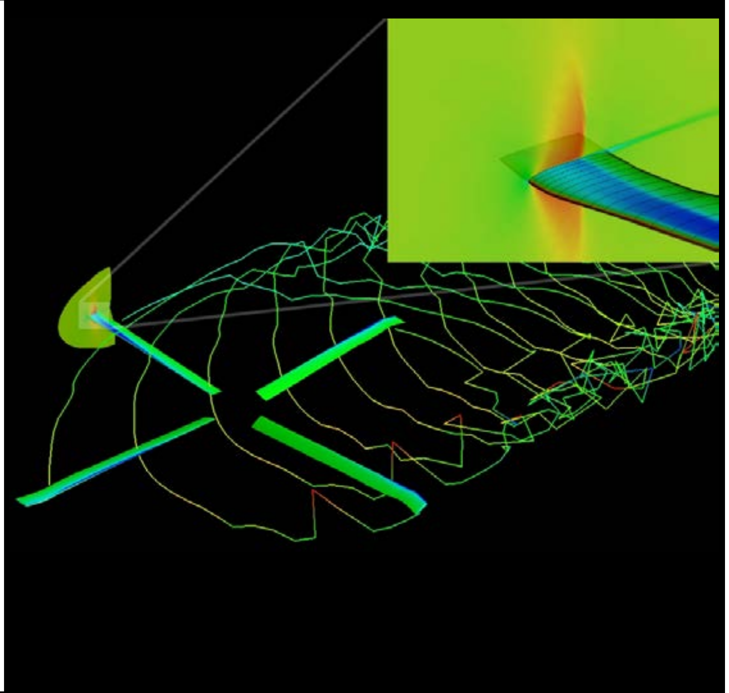
- Joint research initiative to extend aeromechanics analyses to maneuvering flight as well as towards improved accuracy of rotor structural loads and control loads predictions.
- The effort focuses on including additional physics like the drive-train, flexible fuselage, swashplate, variable pitchlink stiffness.

Technical Challenges:

- CFD-coupled CSD has vastly improved our ability to analyze advanced rotor systems at critical flight conditions; however, deficiencies remain.
- The pattern of correlation quality suggests simulation models need improvement with regard to blade root boundary conditions.
- Need better understanding of physics necessary to analyze rotor and hub loads

End Deliverables:

- Improve first pass quality for new rotorcraft development programs, such as Future Vertical Lift



2017 Project Year Technical Accomplishments:

- Task 2 – UH-60A Correlation
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% Invoiced to Date: TBD%