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14. ABSTRACT
A computational research program was performed at Georgia Institute of Technology, Penn State University, and at Northern Arizona University to develop a set of first-principles based computational modeling tools for analyzing and designing advanced helicopter configurations. The approach involved incorporation of advanced numerical algorithms and turbulence models in OVERFLOW 2, development of advanced comprehensive analyses (DYMORE and RCAS) that are seamlessly coupled to the flow analysis, modeling of rotor noise characteristics

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Report Title

Revolutionary Physics-Based Design Tools for Quiet Helicopters

Phase I-B Extension

ABSTRACT

A computational research program was performed at Georgia Institute of Technology, Penn State University, and at Northern Arizona University to develop a set of first-principles based computational modeling tools for analyzing and designing advanced helicopter configurations. The approach involved incorporation of advanced numerical algorithms and turbulence models in OVERFLOW 2, development of advanced comprehensive analyses (DYMORE and RCAS) that are seamlessly coupled to the flow analysis, modeling of rotor noise characteristics using an advanced acoustics prediction tool (PSU-WOPWOP) that is seamlessly coupled to the flow analysis and the comprehensive analyses, and validation and application of the integrated suite of tools for current generation (UH-60, BO105) and next generation configurations.

Under the Phase I-B extension, assessment of this suite of tools is being performed by Ga Tech and Penn State for the Boeing MD-900 model rotor (MDART), an actively controlled rotor (SMART), and the Comanche rotor blade (as an option).

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals: 0.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Jeremy Bain, Ga Tech	0.50
Chris Henness, PSU	0.50
FTE Equivalent:	**1.00**
Total Number:	**2**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Lakshmi Sankar	0.05	No
Ken Brentner, PSU	0.05	No
Stephen Ruffin	0.05	No
Marilyn Smith	0.05	No
FTE Equivalent:	**0.20**	
Total Number:	**4**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Revolutionary Physics-Based Design Tools for Quiet Helicopters

Phase I-B Extension

Final Report

Covering the period

June 1, 2007 – May 31, 2008

Contract No. W911NF-04-1-0419

Submitted to

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September 20, 2008

EXECUTIVE SUMMARY

A computational research program was performed at Georgia Institute of Technology, Penn State University, and at Northern Arizona University to develop a set of first-principles based computational modeling tools for analyzing and designing advanced helicopter configurations. The approach involved incorporation of advanced numerical algorithms and turbulence models in OVERFLOW 2, development of advanced comprehensive analyses (DYMORE and RCAS) that are seamlessly coupled to the flow analysis, modeling of rotor noise characteristics using an advanced acoustics prediction tool (PSU-WOPWOP) that is seamlessly coupled to the flow analysis and the comprehensive analyses, and validation and application of the integrated suite of tools for current generation (UH-60, BO105) and next generation configurations.

Under the Phase I-B extension, assessment of this suite of tools is being performed by Ga Tech and Penn State for the Boeing MD-900 model rotor (MDART), an actively controlled rotor (SMART), and the Comanche rotor blade (as an option).

INTRODUCTION

The goal of this effort is to apply the first-principles based computational modeling tools for analyzing and designing advanced helicopter configurations, developed under Phase I, to advanced configurations of interest to DARPA and ARO. The following tasks are scheduled:

Task 1:

The tools described above will be used to predict the aerodynamic and aeroacoustic characteristics of the MDART rotor configuration. The operating conditions and observer (microphone) locations will be specified by the sponsor. The data generated form the baseline analyses will be supplied in a sponsor-specified format performance/noise for comparisons with wind tunnel tests.

Task 2:

The tools above will subsequently be used to predict the aerodynamic and aeroacoustic characteristics MD 900 SMART rotor (equipped with an actively controlled flap) for a maximum of four operating conditions. The operating conditions, observer locations, and flap schedule will be supplied by the sponsor. The data generated form the baseline analyses will be supplied in a sponsor-specified format performance/noise for comparisons with wind tunnel tests.

Optional Task 3:
The tools described above will be used to predict the surface pressure distribution (as a function of radius and azimuth) for a rotor similar in form to the Comanche blade. Calculations will be done for a single case specified by the sponsor. The surface pressure data (and associated time histories) will be conveyed to the sponsor in a PSU-WOPWOP compatible form for independent modeling of the acoustic characteristics by the sponsor.

Optional Task 4:
The tools described above will be used to predict the surface pressure distribution (as a function of radius and azimuth) for a rotor similar in form to the Comanche blade with an anhedral tip. Calculations will be done for a single case specified by the sponsor. The surface pressure data (and associated time histories) will be conveyed to the sponsor in a PSU-WOPWOP compatible form for independent modeling of the acoustic characteristics by the sponsor.

TECHNICAL PROGRESS

Task 1: MDART Rotor

CFD-CSD simulations of the MDART rotor were completed using OVERFLOW and DYMORE. A DYMORE model of the sponsor supplied structural model has also been refined. After consultation with Dr. Wayne Johnson, a number of modifications were brought to the model structural properties. Fan plots have been generated, and figure 1 shows the comparison between the frequencies computed by CAMRAD and DYMORE, for a 10 degree collective. Furthermore, the prediction of the rotor frequencies using UMARC at the University of Maryland were also made available to us for comparison. Figure 2 shows the comparison of the three sets of predictions for the MD 900 rotor. It is clear that the three independent predictions are in good agreement for the lowest six modes of the rotor, whereas the last 4 modes show significant discrepancies. This should not be unexpected since it is increasingly difficult to predict natural frequencies and mode shapes for higher modes.

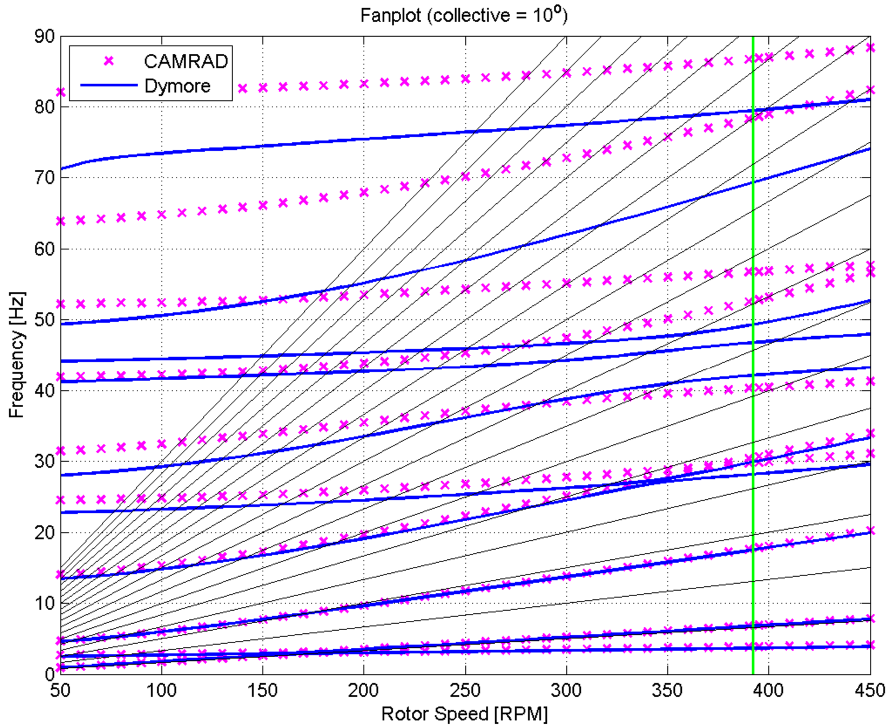

Figure 1. Comparison of fanplots for the MD-900 rotor using CAMRAD and DYMORE.

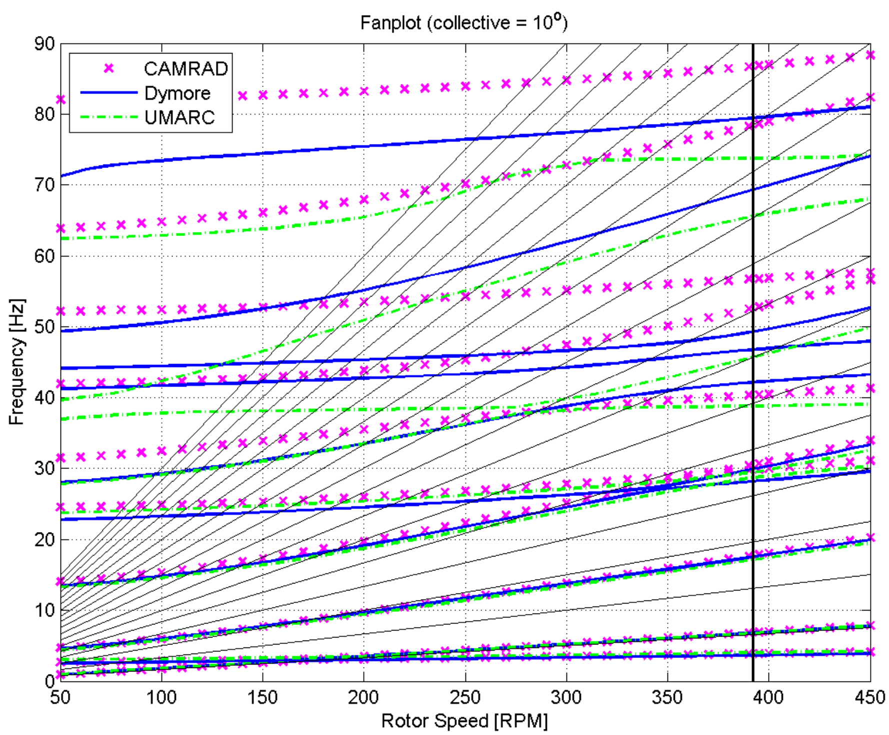

Figure 2. Comparison of fanplots for the MD-900 rotor using CAMRAD, UMARC and DYMORE.

OVERFLOW/DYMORE simulations were run for the MDART rotor case at an advance ratio of 0.3, at a thrust setting C_T/σ = 0.08. The shaft is titled forward 9.1 degrees. Polar plots of the sectional normal force, pitching moment, and chord wise force are shown in Figures 3-5.

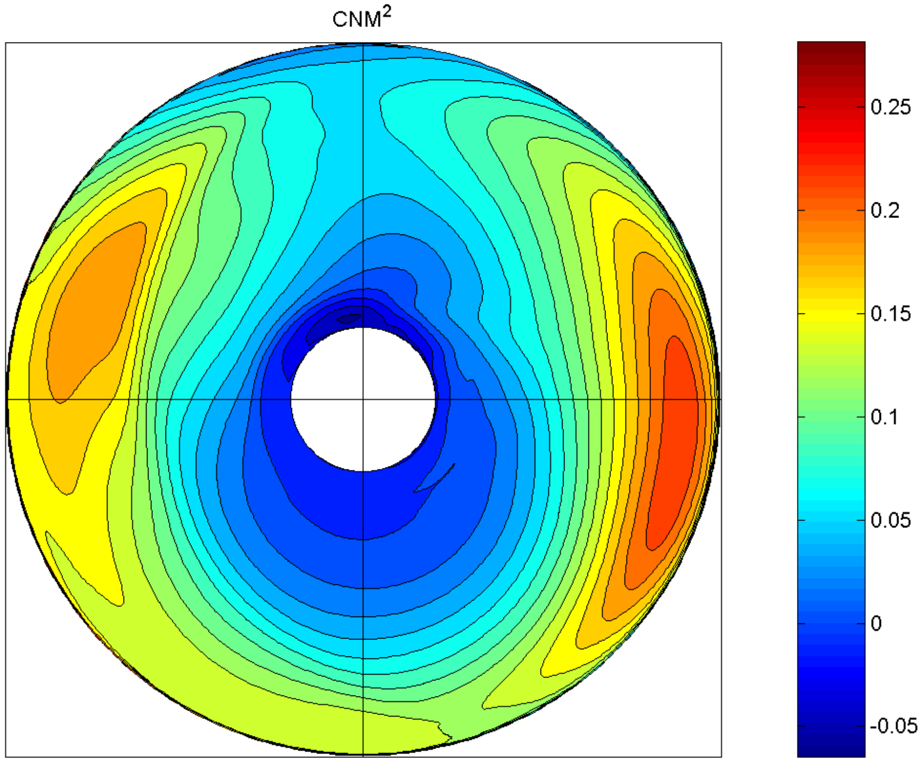

Figure 3. MDART Normal Force Polar Plot

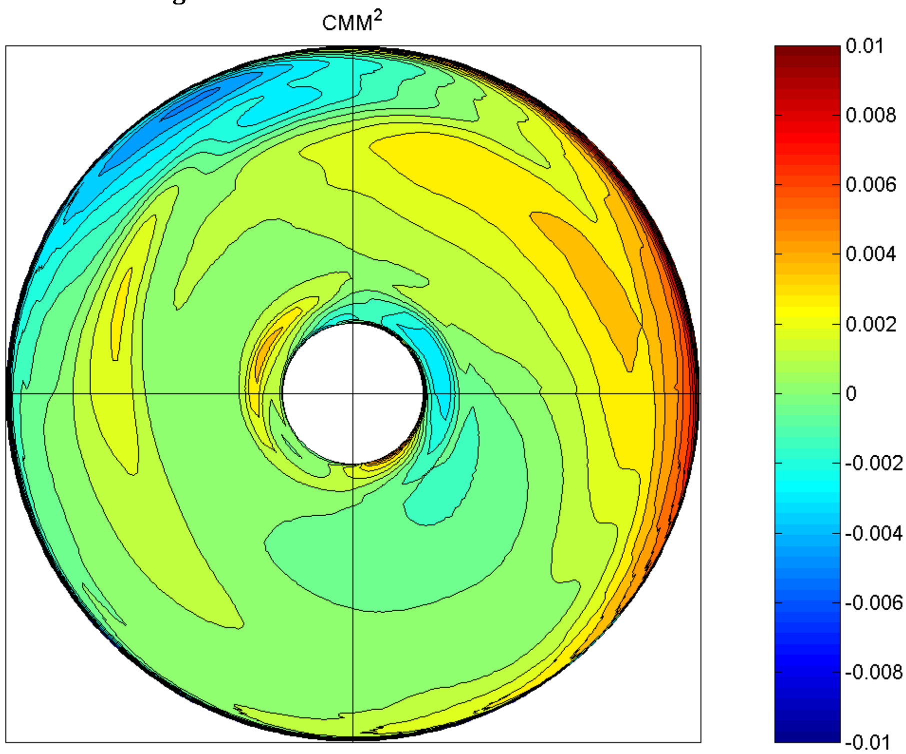

Figure 4. MDART Pitching Moment Polar Plot

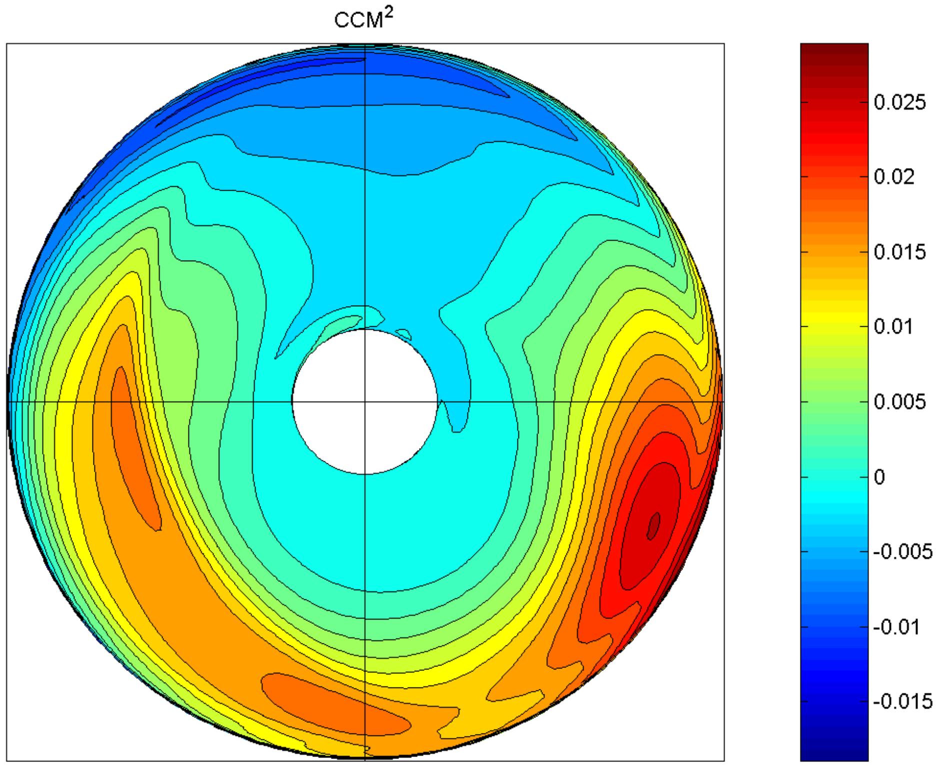

Figure 5. MDART Chordwise Force Polar Plot

Due to the complex nature of the rotor hub geometry, it was modeled in GT-NASCART. Figure 6 shows the details of the NASCART grid, and the associated flow field in the hub region.

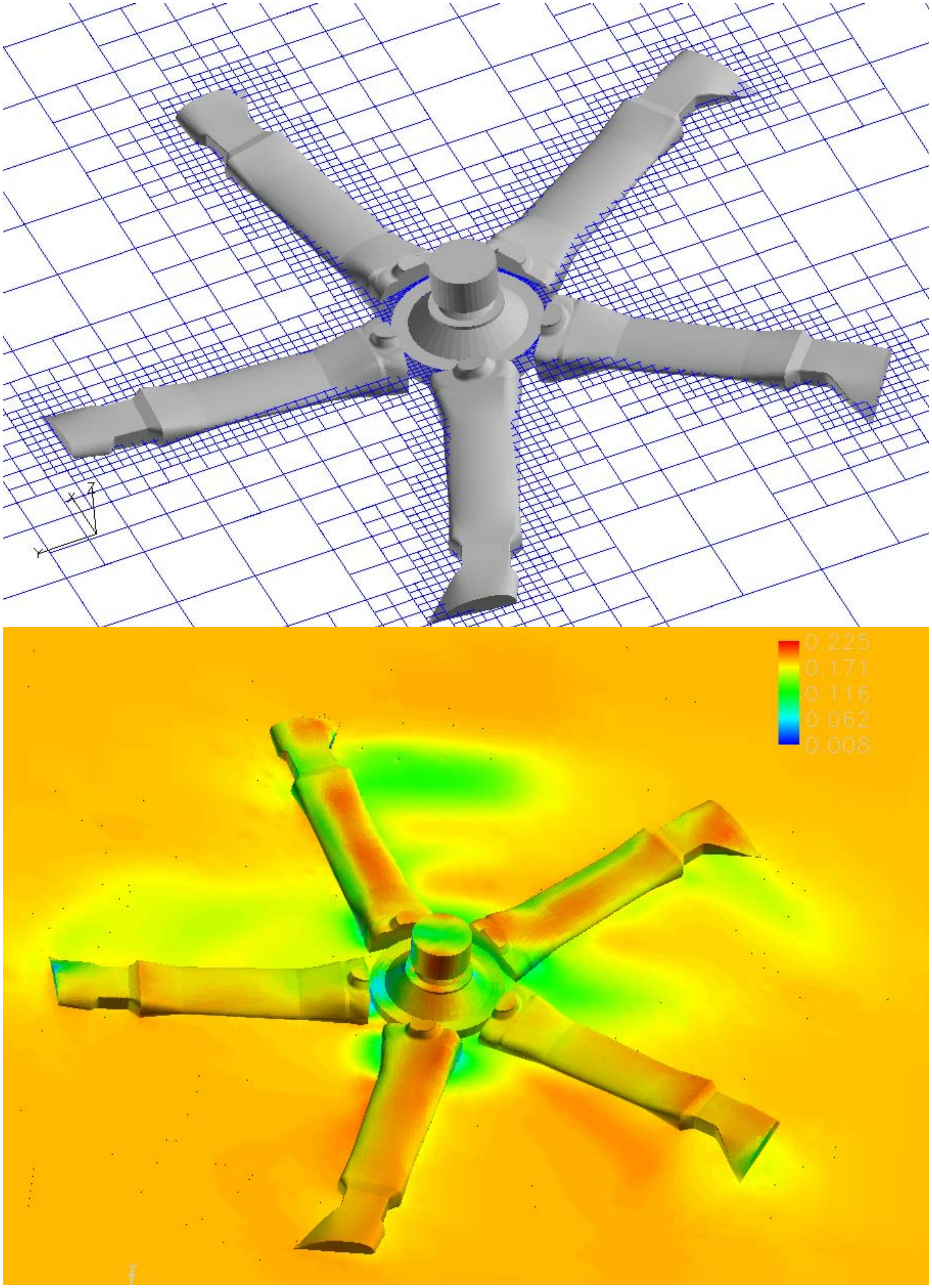

Figure 6. NASCART-GT Representation of the MDART Rotor Hub

Task 2: SMART Rotor

The SMART rotor has been modeled in DYMORE as follows:

- Hub
  - Revolute joint
- Blade
  - Blade (30 cubic beam elements)
  - Flexible beam (5 cubic beam elements)
  - Snubber (flexible joint)
  - Lumped masses (8 concentrated masses)
- Trailing edge flap
  - Flap (6 cubic beam elements)
  - Inner board connecting bracket (1 cubic beam element)
  - Outer board connecting bracket (1 cubic beam element)
- Pitch link
  - Pitch horn (rigid body)
  - Pitch link (rigid body)
  - Swash plate (prismatic, universal, and revolute joints)

Figure 7 shows a pictorial view of the model:

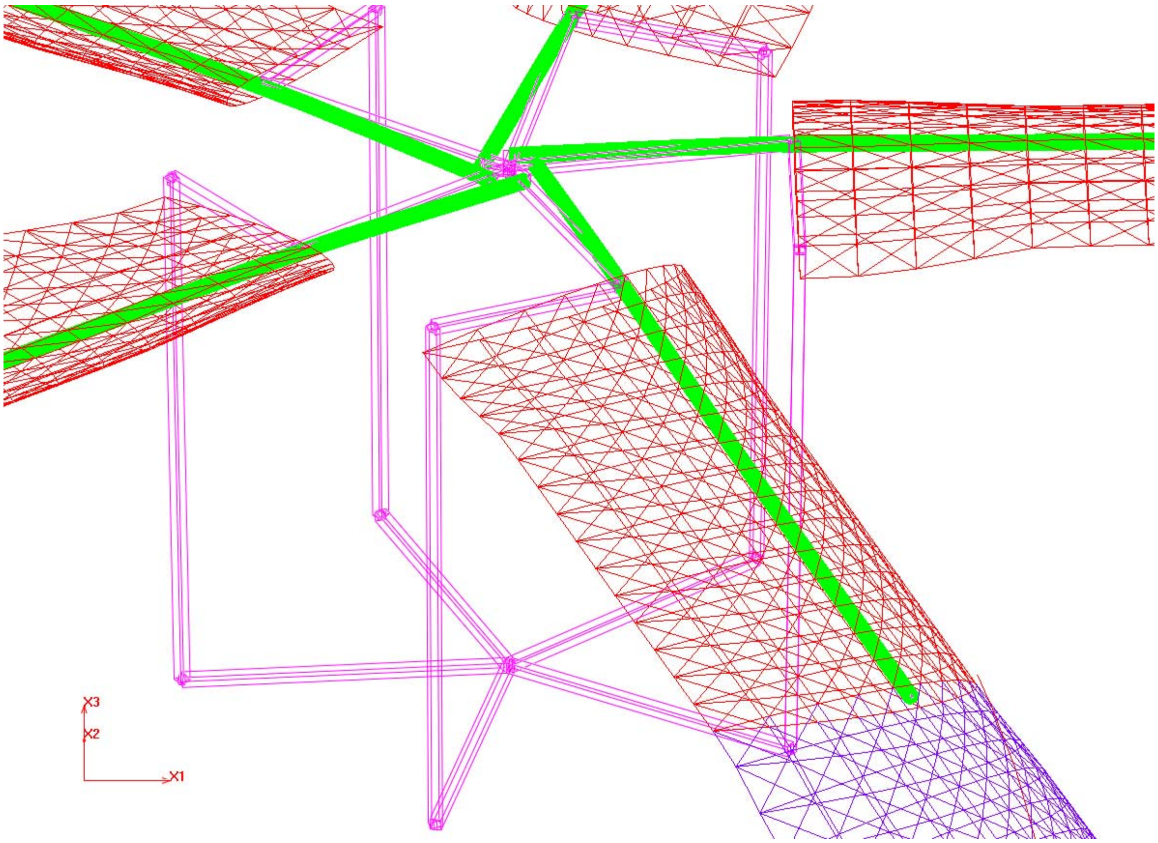

Figure 7. SMART Model Description

The natural frequencies of the SMART rotor have been compared against the baseline MDART rotor. The fan plots shown on Figure 8 indicate that there are negligible differences in the first several modes that are of interest to the aerodynamic, aeroelastic, and aeroacoustic modelers.

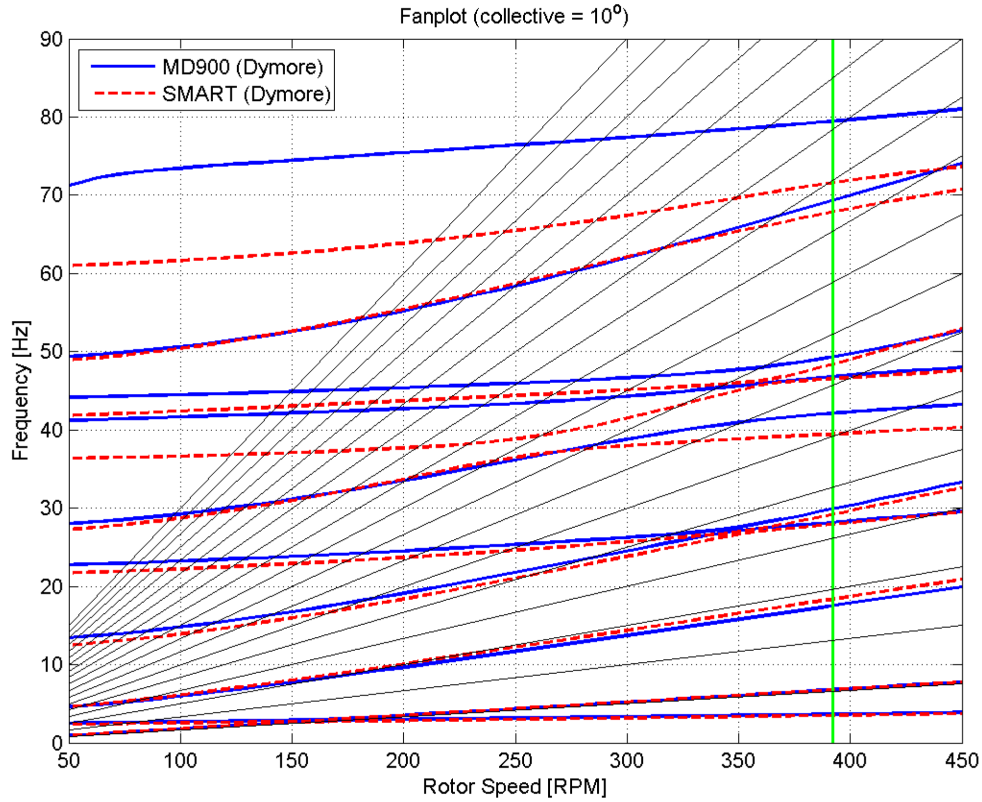

Figure 8. Comparison of MD 900 and SMART Rotor Fan plots

Figure 9 compares the fan plot for the SMART rotor from the present DYMORE model against the CAMRAD-II predictions. Again, for the first several modes of interest, these two comprehensive analyses agree well with each other.

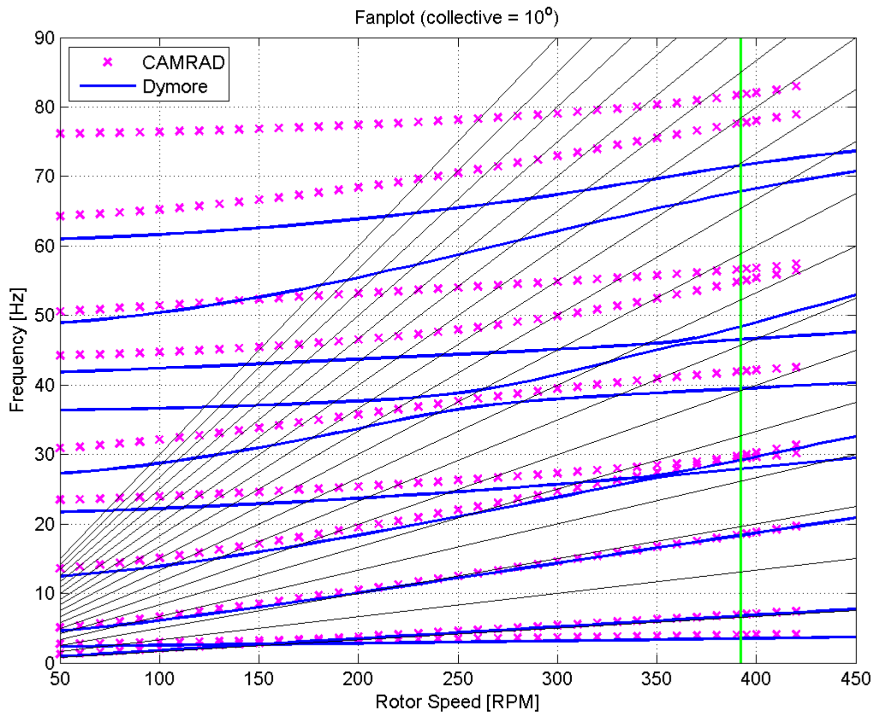

Figure 9. Comparison of DYMORE and CAMRAD-II Predictions for the SMART Rotor at 10 Degree Collective

The SMART Rotor was run using OVERFLOW and DYMORE for four different flight and flap conditions summarized below.

Table 1. SMART Rotor Cases

Case Number	Shaft Axis Thrust CT/s	Shaft Angle	Adv Ratio	Adv Tip Mach No	Flap Schedule
0	0.080	- 9.1 (forward)	0.3	0.805	**Theta ($flap_k$) = 0**
1	0.080	- 9.1 (forward)	0.3	0.805	**Theta ($flap_k$) = 2.0*sin (5*psi_k + 90)**
2	0.080	- 9.1 (forward)	0.3	0.805	**Theta ($flap_k$) = 2.0*sin (3*psi_k + 60)**
3	0.070	-9.1 (forward)	0.38	0.852	**Theta ($flap_k$) = 1.0*sin (5*psi_k + 180)**
4	0.075	+ 1.5 (aft)	0.2	0.746	**Theta ($flap_k$) = 2.0*sin (2*psi_k + 240) + 1.0*sin (5*psi_k + 330)**

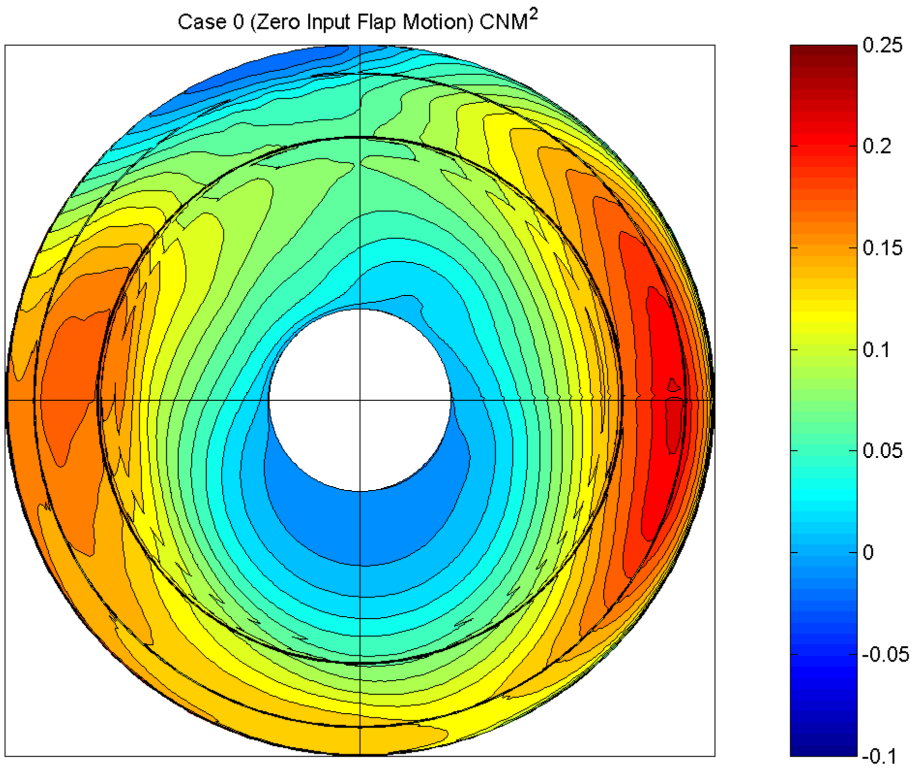

Figure 10. SMART Case 0 Normal Force Polar Plot

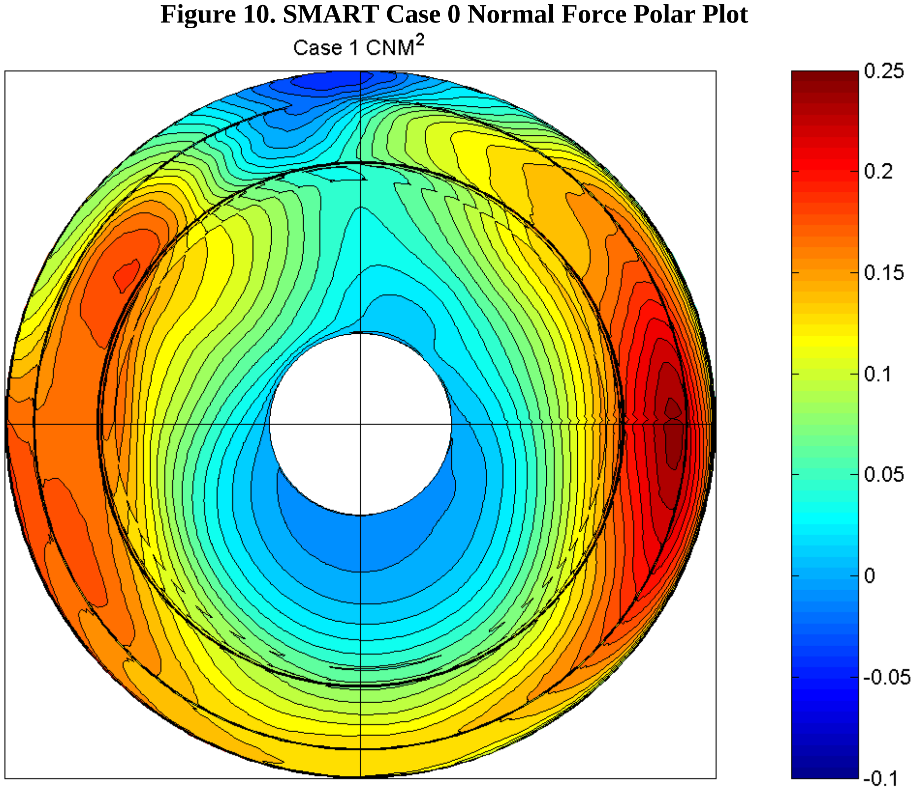

Figure 11. SMART Case 1 Normal Force Polar Plot

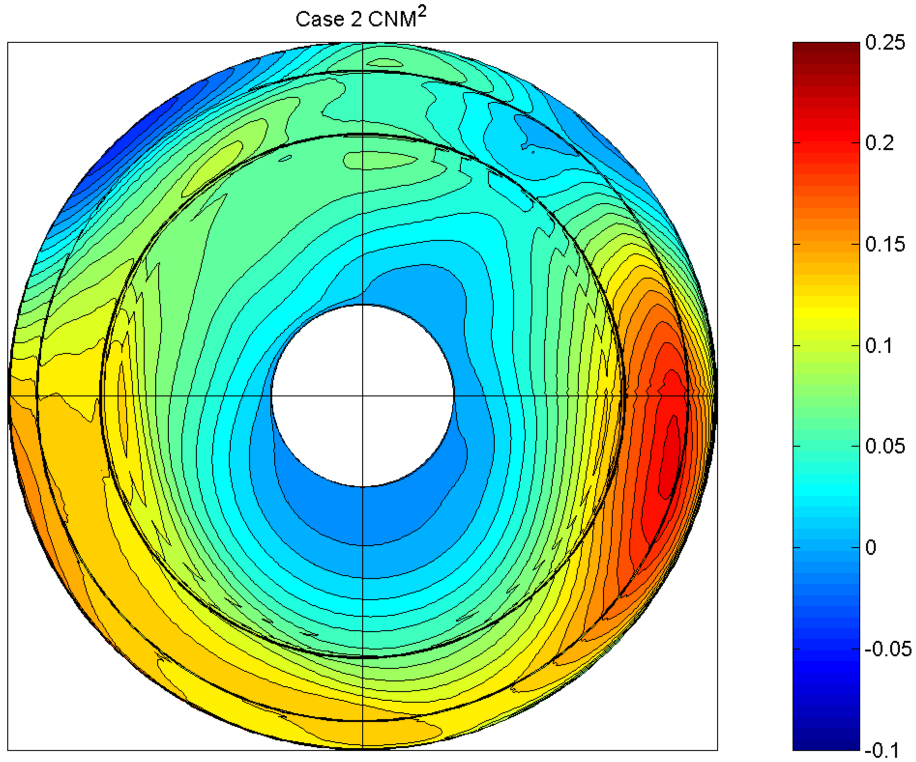

Figure 12. SMART Case 2 Normal Force Polar Plot

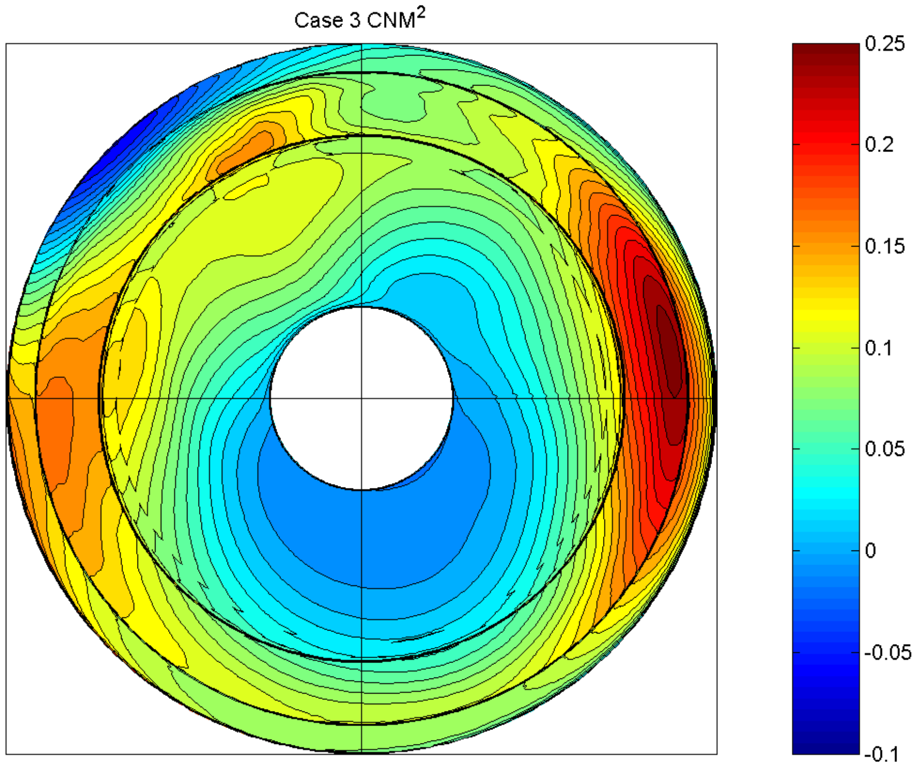

Figure 13. SMART Case 3 Normal Force Polar Plot

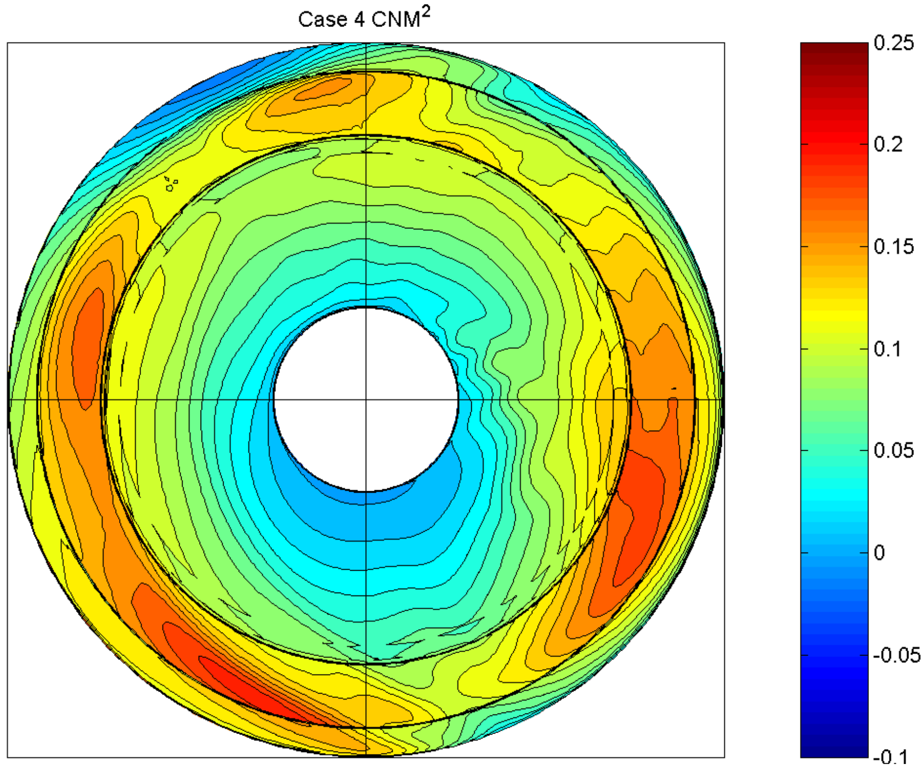

Figure 14. SMART Case 4 Normal Force Polar Plot

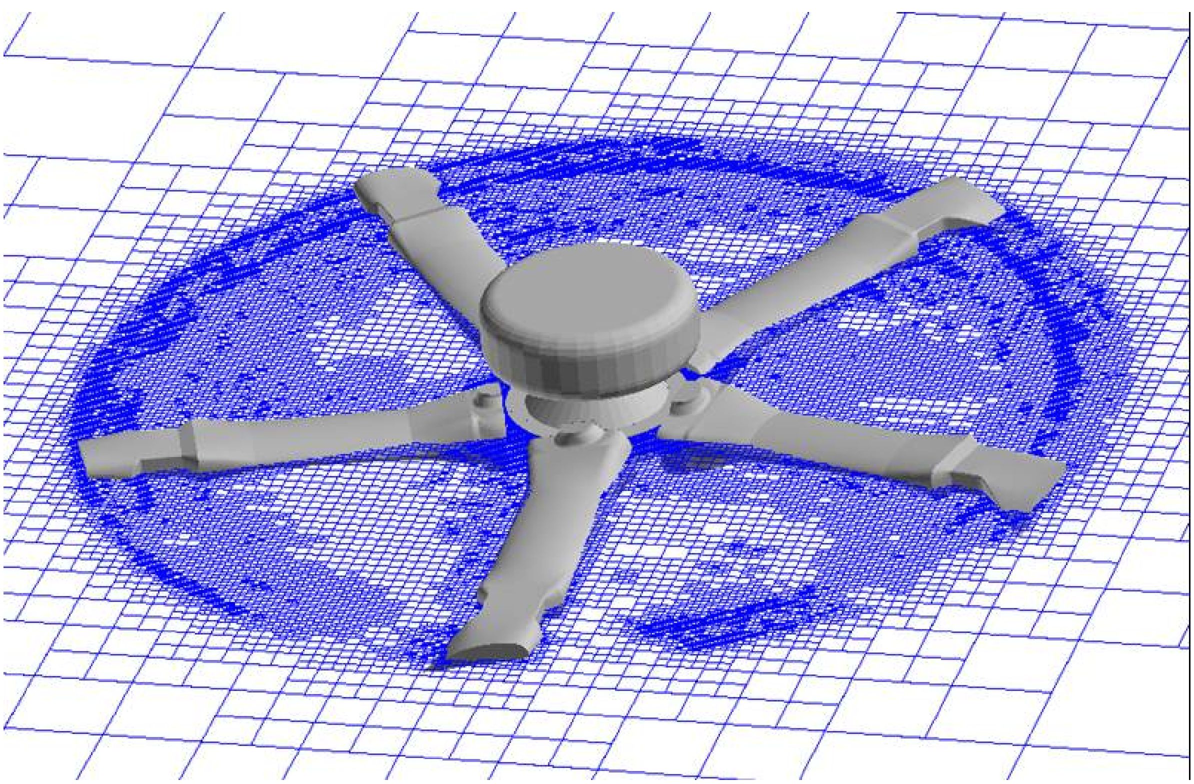

Figure 15. NASCART-GT Grid for Rotating SMART Hub

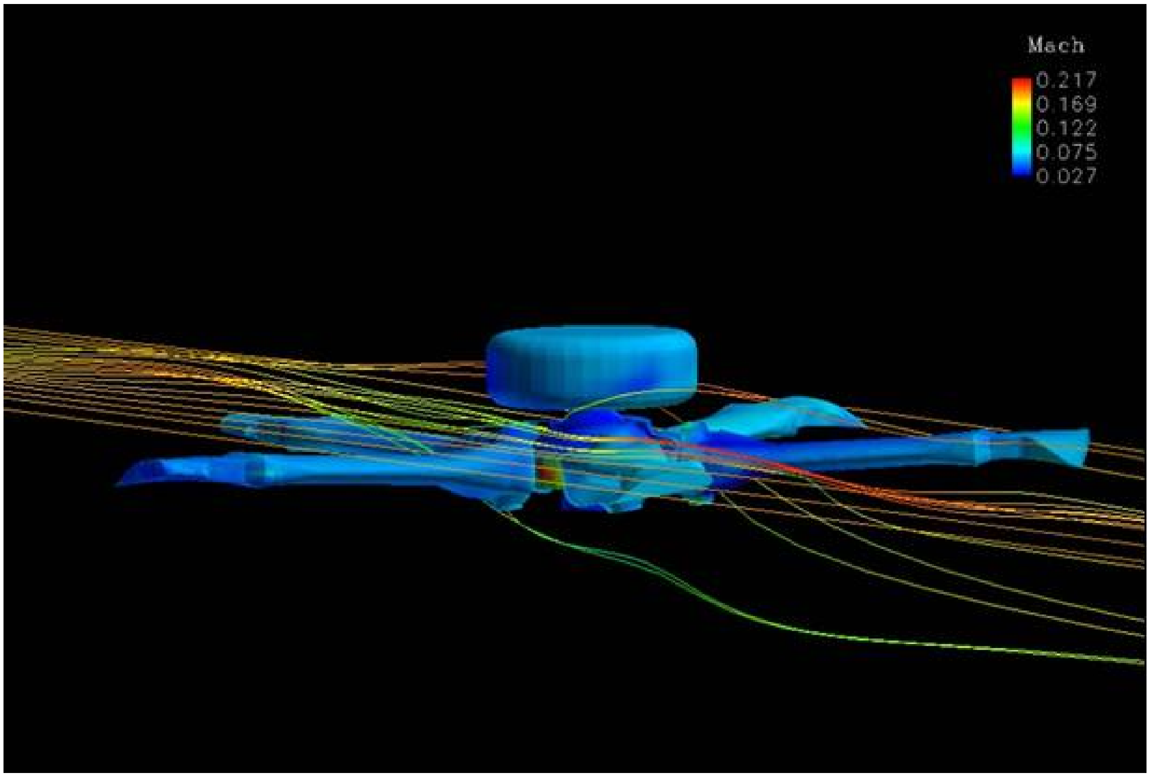

Figure 16. NASCART-GT SMART Hub Streamlines at Shaft Angle of -9.1

Optional Task 3: Comanche-like Rotor

A structural dynamics model of the Comanche rotor was developed based on the data in the ADS-10 document, as well as the electronic data provided to us. At first, the fan plot of the rotor system was generated and is for the nominal rotor speed and a 0 degree collective angle. All the frequencies below 4000 CPM were found to be in good agreement with the fan plot given in the ADS-10 document. Significant differences were observed for the frequencies above 4000 CPM, probably due differences in the modeling assumptions. Mode shapes for the lowest 10 modes of the rotor were also generated. Good correlation was found between the predicted modes shapes and those documented in the ADS-10 report.

OVERFLOW grids were provided to the investigators by Mark Potsdam of AFDD. The rotor was run for the two cases representing high speed flight and descending flight. The first flight case was run with the SA and KES turbulence model. DYMORE and OVERFLOW results and PSU-WOPWOP input files are available for analysis for these cases.

Optional Task 4: Comanche-like Rotor with Anhedral Tip

The DYMORE files for the baseline rotor were modified to account for the anhedral tip. The OVERFLOW grid was extended and then the anhedral tip was added. Two flight conditions were run representing descending flight. DYMORE and OVERFLOW results and PSU-WOPWOP input files are available for analysis for these cases.

Appendix

Changes to the Coupling Framework for the SMART Rotor

Due to the complex nature of the SMART rotor, changes were required in the coupling interface between OVERFLOW and DYMORE. The flap is modeled as a separate lifting line in DYMORE and acts like a separate rotor. The FSI format was modified for this change. The order of the lifting lines in Deflections file written out by DYMORE is as follows: blade1, flap1, blade2, flap2, ext. The original translator to read the DYMORE Deflections file in FSI and translate to an OVERFLOW compatible motion file assumed that all components had the same number of span stations. Another variable was added to the data arrays to track the component number and allow for the different number of span stations. The FSI Airload files were modified in the same manor.

OVERFLOW is able to read in multiple motion files and apply these motions to all the grids associated with each component. This puts a requirement that the order of grids in the grid.in file list all blade grids for all blades are first and the followed by all the flap grids. Due to the closeness of the flap to the main blade, very small differences in the reference positions in the CFD and CSD code can cause the flap to move inside the blade.

OVERFLOW implicitly assumes that there is one blade grid on each rotor blade that is of relevance for load computation. The loads on the root and tip caps are neglected in standard CFD/CSD coupling. One main grid on the flap is practical and used in this case. This is not the case for the main rotor blade. In order to accommodate multiple different grids, an external load calculation routine was used. This also allows for overlapping surface grids even though it was not used in this case. Using an external code avoids any modification of OVERFLOW source code. Due to the uniqueness of this configuration, it would be difficult to modify the OVERFLOW routines for this and other similar situations. The below namelist was added so the OVERFLOW would write out the location and flow properties of each blade and three viscous layers.

```
 $FLOVIS
  ITYPE = 3
  NAME ='loads'
  FNAME = 'loads'
  IBODYS = 1
  IBODYE = 10
  NVISC = 3
  ITS = 7200
  ITE = 999999
  ITINC = 20
  IPRECIS = 2
$END
```

The load calculation algorithm used in GT-HYBRID was modified to read all the needed files and write out the required files for DYMORE. Only 1/n revolutions of data are required. The code has a text input file that allows for multiple main grid components and modified load calculation location. This code has been provided to AFDD (Mark Potsdam and Gene Ruzicka). The code allows for calculation of forces about points other than the local quarter chord. The flap forces were computed about the hinge line. The forces on the main blade in the flap region were calculated about the quarter chord of the full blade rather than the local quarter chord. The files are around 1-2 GB depending on grid size and the entire load calculation takes approximately 2 minutes. Normal force is compared in Figure 17 using the OVERFLOW internal calculation (O2) and the calculation from the GT-HYBRID based computation (GT) for the first main blade grid that goes until the flap.

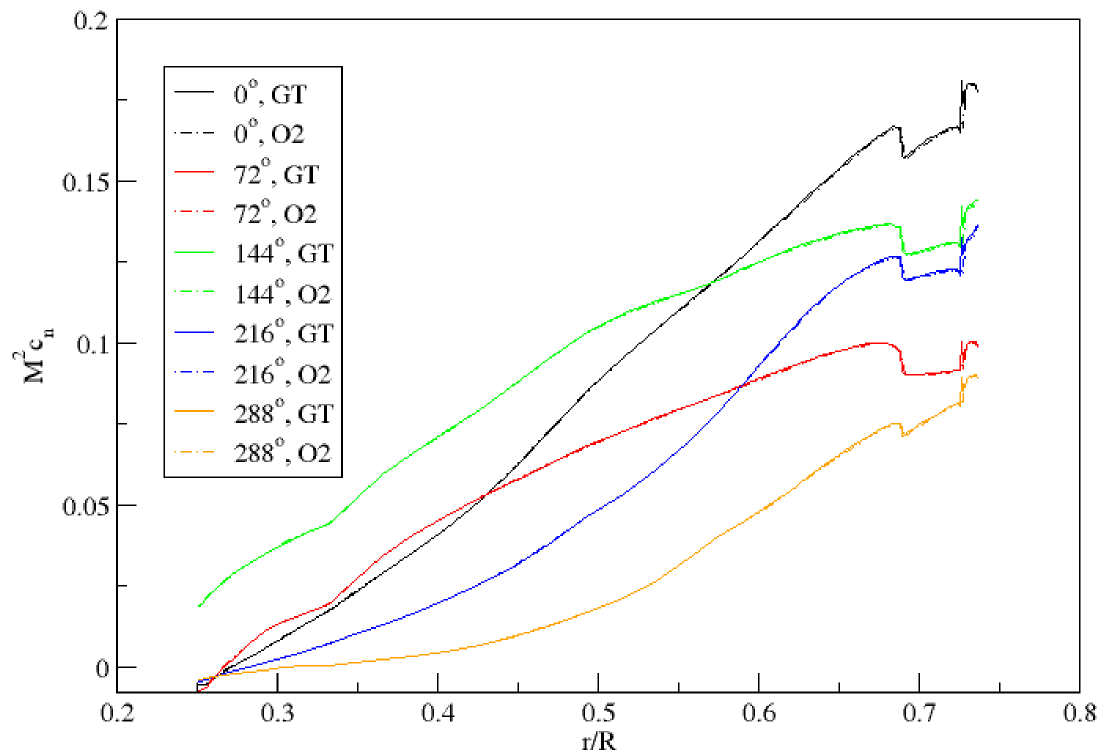

Figure 17. Comparison Between OVERFLOW and GT-HYBRID Normal Force (Results from Gene Ruzicka)

Due to the overlapping near body volume grids, small, high density xrays were required. The below lines in xmove.F were commented out after consultation with Mark Potsdam. This prevents the small xray boxes in the region of the flap from being resized to encompass the entire rotor. The xray boxes are required to be large enough to contain the relative motion of the rotor blade which primary consists of lead lag motion.

```
!       Use previous xray spacing
...
!        XBOXES(1,NX) = MINVAL(GRIDX) - DELMAX
!        XBOXES(2,NX) = MAXVAL(GRIDX) + DELMAX
!        XBOXES(3,NX) = MINVAL(GRIDY) - DELMAX
!        XBOXES(4,NX) = MAXVAL(GRIDY) + DELMAX

...

!       BBOX changed, evaluate new dimensions
!
!       JXP = ( XBOXES(2,NX) - XBOXES(1,NX) )/DS + 1
!       KXP = ( XBOXES(4,NX) - XBOXES(3,NX) )/DS + 1

!       JX(NX) = JXP
!       KX(NX) = KX
```