UH-60A Airloads Wind Tunnel Test Summary

Airloads Workshop

Tom Norman

February 17, 2011

Outline

- Test Summary
- Efforts since August 2010
- Data Evaluation Status
- Interesting Measurements
  – Rotor Thrust
  – Blade Deflection
  – PIV
- Sample Results
  – Stall sweep
  – Speed sweep
  – Flight test match – 8424
  – DNW match – 13.20
  – High advance ratio
- Data Availability
- Summary

Test Summary

- Test completed May 2010
- Six test phases
  - Parametric Sweeps
  - 1-G Level Flight
  - Airloads Flight Matching
  - DNW Wind Tunnel Matching
  - High Advance Ratio
  - Particle Image Velocimetry (PIV)

Efforts Since August 2010

- 5 conference papers accepted for presentation
  - 3 at AHS Forum
    - Test overview
    - CFD correlation
    - High advance ratio
  - 2 at June AIAA Applied Aero meeting
    - PIV technique
    - Blade deflection technique
- Made tentative plans for control stiffness testing and blade contour measurements (later this year)

Efforts Since August 2010

- Continued data evaluation efforts, focusing on conditions needed for conference papers
  - Stall sweep - Mtip=0.625, mu=0.30, alpha=0, hub moments=0, vary collective
  - Speed sweep - Mtip=0.650, Ct/s=0.09, mu=.15 to .40, representative moments, representative Xforce
  - High advance ratio runs
  - Flight 8424 and DNW 13.20
- Continued development and data reduction for Blade Displacement, PIV, and RBOS systems

Data Evaluation Status

- Key Measurements
  - Blade Pressures and Integrated Parameters
  - Rotor Performance
  - Blade Structural Loads
  - Blade Root Motion Measurements

Data Evaluation Status

- Blade Pressures and Integrated Parameters
  - Identified suspect pressures on chordwise arrays for key data points
  - Blade load integrations performed
    - Same integration method as used for flight test data
    - No suspect channels used in integrations
    - Valid stall sweep stations (working transducers/total transducers)
      - r/R= .**225** (19/20), **.400** (20/20), **.675** (18/20), .**775** (22/24), .**865** (25/28), .**920** (27/29), .**965** (25/28), .**990** (25/27)
    - Valid speed sweep stations (working transducers/total transducers)
      - r/R= .**225** (19/20), **.400** (20/20), **.675** (14/20), .**775** (16/24), .**865** (25/28), .**920** (27/29), .**990** (21/27)
    - Valid high advance ratio stations (working transducers/total transducers)
      - r/R= .**225** (17/20), .**865** (25/28), .**920** (25/29)
  - Some suspect pressures may be usable with further data review
    - Delete bad revs, correct for common power problems, etc
    - Requires dedicated effort/time for each test condition

Data Evaluation Status

- Rotor Performance
  - Fixed-system hub forces/moments and shaft torque from rotor balance valid for all runs
    - Weight and aero tares applied
    - Corrected alpha (Prandtl-Glauert wall correction) derived from balance data and tunnel velocity
    - Rotor Lift/Drag with and without wall corrections
  - Repeatability between primary and backup gages generally good
    - Some drift requires additional assessment for specific test points, particularly for high advance ratio testing (lower loads)

Data Evaluation Status

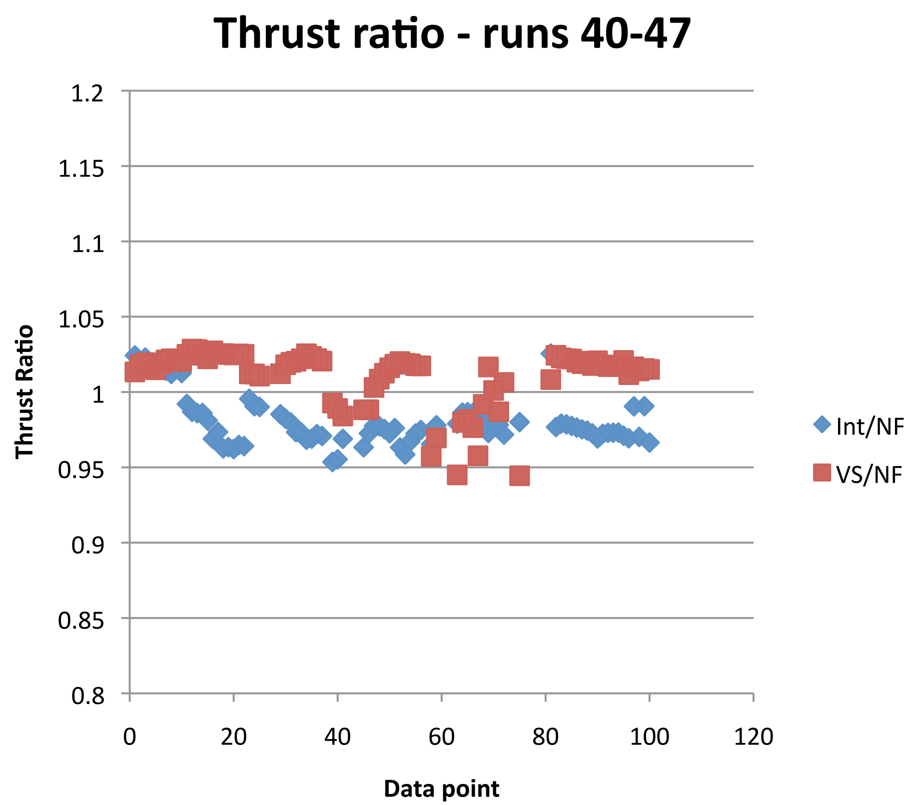
- Blade Structural Loads (NB, EB, Torsion)
  - Evaluating gages for key data points
    - Stall and speed sweeps
      - All working except EB50 and NB80
    - High advance ratio
      - Number of gages show intermittent problems yet work most of the time
        - EBX, EB20, EB30, EB50, EB60, NBX, NB50, Torsion 20, 30, 50, 60, 70, 90
      - Requires point by point evaluation to verify gage integrity
  - Further review of blade calibration suggests need for coupled calibration coefficients
    - NB70 and Torsion 70 electrically coupled – affects all runs
    - Calibration shows significant effect of NB on EB for many stations (esp. 20 and 30)
      - Has minimal effect on full RPM runs
      - Significant effects on high advance ratio runs (because of high NB loads)
  - Some gages showed mean CF effect during RPM sweep – evaluation underway
  - Still need to apply CF and coupled calibration corrections to data

Data Evaluation Status

- Blade Root Motion Measurements
  - 12 crabarm and 12 laser measurements – requires 3 on each blade to determine root pitch, flap, and lag
  - All gages working at start of test and most working at end – attempted to fix problem channels during test
  - Accuracy of blade motion dependent on in-place calibration
    - Performed "best-fit" calibration prior to test – should re-look at cal data to improve calibration if possible
    - Current approach is susceptible to transducer drift from beginning to end of test (mean shift)
  - Results show some blade-to-blade differences and method-to-method differences – especially means
    - Evaluation underway but not yet resolved
    - Blade deflection data will help evaluation process

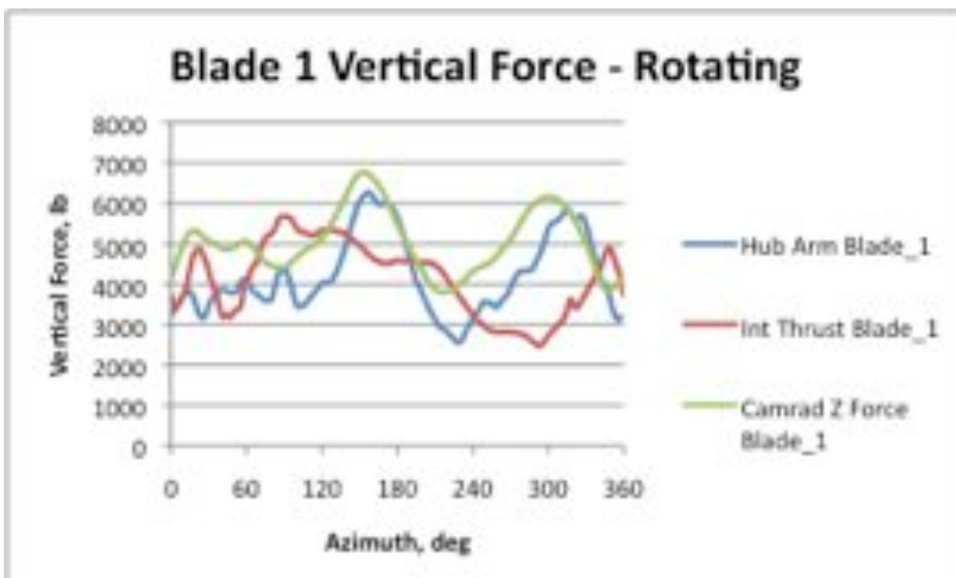
Rotor Thrust Comparisons

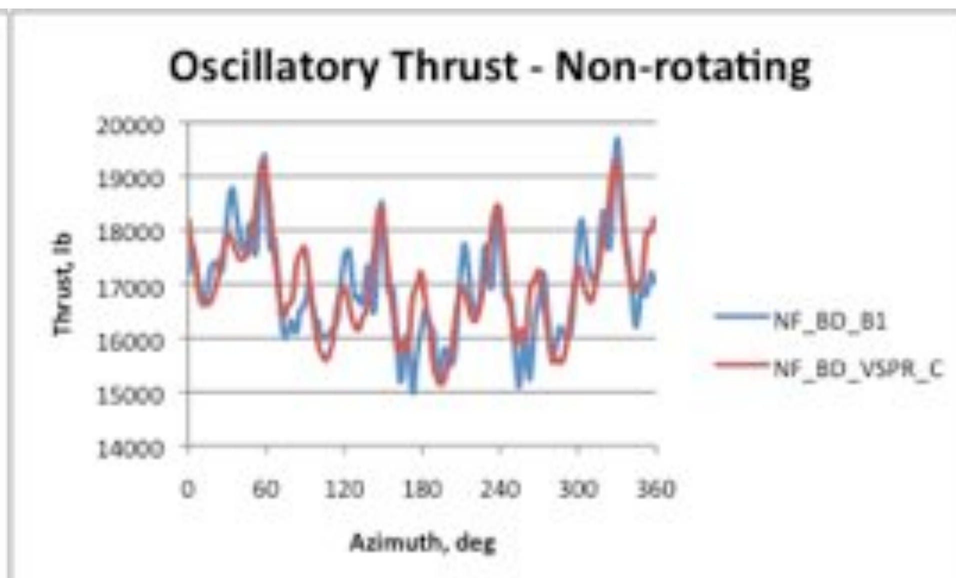
- Rotor thrust estimated by three independent measurements
  - Rotor balance
  - Integrated pressure blade loads
    - Accounts for blade twist (coll, cyclic, built-in twist)
    - Other 3 blades assumed identical
  - Hub arm vertical shear force
    - Gage on each arm
    - Corrected for CF effect
- Alternate measurements of mean thrust nominally consistent
  - Integration mostly low 2-4%
  - Hub arm mostly high 2%



Rotor Thrust Comparisons

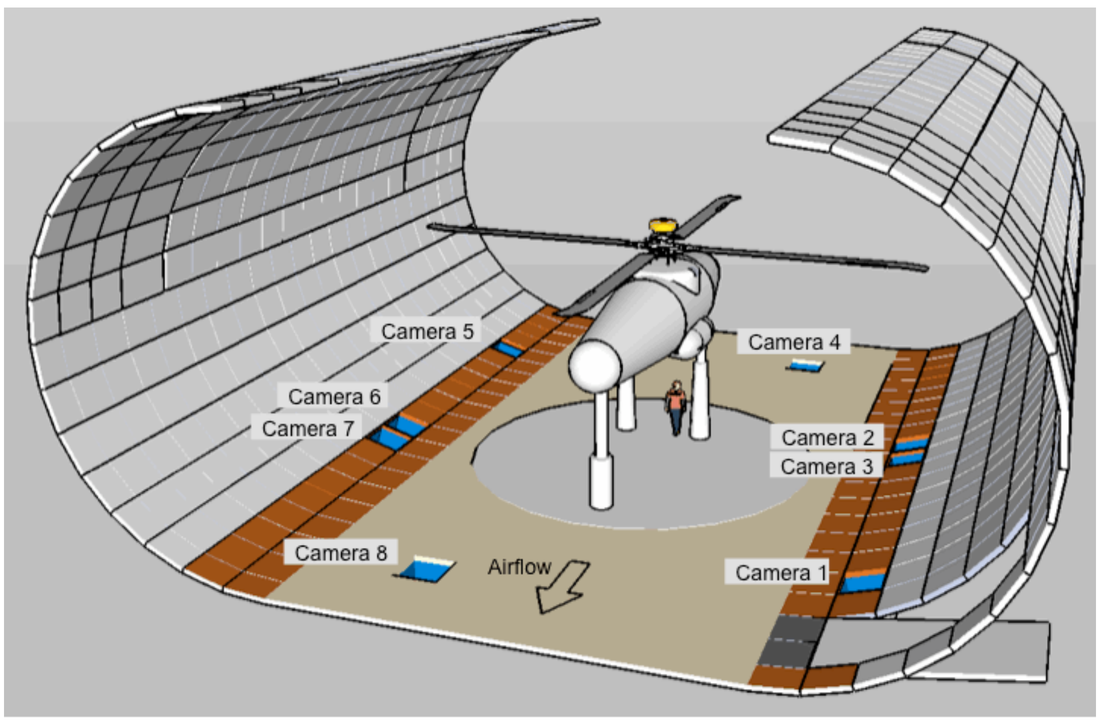
- Measurements provide end to end check of rotor thrust
  - Rotating frame – integrated thrust + inertial loads = hub vertical shear
  - Non-rotating frame – 4 hub shears transformed to fixed system
- Example at Mtip=.625, , Ct/s=.08, mu=.30, alpha=0
  - No dynamic calibration applied

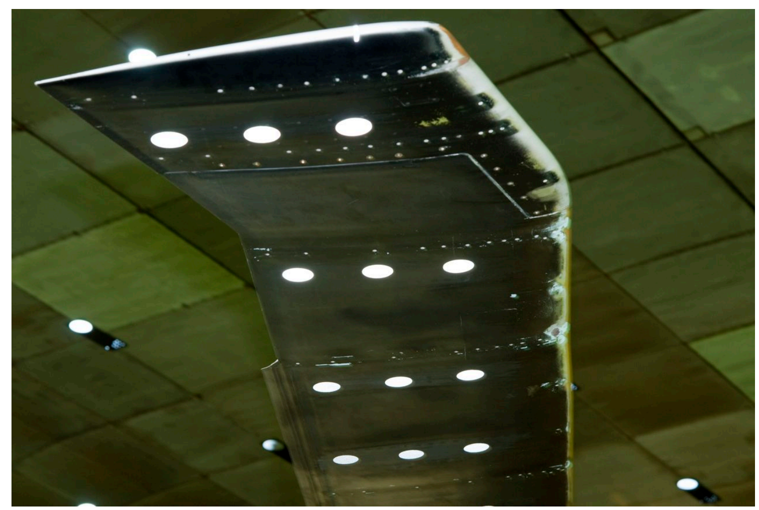




Blade Displacement

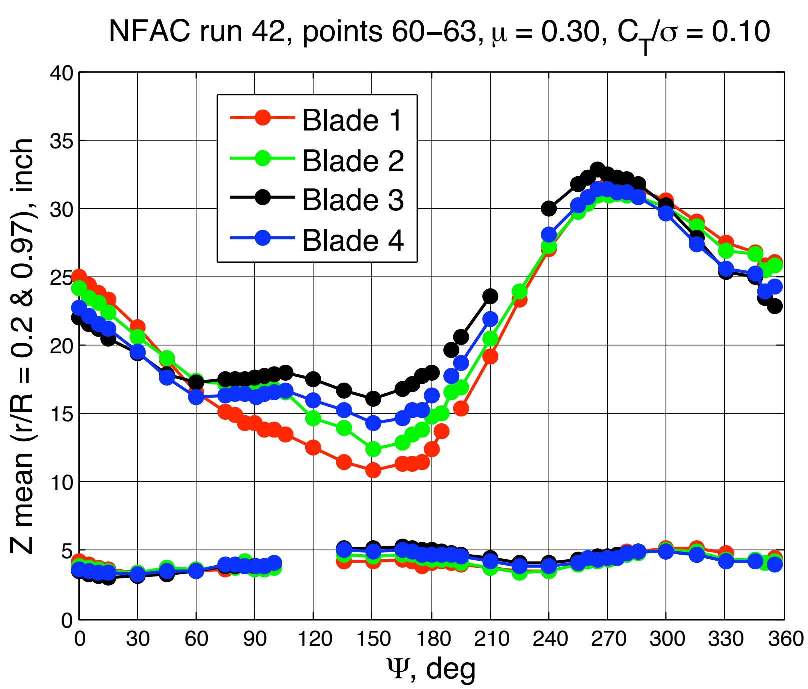
- What was measured?
  - Simultaneous images from multiple cameras of radial and spanwise array of retro-reflective targets on each of 4 blade
  - From target images, will extract
    - Location of blade section chord lines along the blade span in the hub coordinate system
    - Accuracies to 0.2 deg (pitch, flap, lag)

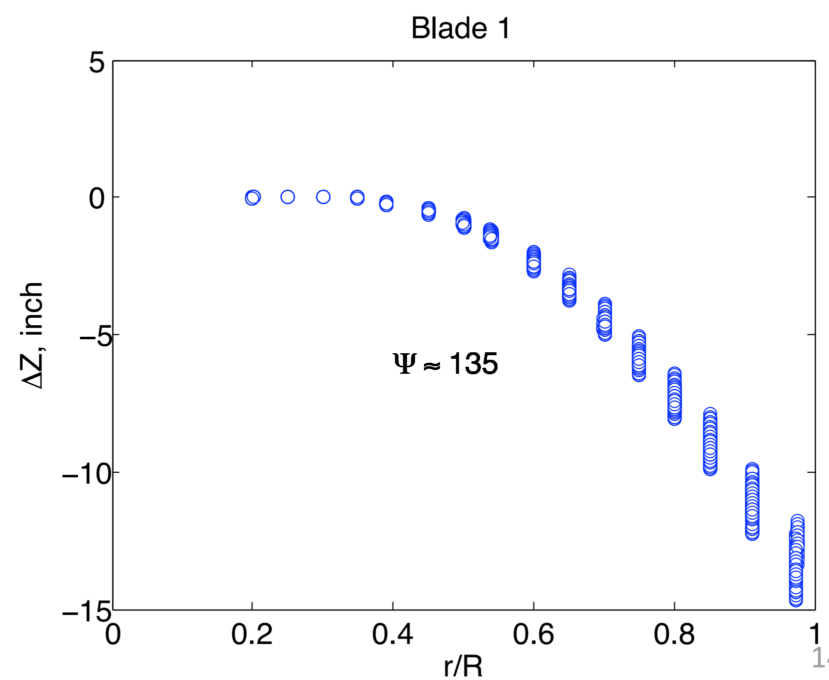




Blade Displacement

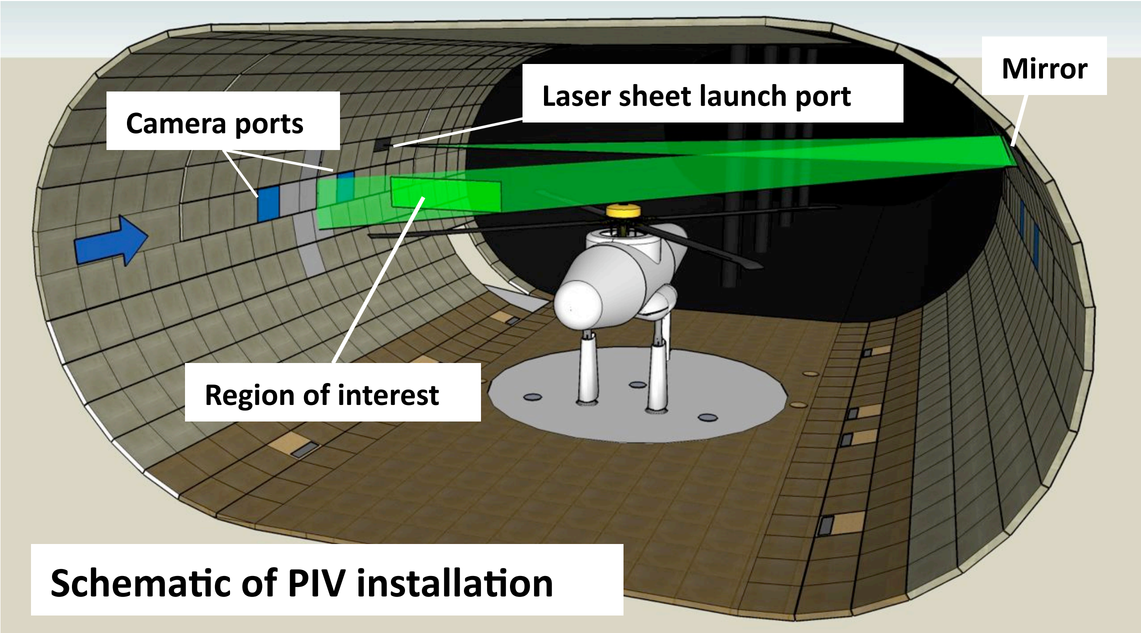
- Data reduction and evaluation process still being developed but making excellent progress
  - Most confident with flap measurements
- Sample Results
  - Ct/s=.10, mu=.3, alpha=0
  - Data suggests blades fly differently (not unexpected)
  - Can use average deflection over inboard blade to compare with blade root measurements
  - Data at single azimuth shows blade bending





PIV Data

- What was measured?
  - 3-D velocity field in stationary cross-flow plane at approximately 90 deg azimuth, covering outer 50% of rotor radius
  - From velocity field, will extract
    - Tip vortex core size
    - Rotor wake geometry (tip vortex trajectory in laser sheet)
    - Vortex strength and vortex structure

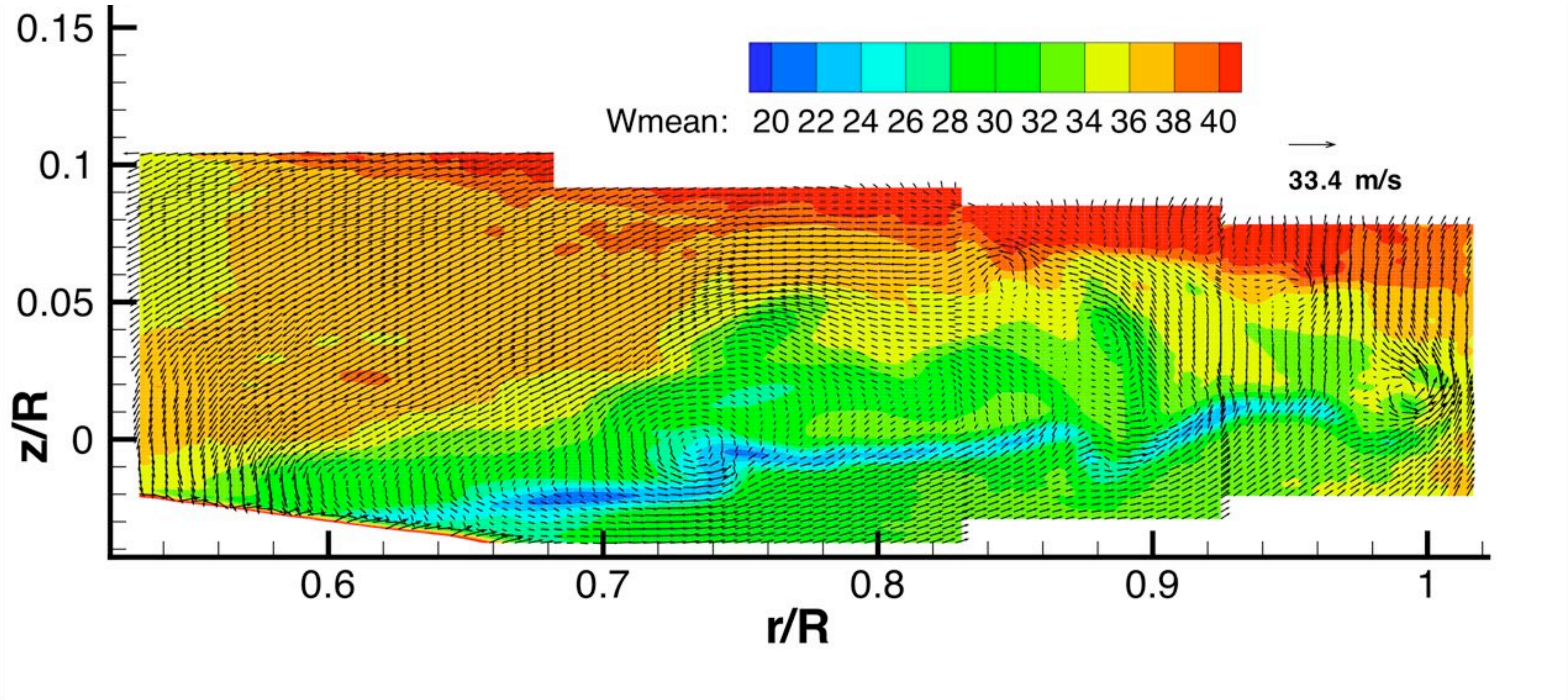


Schematic of PIV installation

PIV Data

- Data Reduction Status
  - Completed first pass through images using approximate calibration and PIV software.
  - Will soon begin analysis of individual vortices. This requires
    - Corrections for laser light sheet movement
    - Application of separate inner/outer calibrations
    - Conditional sampling to remove vortex wander effects
- Initial results are very promising
  - Sample results for Ct/s=.08, mu=.149, alpha=0

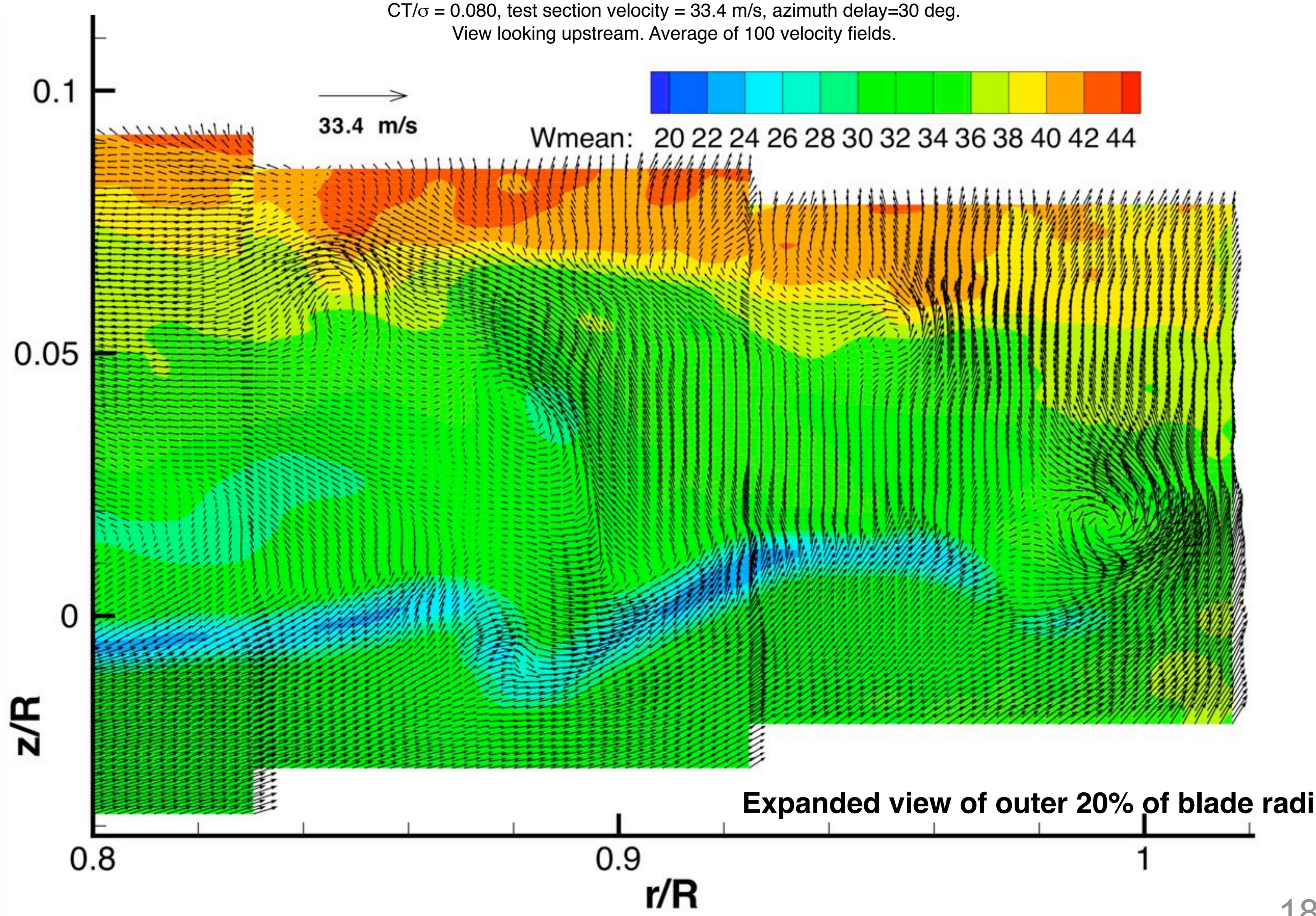
Preliminary data: Ensemble averaged velocity field



Run 73, NFAC pts. 20-22. Test conditions: rotor shaft angle = 0 deg, Mtip = 0.650, advance ratio = 0.149, CT/σ = 0.080, test section velocity = 33.4 m/s, azimuth delay=30 deg.
View looking upstream, every other vector shown. Average of 100 velocity fields.

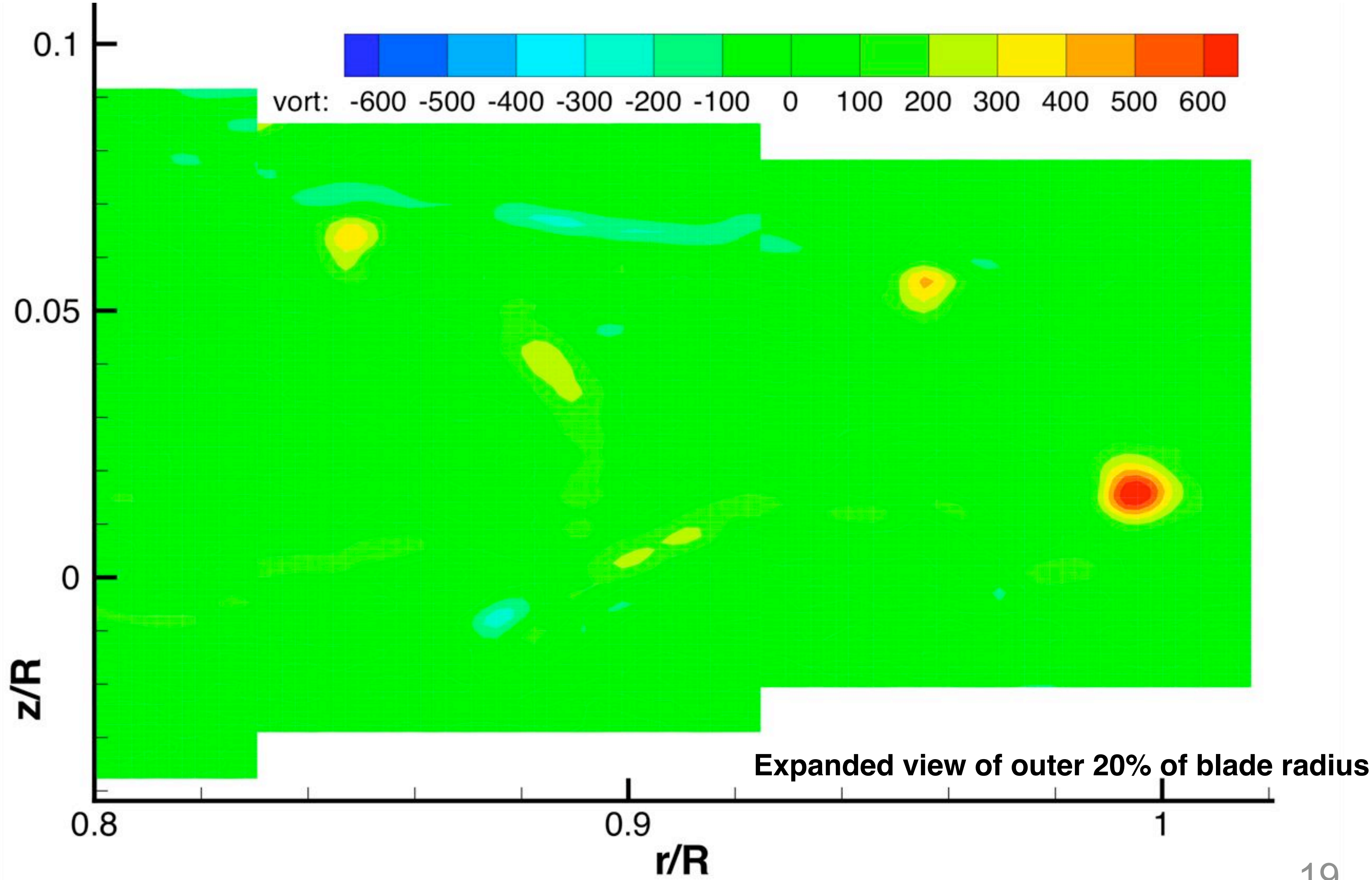
Preliminary data: Ensemble averaged velocity field

Run 73, NFAC pts. 20-22. Test conditions: rotor shaft angle = 0 deg, Mtip = 0.650, advance ratio = 0.149,
CT/σ = 0.080, test section velocity = 33.4 m/s, azimuth delay=30 deg.
View looking upstream. Average of 100 velocity fields.



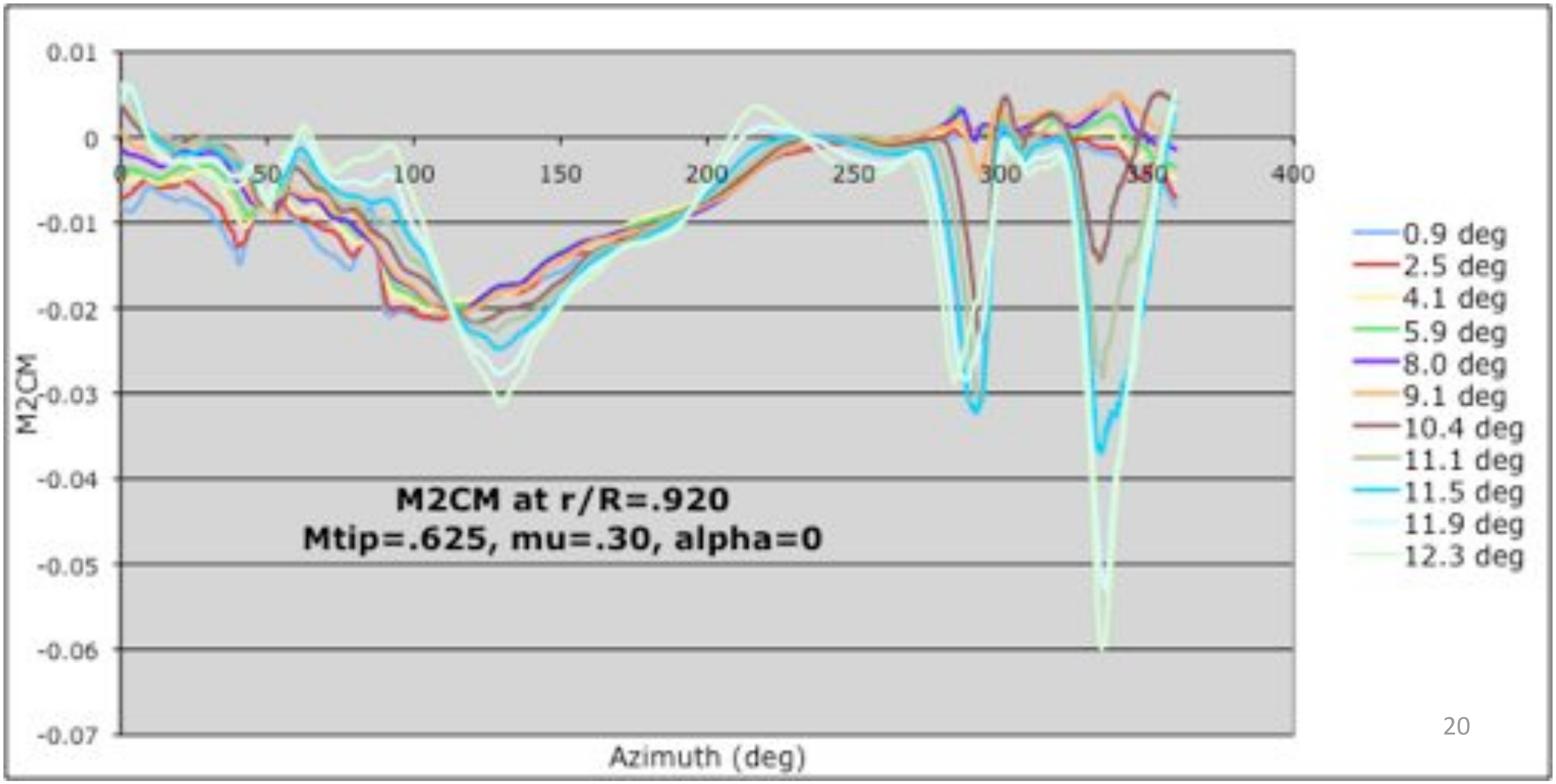
Preliminary data: Ensemble averaged vorticity field

Run 73, NFAC pts. 20-22. Test conditions: rotor shaft angle = 0 deg, Mtip = 0.650, advance ratio = 0.149, C_T/σ = 0.080, test section velocity = 33.4 m/s, azimuth delay=30 deg.
View looking upstream. Average of 100 vorticity fields.



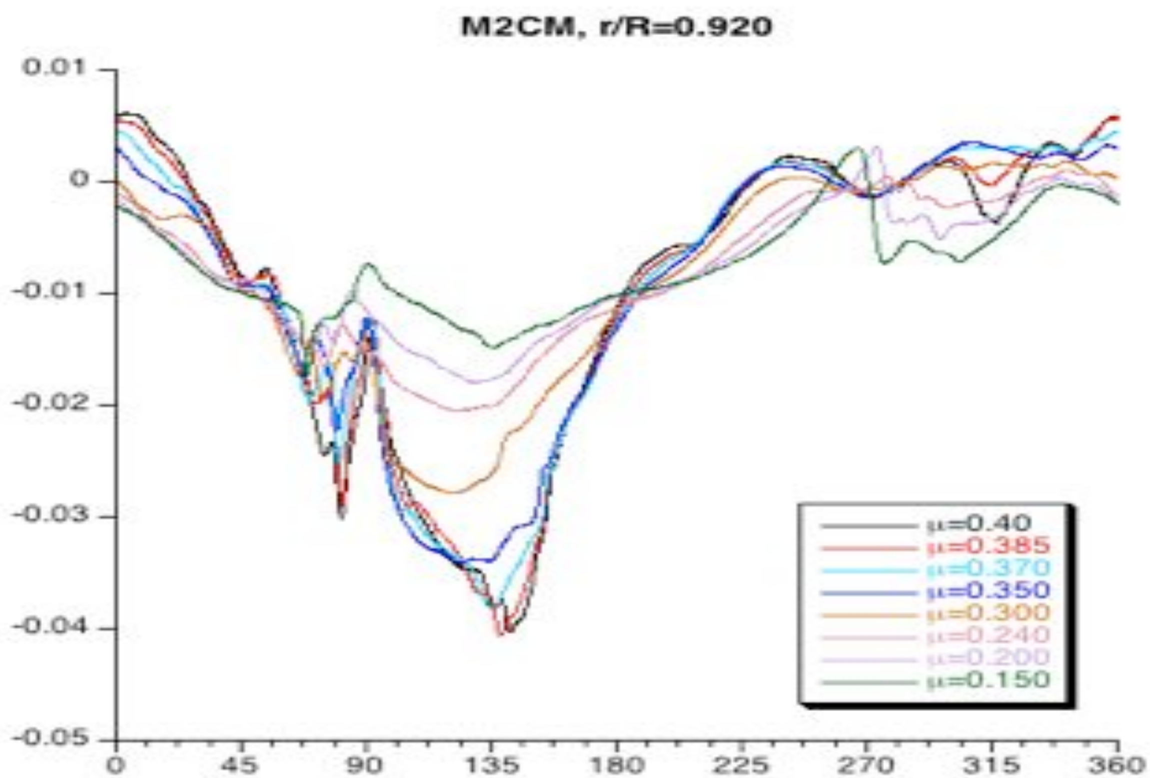
Sample Data – Stall Sweep

- Mtip=.625, mu=.30, alpha=0, Ct/s = .02 to max (stall)
- Average M2CM at r/R = 0.92 as a function of collective
  - Magnitude of 2nd stall cycle highly sensitive to collective



Sample Data – Speed Sweep

- Mtip=0.650, Ct/s=0.09, mu=.15 to .40
- Average M2CM at r/R = 0.92 as a function of advance ratio
  - Smooth changes between mu=.35 to .40



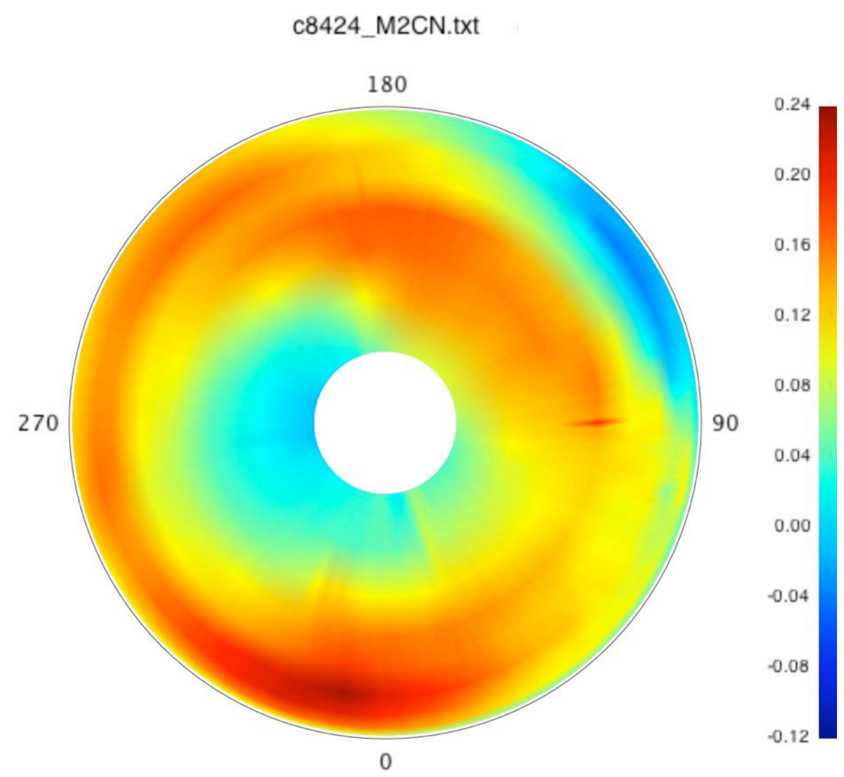
Comparison with Flight C8424, Ct/s=.087

- Adjusted trim parameters in attempt to match flight
  - Set Mtip, corrected alpha, advance ratio, Ct/s, and pitching and rolling moment coefficients (from shaft bending gage) to match flight test values
- Acquired data at derivative conditions to determine sensitivity of trim conditions
  - Pitching moment, rolling moment, thrust, shaft angle varied one at a time
  - All other parameters re-trimmed to original value
- Only thrust derivatives showed significant effect on integrated airloads
  - Ct/s = 0.087 +- 0.005

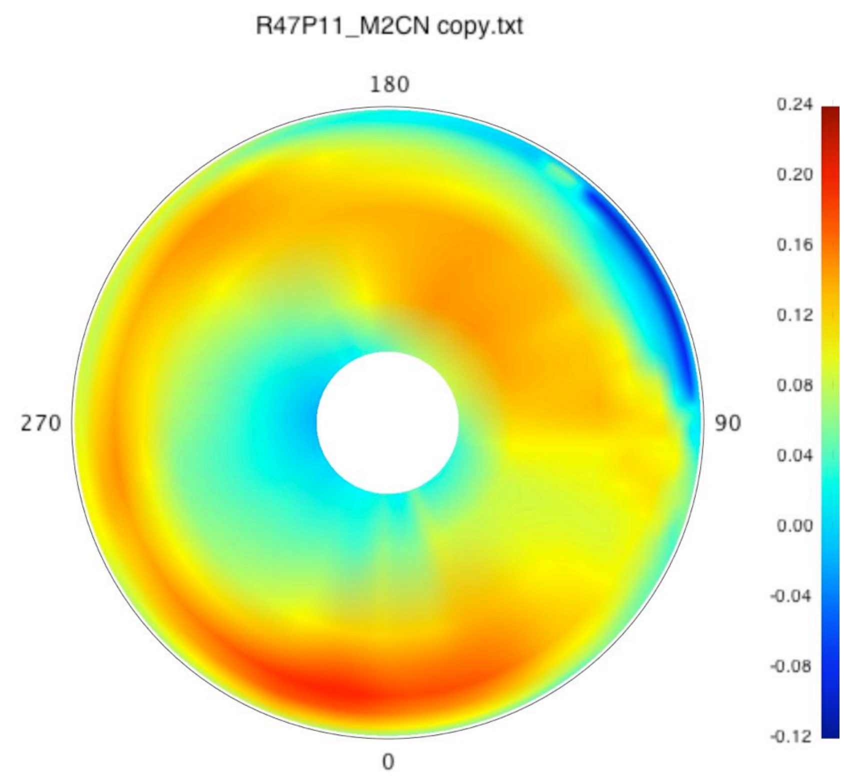
Comparison with Flight C8424, Ct/s=.087

- M2CN comparison

Flight 8424

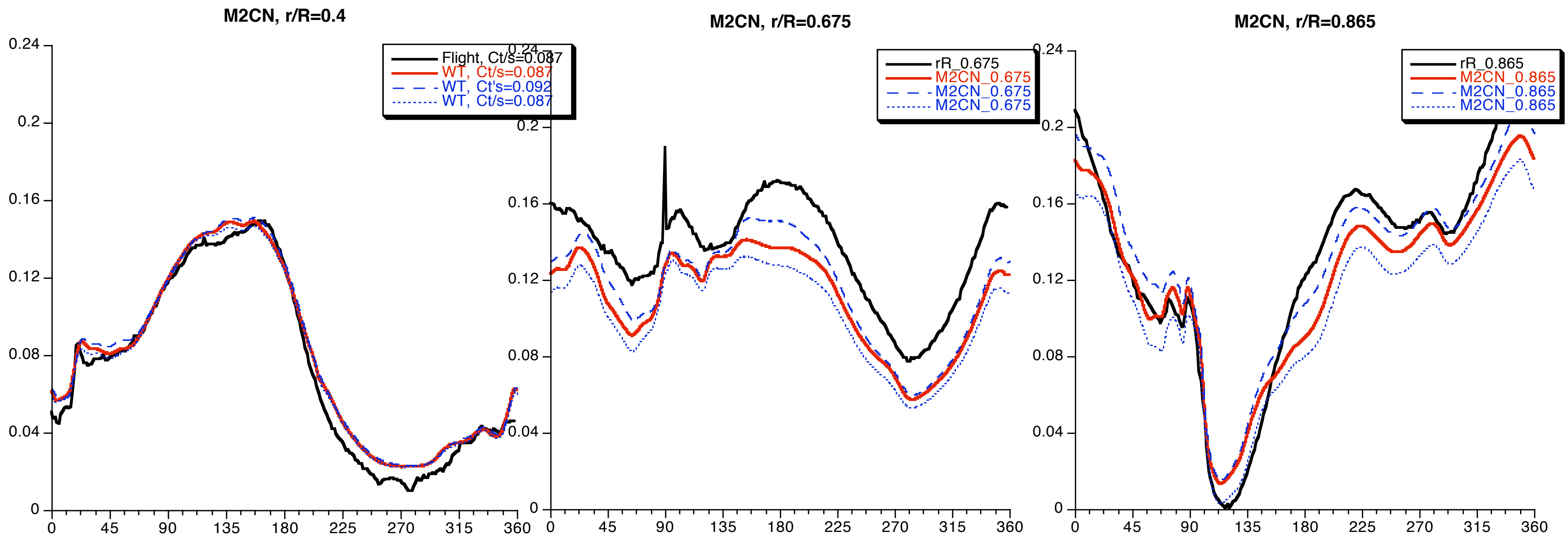


40x80 4711



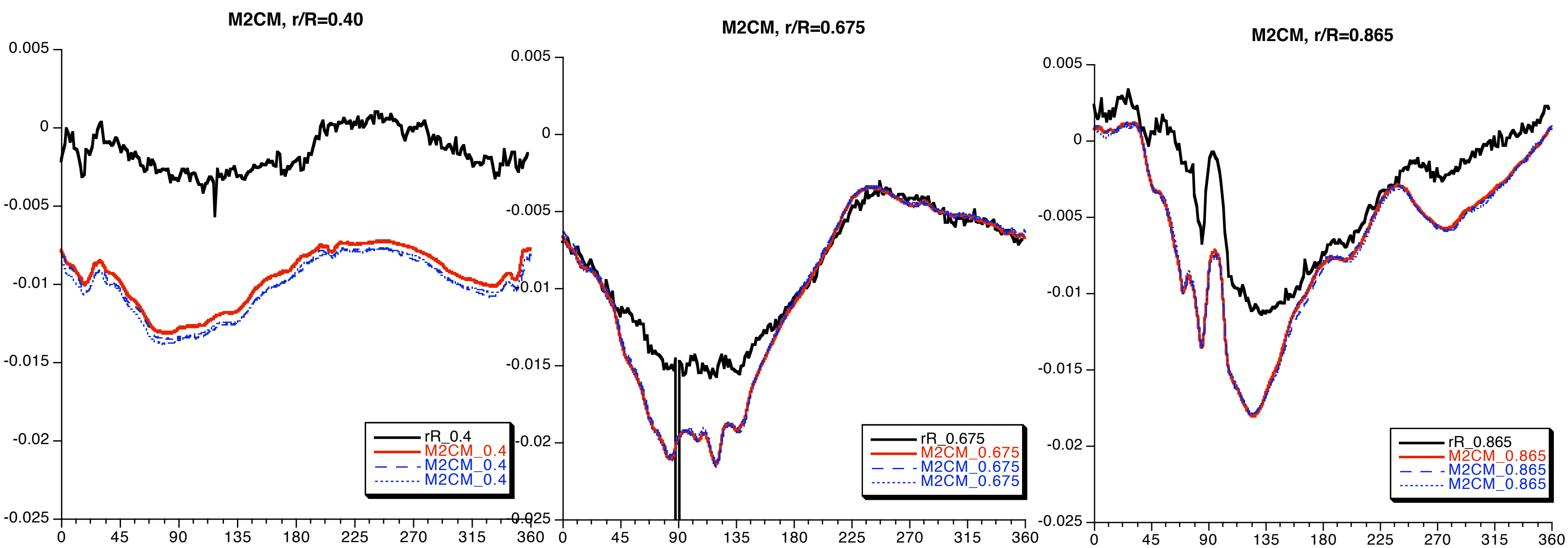
Comparison with Flight C8424, Ct/s=.087

- M2CN comparison



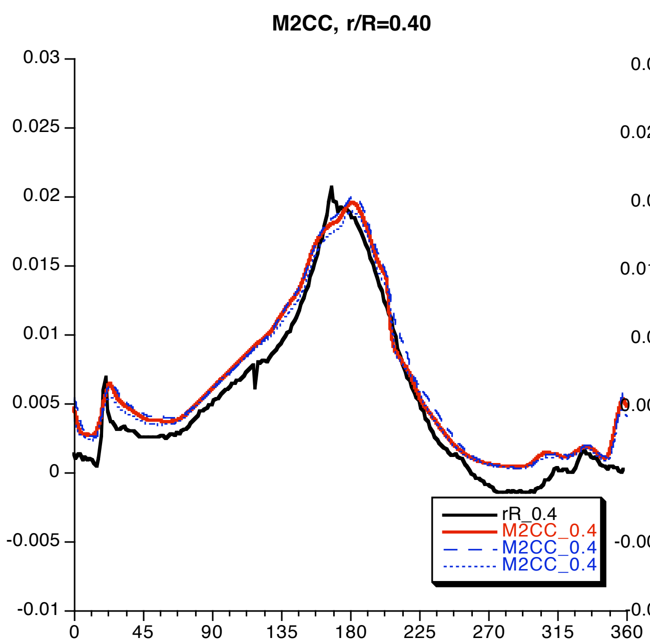
Comparison with Flight C8424, Ct/s=.087

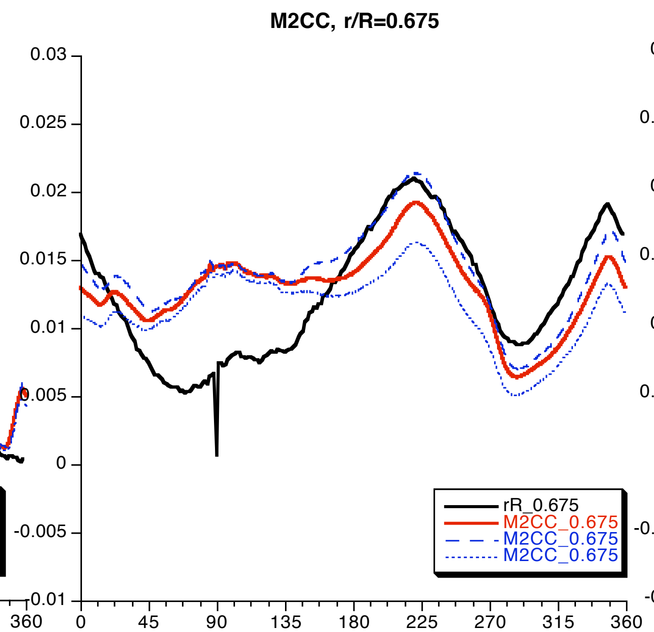
- M2CM comparison

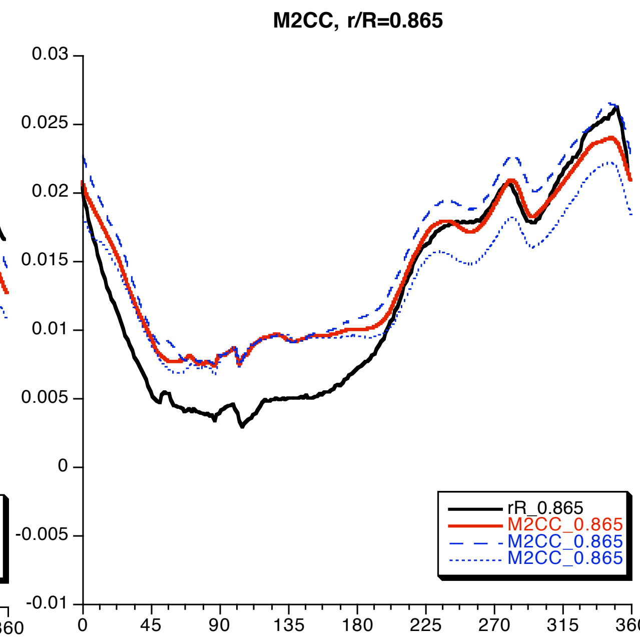


Comparison with Flight C8424, Ct/s=.087

- M2CC comparison







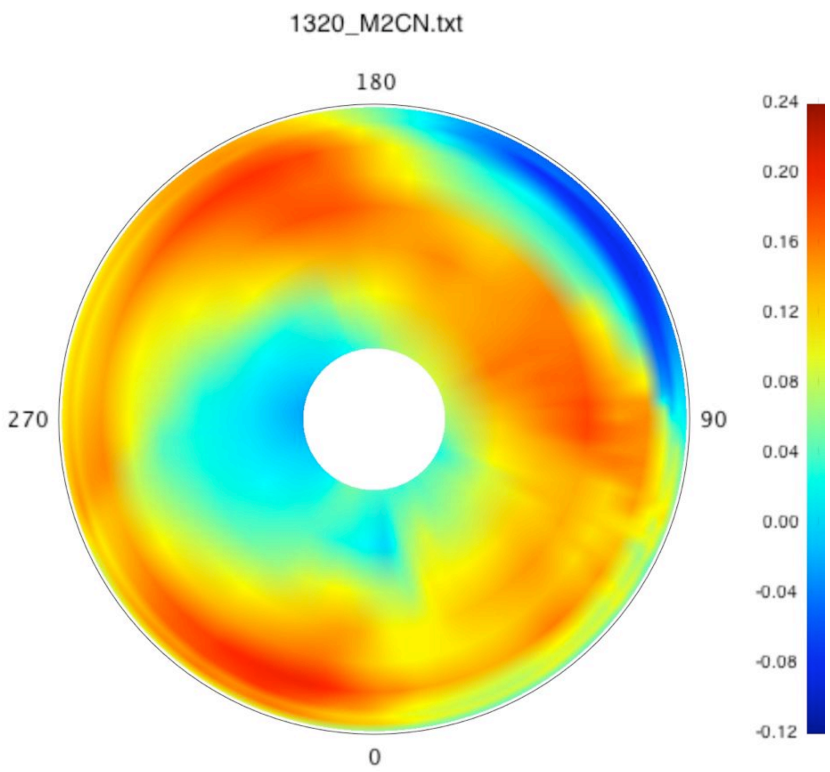
Comparison with DNW 13.20, Ct/s=.10

- Adjusted trim parameters in attempt to match DNW
  - Set Mtip, corrected alpha (both DNW and 40x80), advance ratio, Ct/s, and minimized 1/rev flapping (blade 1) to match DNW test values
- Acquired data at derivative conditions to determine sensitivity of trim conditions
  - 1/rev flapping, thrust, shaft angle varied one at a time
  - All other parameters re-trimmed to original values
- Only thrust derivatives showed significant effect on integrated airloads
  - Ct/s = 0.10 +- 0.005

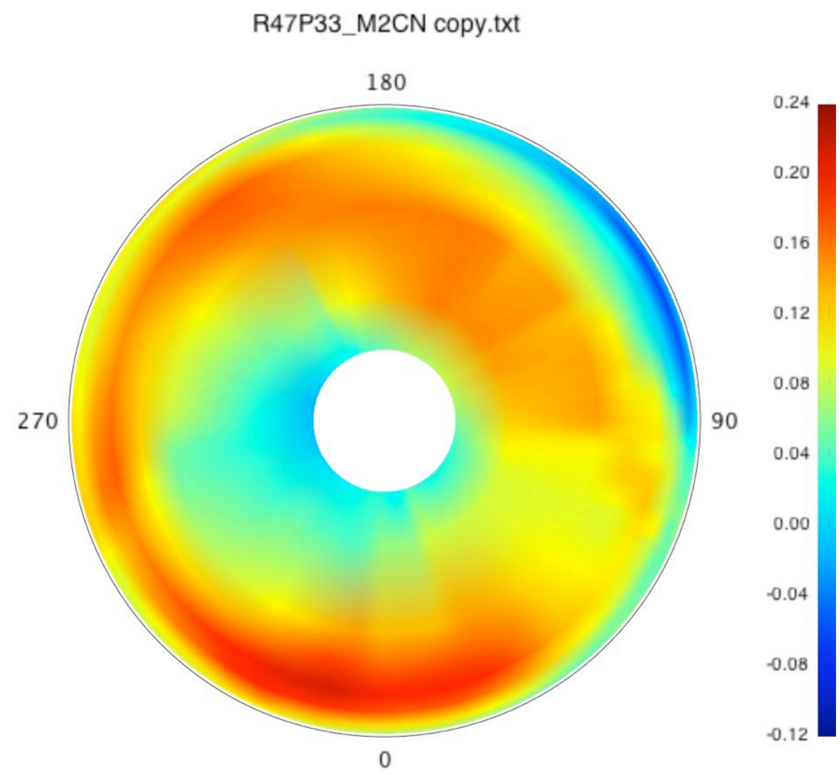
Comparison with DNW 13.20, Ct/s=.10

- M2CN comparison

DNW 13.20

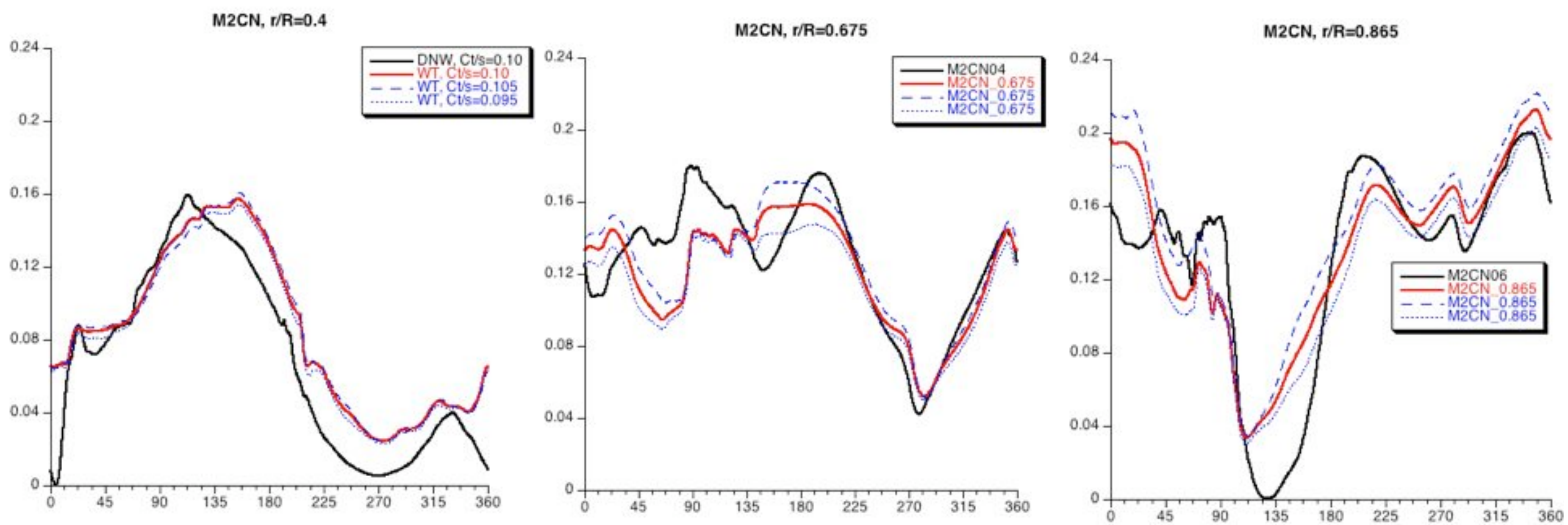


40x80 4733



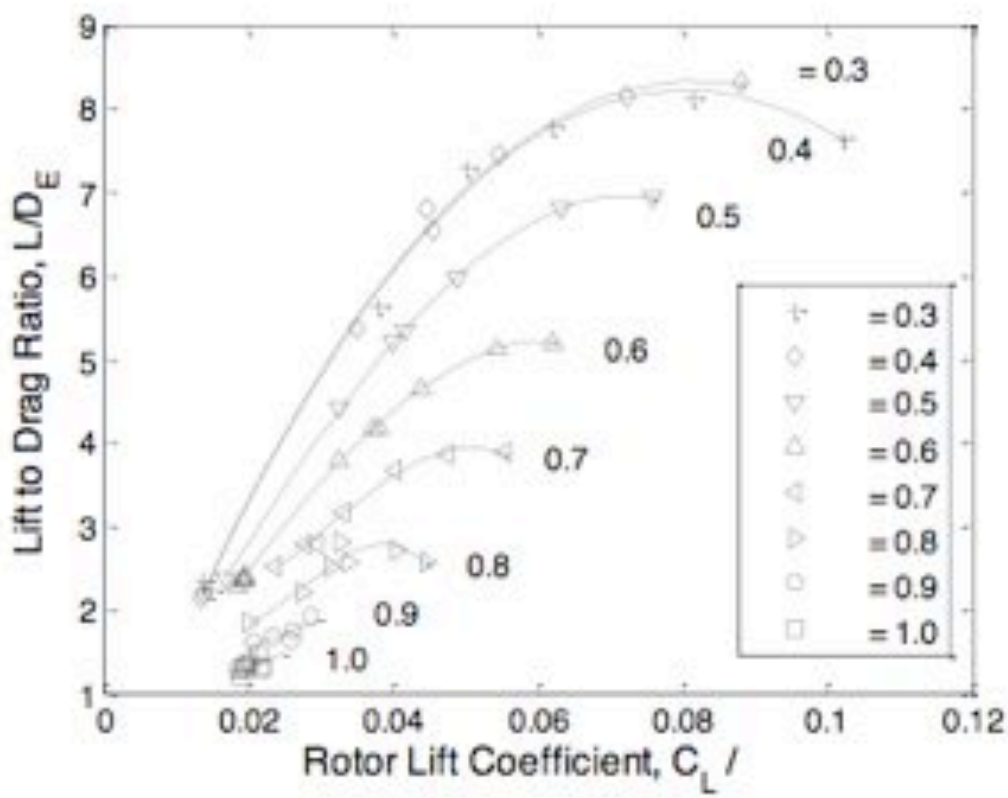
Comparison with DNW 13.20, Ct/s=.10

- M2CN comparison



Sample Data – High Mu

- RPM=40% NR, alpha=0, mu=0.3 to 1.0
- Rotor L/De as function of Ct/s



Data Availability

- When will data become more widely available?
  - It depends on what is being requested and whether it needs to be verified and/or corrected
    - Key data points will be available before other conditions
    - Still have work to do (blade motion, blade structural loads, verifying pressure integrations, completing bad channel lists). How much of this must be completed before data release?
    - Earlier release means greater chance for bad channels/data to be included
  - Final data release will require complete definition of data to be included and format for data files
    - Time history and harmonics? If so, how many harmonics?
    - Include more or less data than flight test?
    - PlotDB-like database format or other?

Summary

- Making good progress on evaluating/verifying data from key data points
  - Results continue to look very promising
  - Still have work to do (blade motion, blade structural loads, etc., verifying pressure integrations)
- Blade deflection measurements and PIV/RBOS data reduction underway
  - Initial results look very good
  - Will provide unique validation data
- Need to define requirements before data can be made more widely available

Near Term Plans

- Prepare publications for AHS Forum and AIAA meeting
- Complete data review and evaluation of key data points
- Prepare for and conduct control stiffness test
- Measure blade contours and compare with CAD results for consistency