National Aeronautics and Space Administration

Fundamental Aeronautics Program

Subsonic Rotary Wing Project

Status of Blade Displacement Measurements & Analysis

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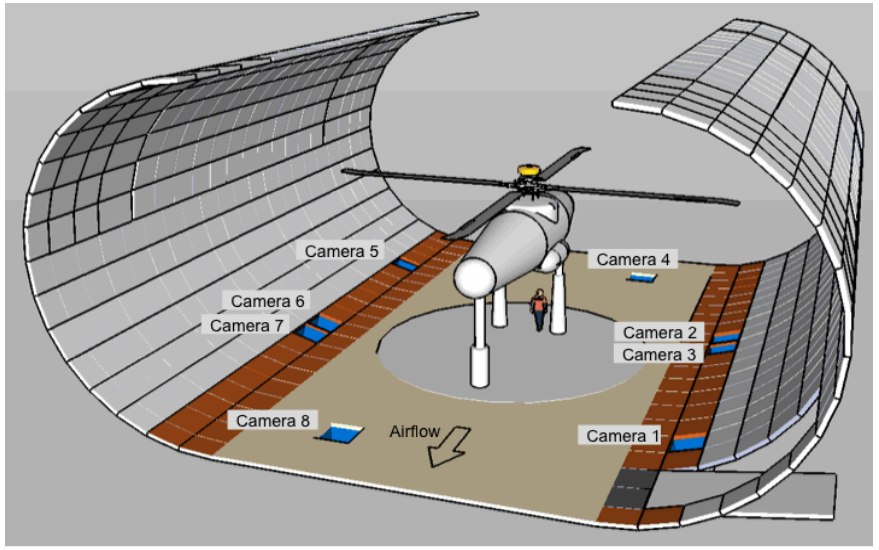
Outline

- Blade Displacement Measurements
- Data Reduction and Validation
- Future Considerations
- Closing Remarks

Blade Displacement Measurements

Setup/Hardware

- 8-cameras, 2 per rotor quadrant
- 4-Mega-pixel, 12-bit CCD progressive scan digital cameras, with a pixel resolution of 2048 × 2048 pixels
- Nikon 10.5 mm f/2.8 DX (fish-eye) lenses
- Xenon flash-lamp 50 mJ strobes

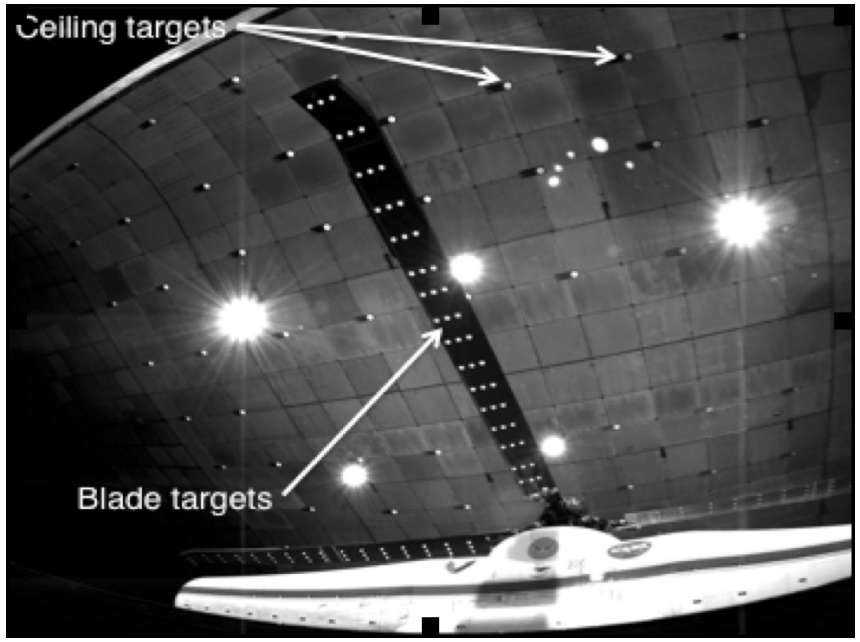


Blades

- Targets on the lower surface of each blade
- 48 retro-reflective targets, 2 inch dia.
- 3 per radial station at r/R from 0.2 to 0.97

Ceiling

- 84 retro-reflective targets, 6 inch dia.
- 84 coded targets



Blade Displacement Measurements

Primary data conditions

- 27 primary data conditions
- Includes cases with all Airloads data types
- Matched conditions with PIV and RBOS data
- Most images have been processed
- Centroid inspections continue

Secondary data conditions

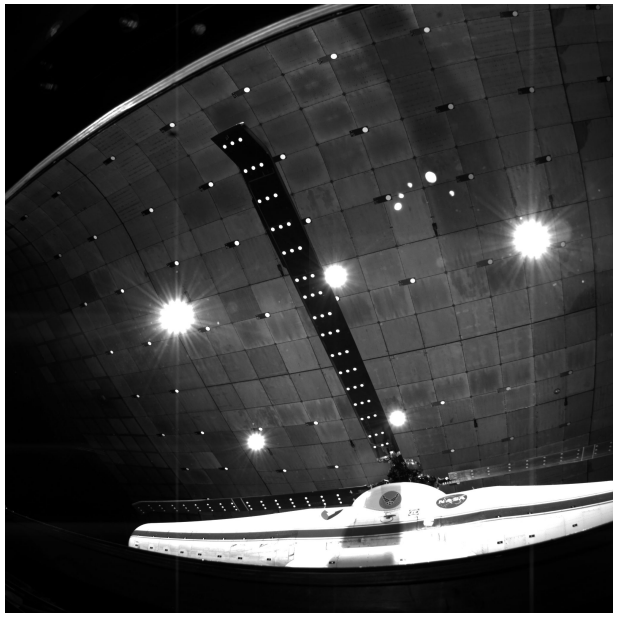
- Most Airloads data points
- Image processing is underway

	Primary	Secondary
Blades per quadrant	4	1
Azimuth positions	40	11
Images per camera	60	12
Total acquisition time	10 min	1 min

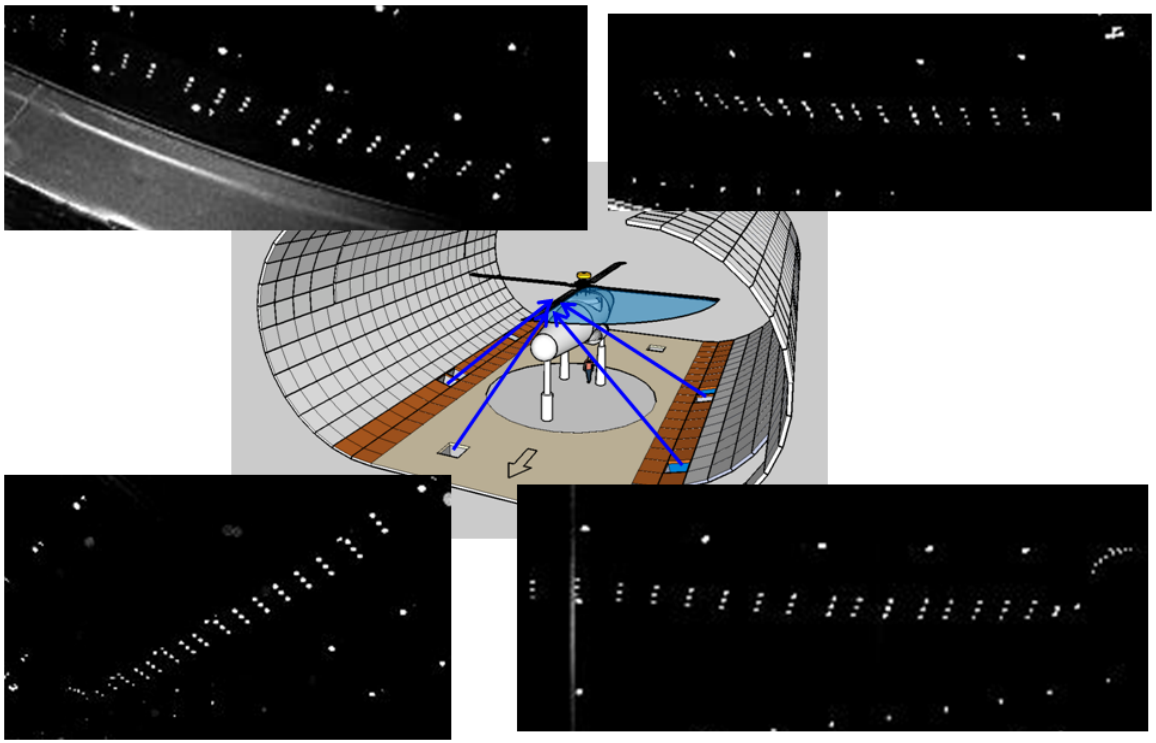
Data Reduction and Validation

Camera Intersection Example

Synchronously Captured Images for Cameras 1, 2, 7, 8
Blade 1, $\psi = 0°$



Long-exposure (~10ms) view of quadrant-1 from BD data camera 2

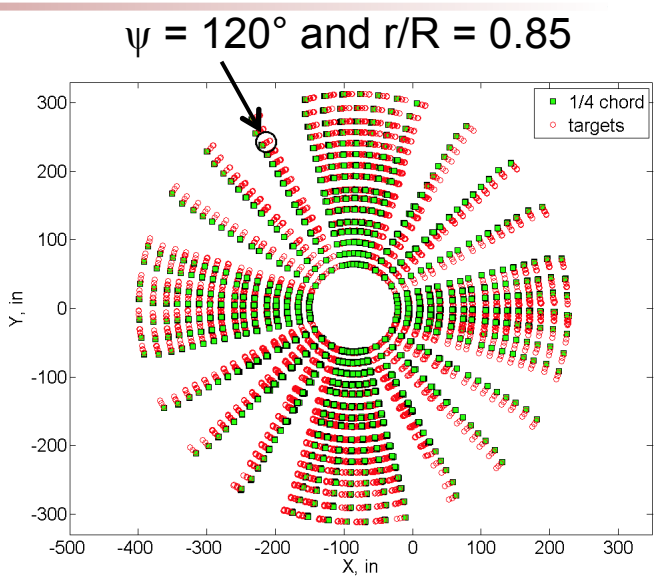


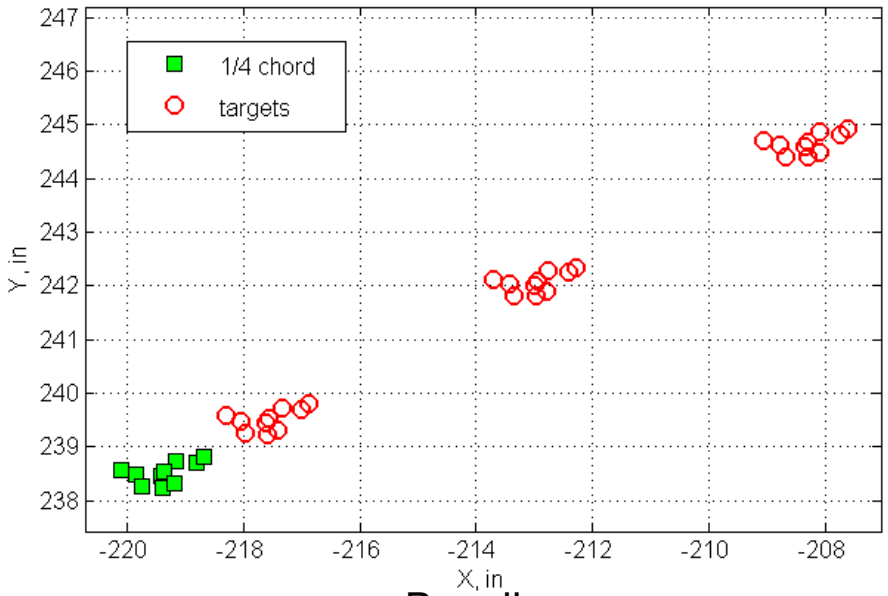
10 μ-sec data shot exposures

Data Reduction and Validation

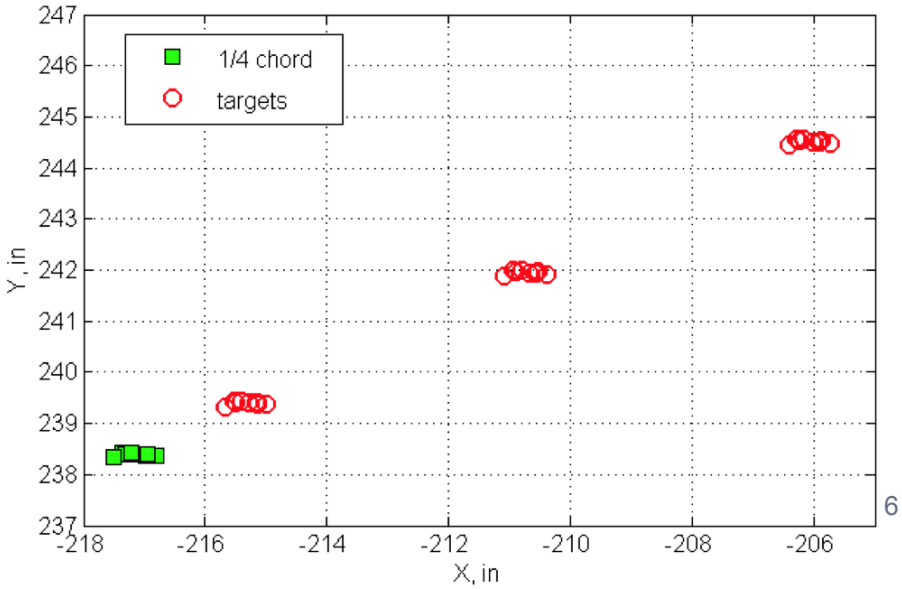
Camera Calibration Optimization

- Currently under investigation
- Static test data, 0° shaft angle, 40 azimuth positions and 3 images/azimuth
- Optimized the 3 camera position coordinates and 3 angles of each camera





Baseline



Optimized

Data Reduction and Validation – Uncertainty Considerations

Static Precision and Bias

- Static, wind-off measurements over 360°
- 0° shaft angle
- 40 azimuth positions,160 data points, 3 images each
- Mean of 160 determinations of the standard deviation at a single azimuth was used to compute precision
- Bias error was computed as the standard deviation of the 160 samples over 360° after removing the mean values of each blade

	r/R	Precision	Bias
Pitch		0.007°	0.267°
Flap		0.007°	0.372°
Lag		0.002°	0.366°
Z	0.20	0.002 in	0.432 in
	0.97	0.066 in	1.429 in
Elastic Z	0.20	0.002 in	0.098 in
	0.97	0.038 in	1.122 in
Elastic Twist	0.20	0.012°	0.200°
	0.97	0.025°	0.229°

Data Reduction and Validation – Uncertainty Considerations

Mean bias offset error

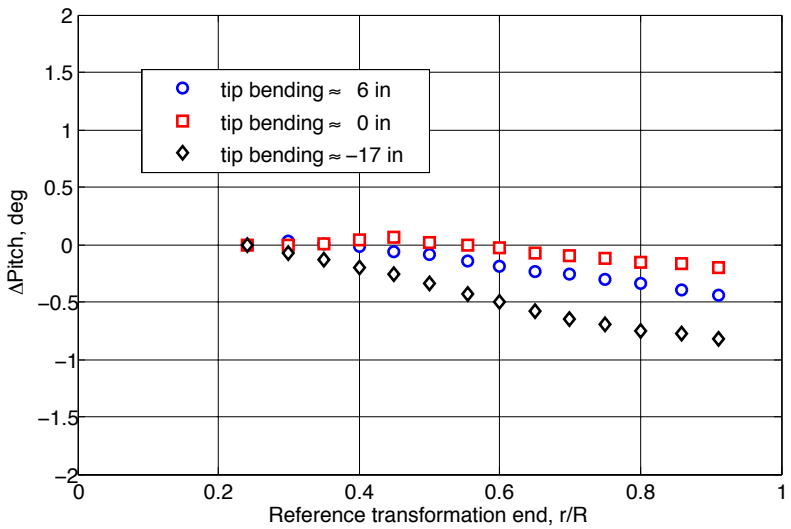
- Static, wind-off measurements over 360°
- 40 azimuth positions
- 160 data points, 3 images each
- 0° shaft angle
- Collective pitch set to 0°
- Lag angle and elastic twist are expected to be near 0°
- Mean offset from 0 can be viewed as a bias offset error.

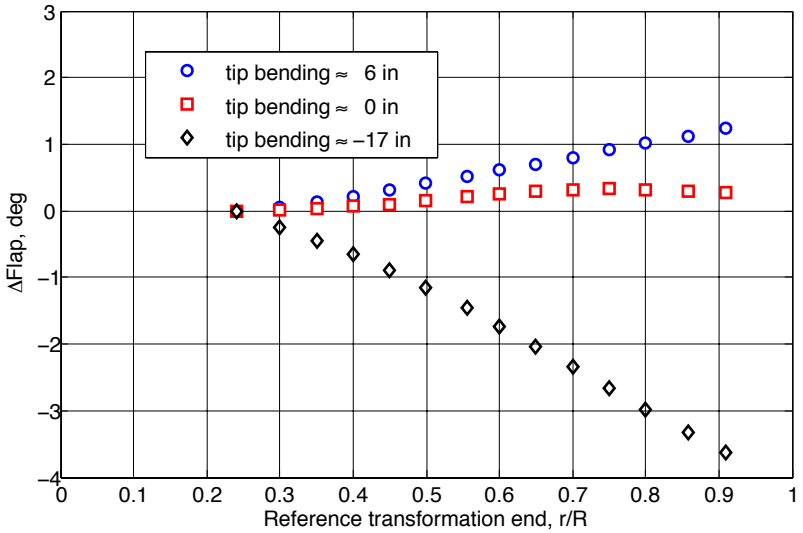
	r/R	Bias
Pitch	0.97	0.102°
Lag	0.97	2.253°
Elastic Twist	0.97	-0.023°

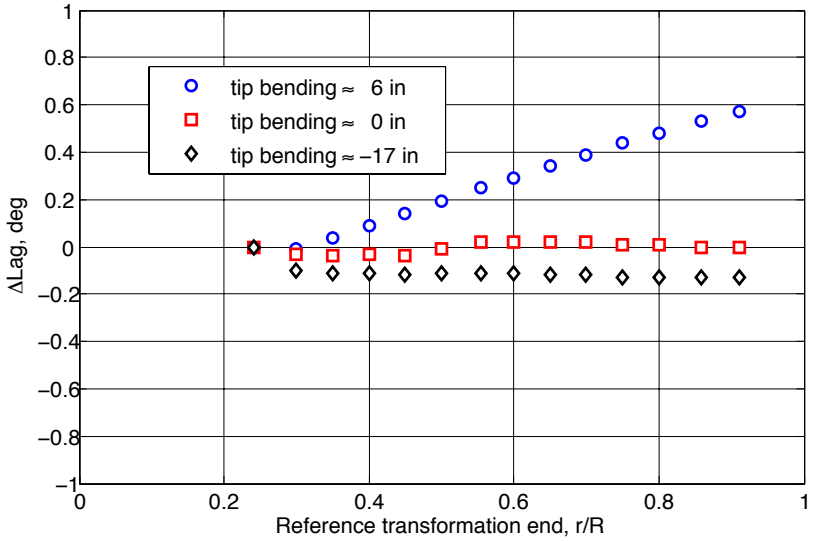
Data Reduction and Validation

Bias Error vs Reference Transformation End r/R

$\mu = 0.30$, $C_T/\sigma = 0.10$, $M_{tip} = 0.65$



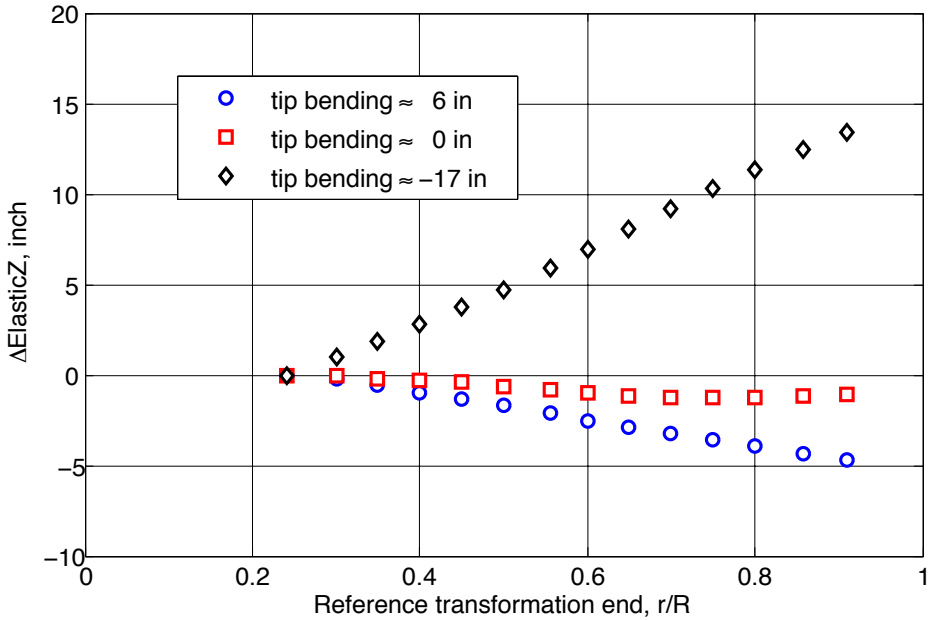


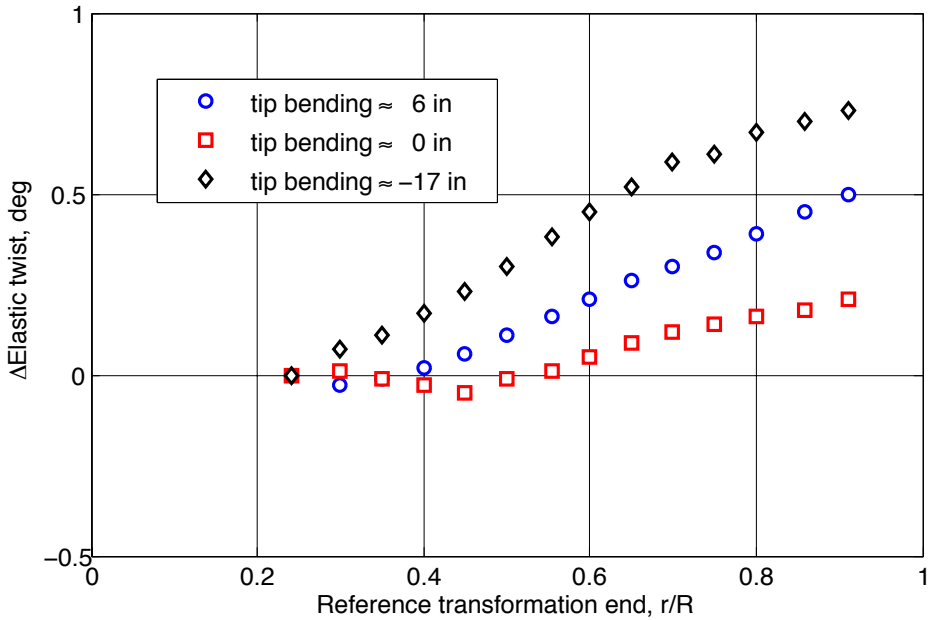


Data Reduction and Validation

Bias Error vs Reference Transformation End r/R

$\mu = 0.30$, $C_T/\sigma = 0.10$, $M_{tip} = 0.65$

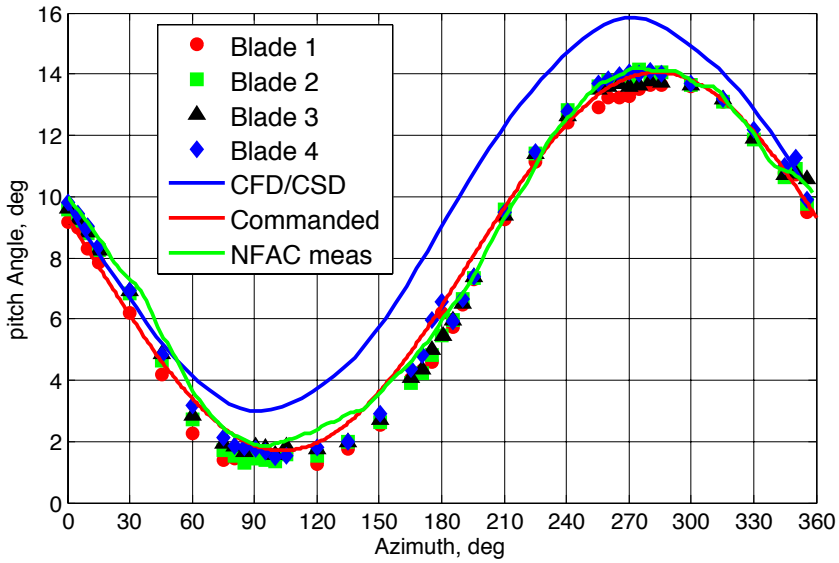


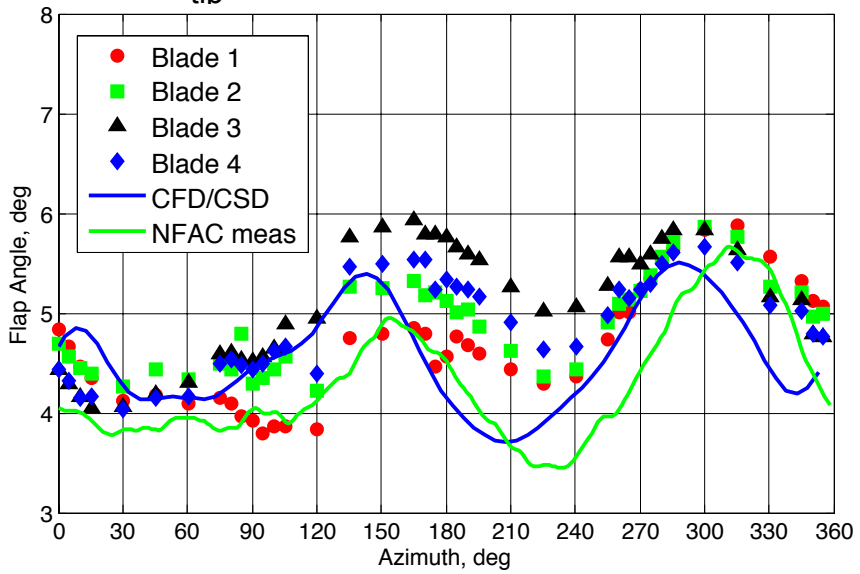


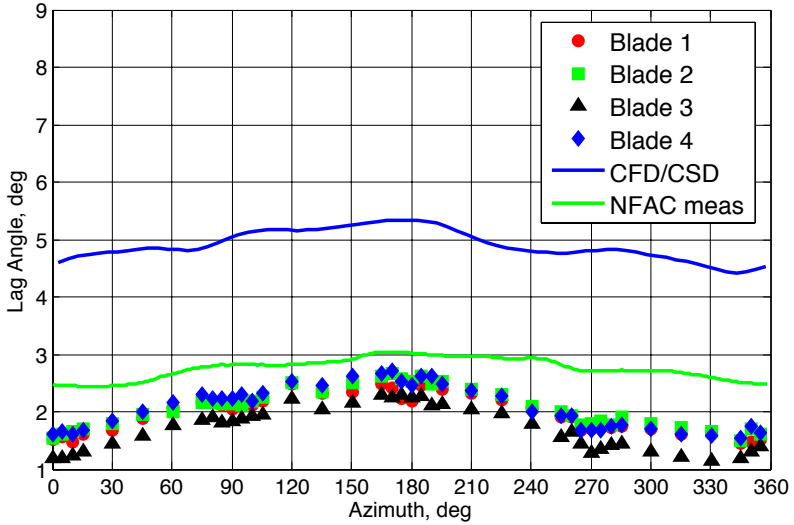
Data Reduction and Validation

Pitch, Flap and Lag with NFAC measured and CFD

$\mu = 0.30$, $C_T/\sigma = 0.10$, $M_{tip} = 0.65$



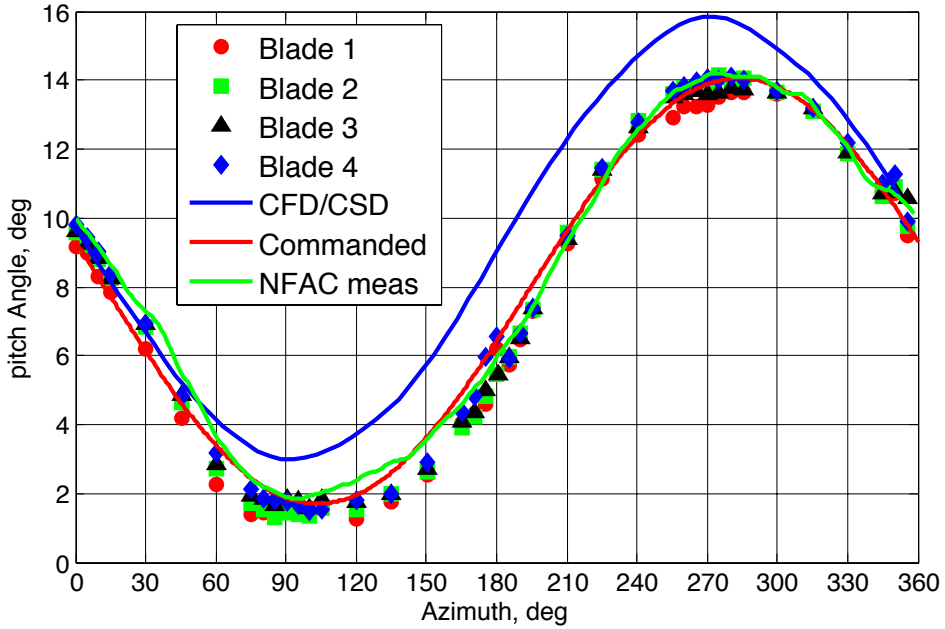




Data Reduction and Validation

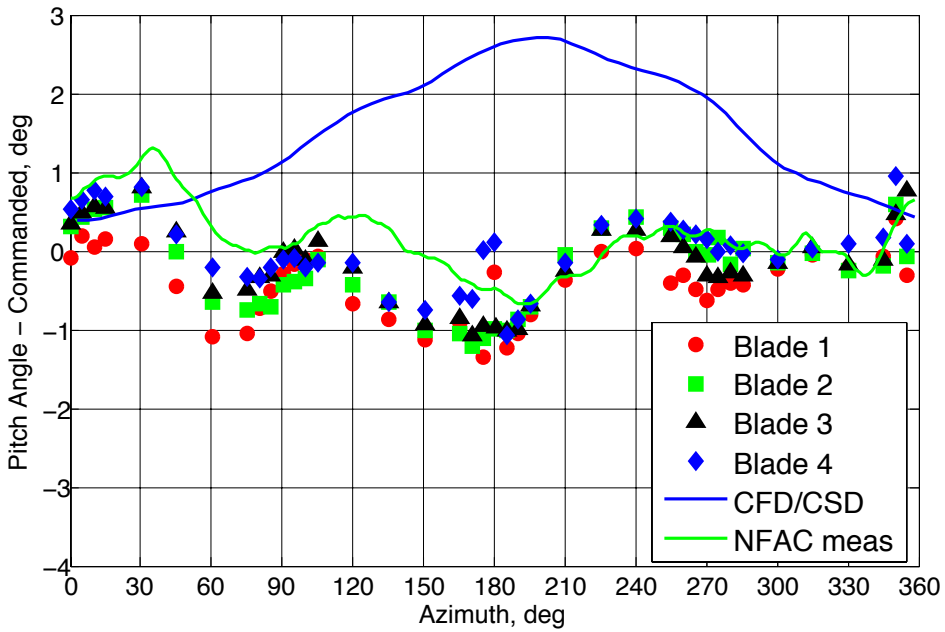
Pitch vs Azimuth

$\mu = 0.30$, $C_T/\sigma = 0.10$, $M_{tip} = 0.65$



Pitch − Commanded vs Azimuth

$\mu = 0.30$, $C_T/\sigma = 0.10$, $M_{tip} = 0.65$

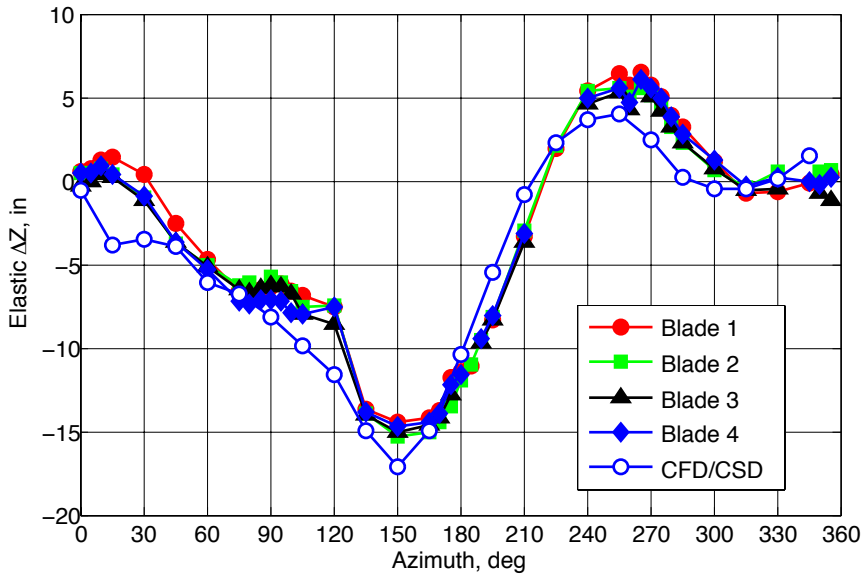


Data Reduction and Validation

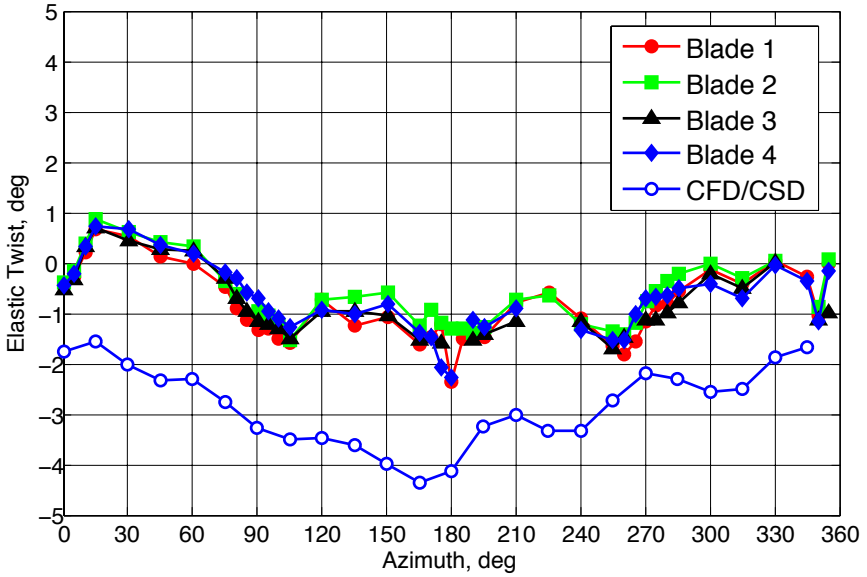
Elastic Bending and Elastic Twist with CFD

$\mu = 0.30$, $C_T/\sigma = 0.10$, $M_{tip} = 0.65$, r/R = 0.97

Elastic Bending



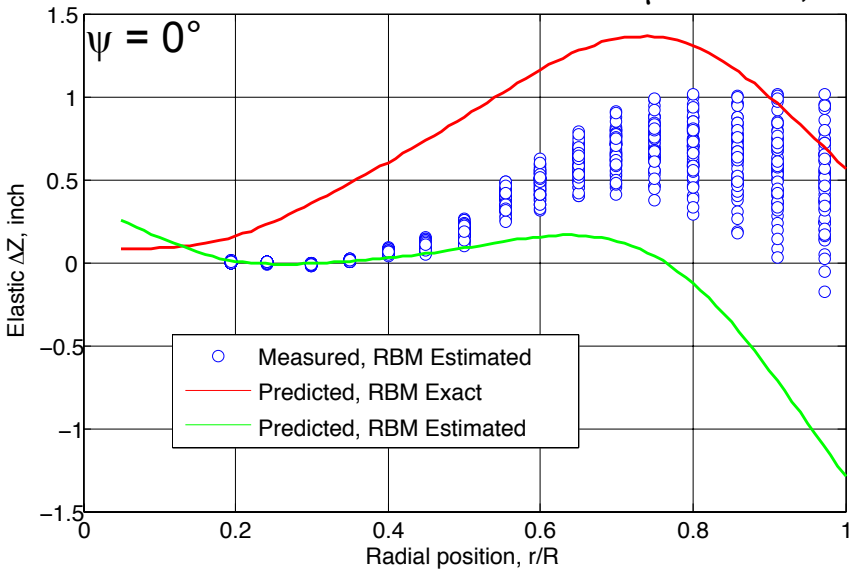
Elastic Twist

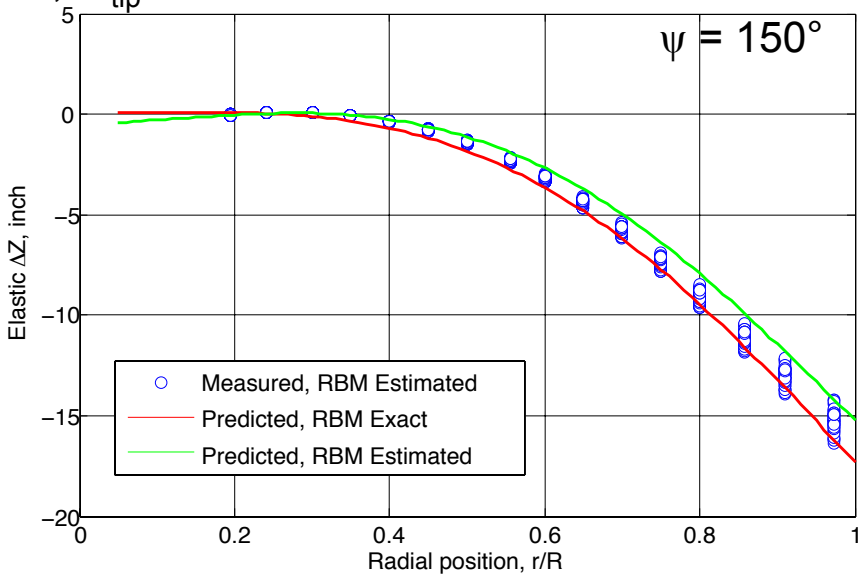


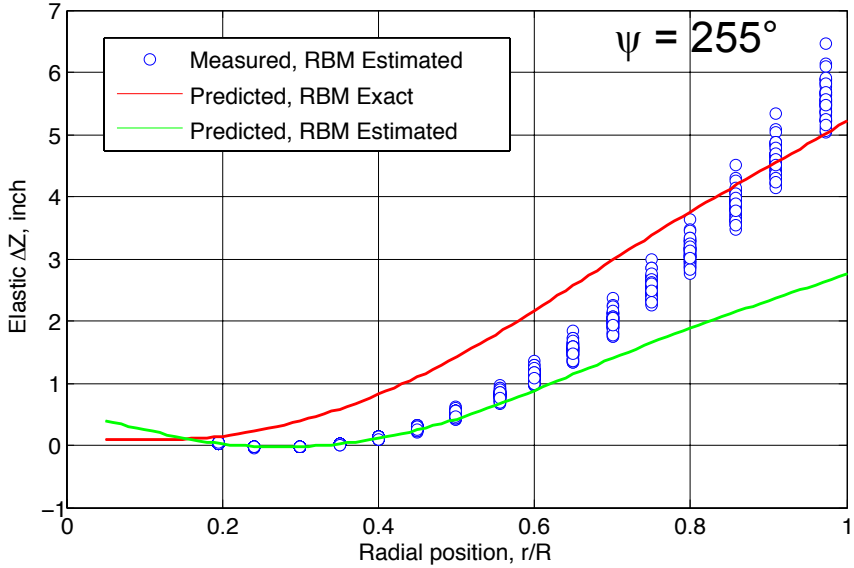
Data Reduction and Validation

Elastic Bending with CFD

$\mu = 0.30$, $C_T/\sigma = 0.10$, $M_{tip} = 0.65$



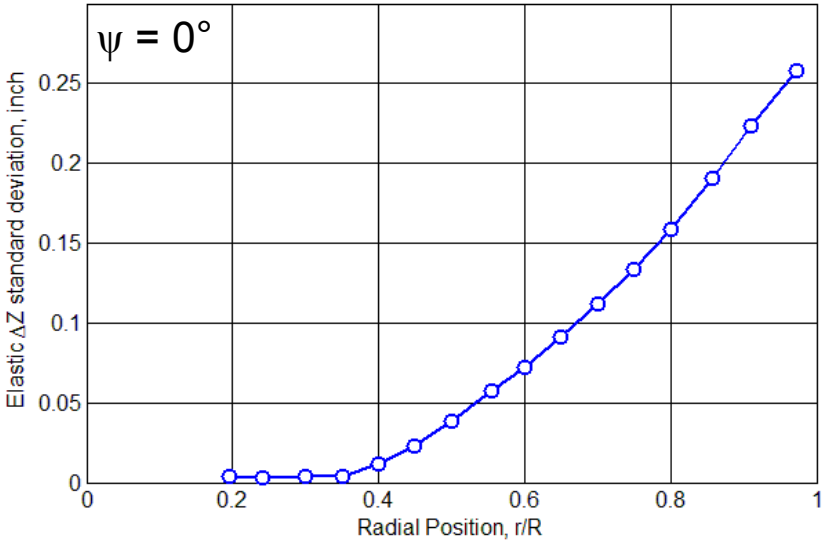


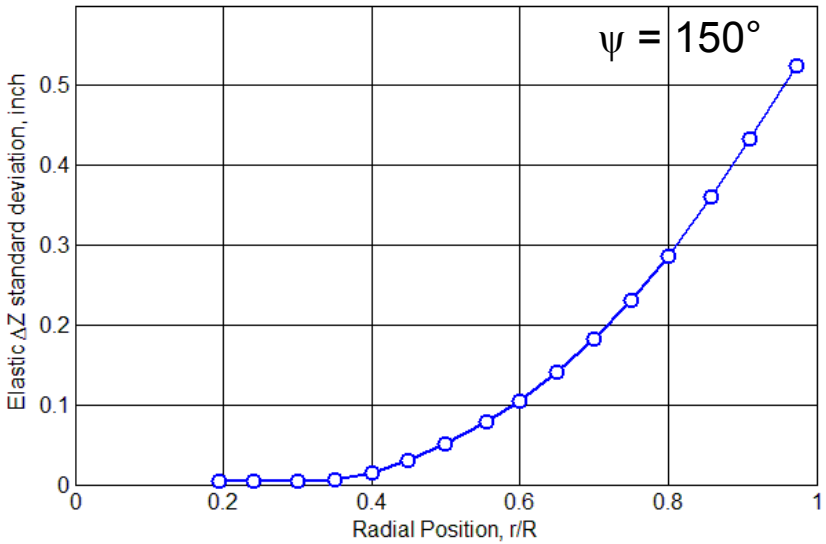


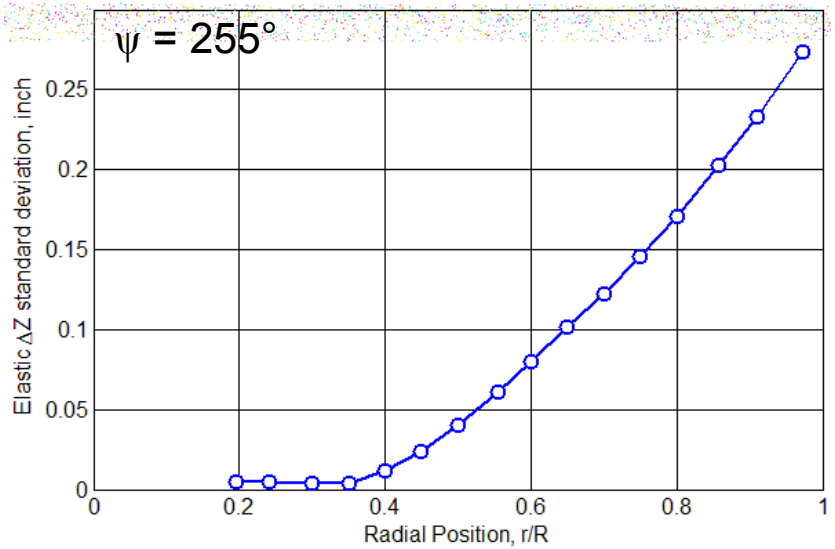
Data Reduction and Validation

Elastic ΔZ Standard Deviation vs r/R

$\mu = 0.30$, $C_T/\sigma = 0.10$, $M_{tip} = 0.65$



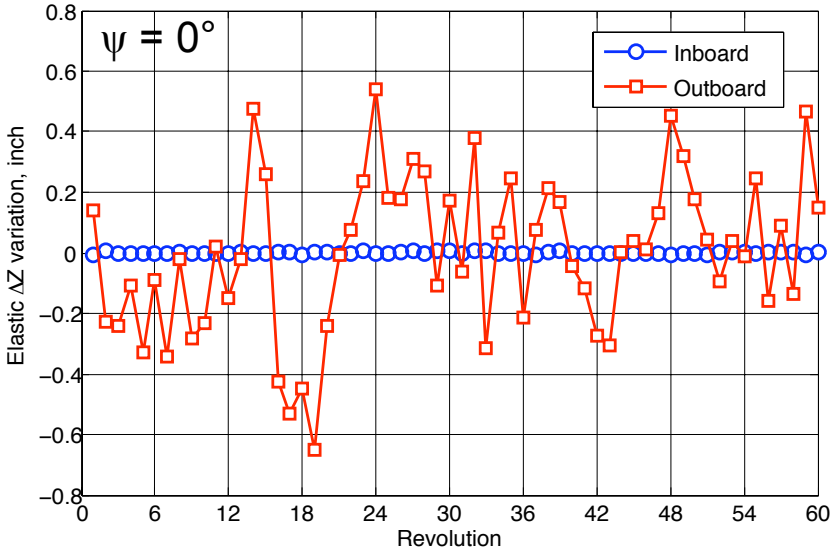


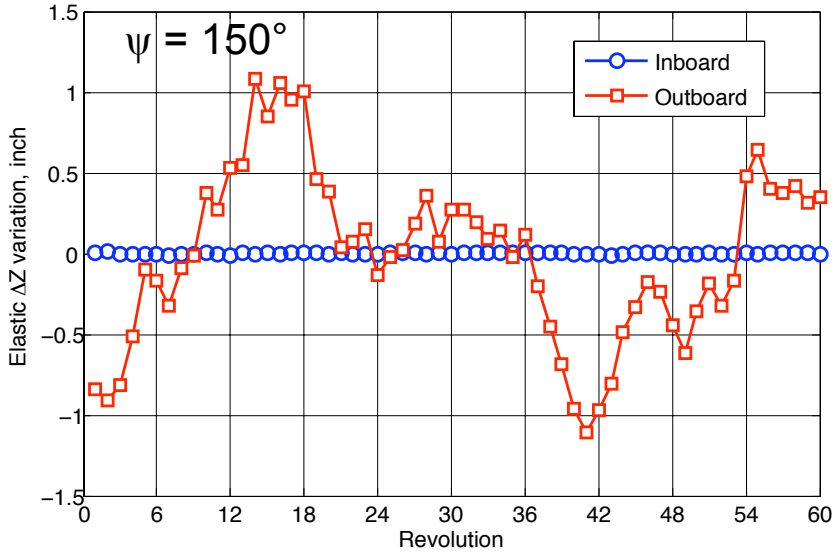


Data Reduction and Validation

Change in ¼-chord Elastic Bending vs Revolution

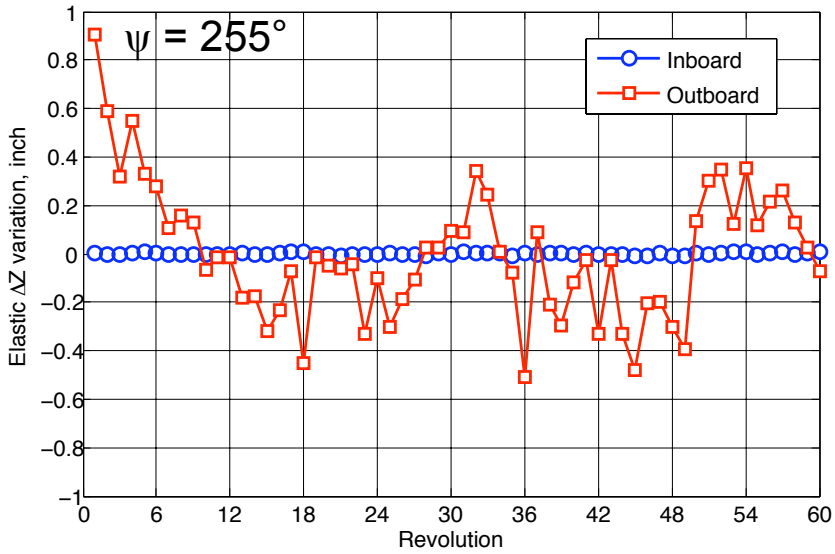
$\mu = 0.30$, $C_T/\sigma = 0.10$, $M_{tip} = 0.65$





r/R = 0.97

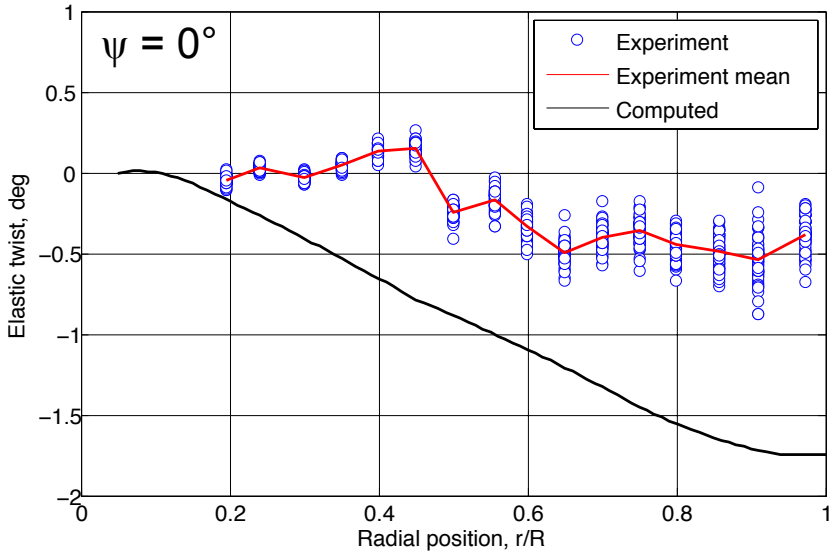
r/R = 0.20

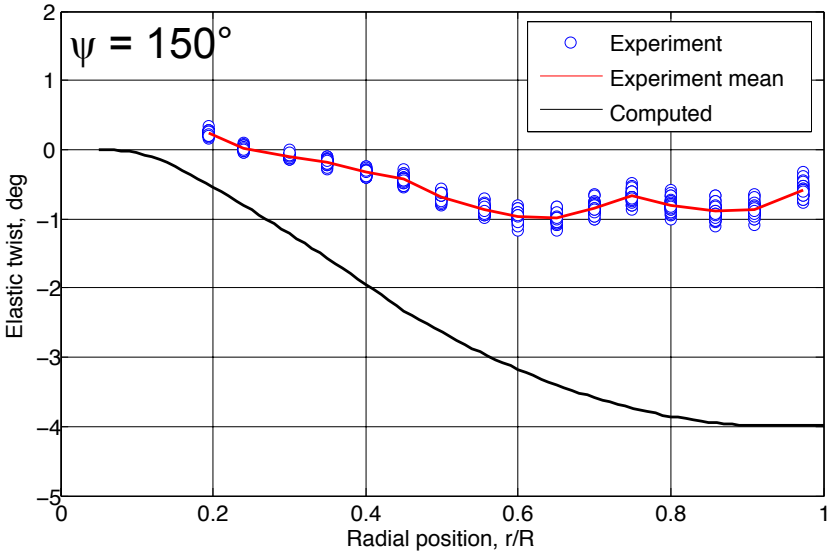


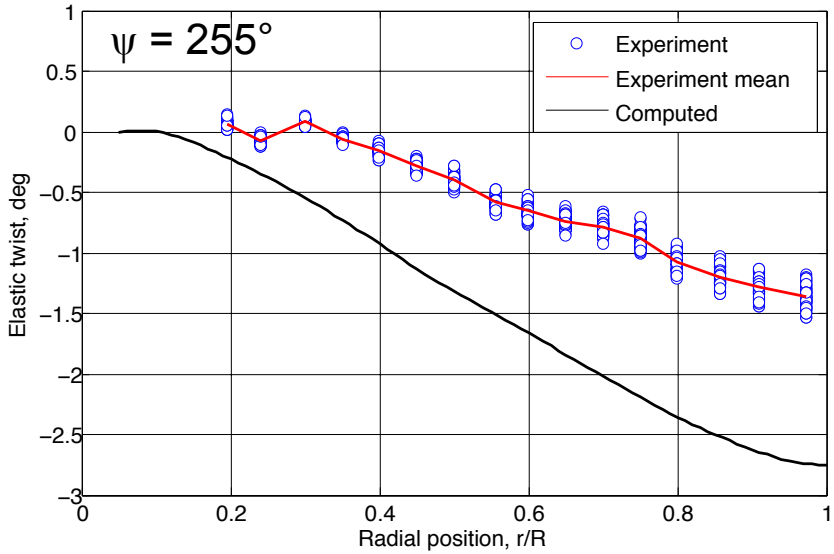
Data Reduction and Validation

Elastic twist with CFD

$\mu = 0.30$, $C_T/\sigma = 0.10$, $M_{tip} = 0.65$







Data Reduction and Validation

Elastic twist standard deviation vs r/R

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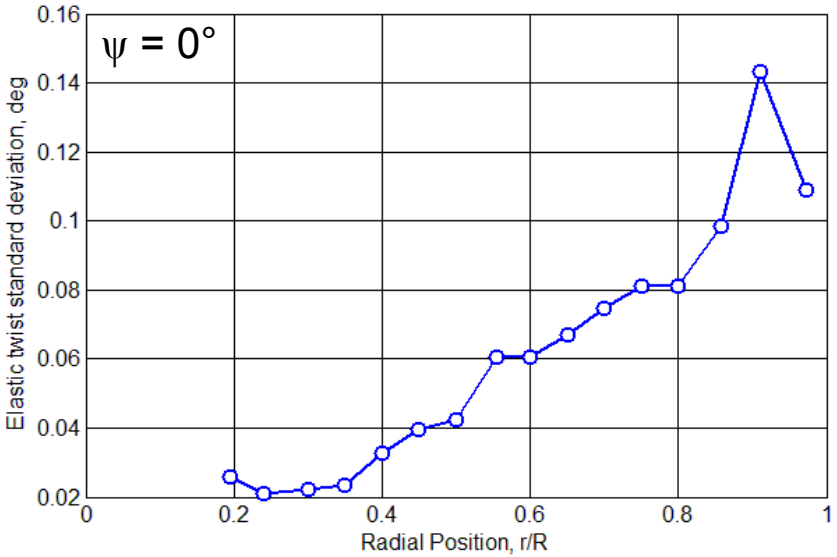
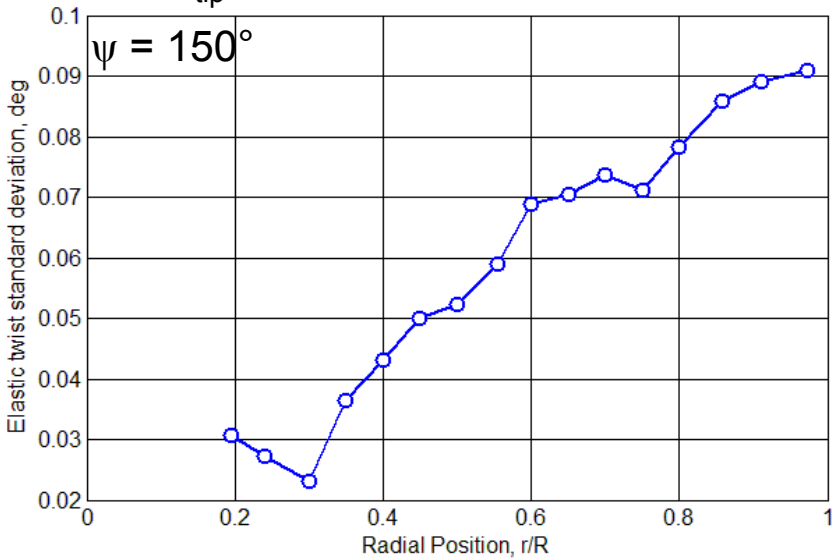
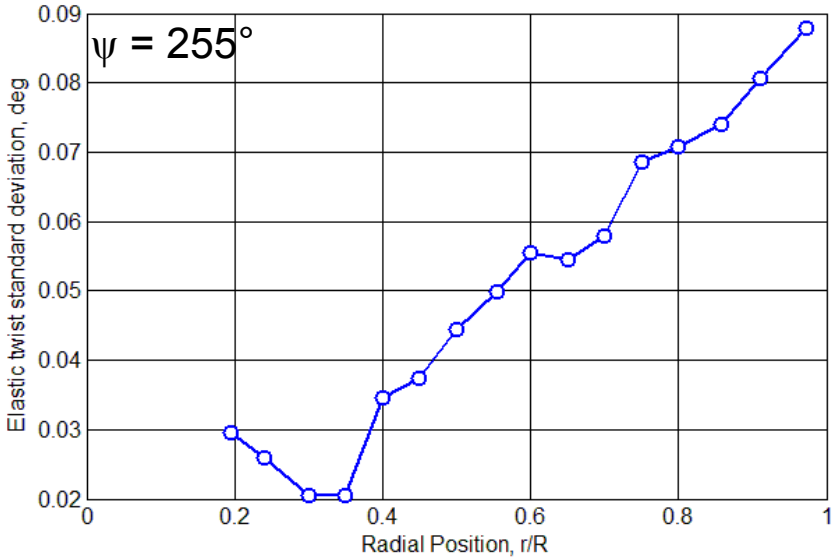


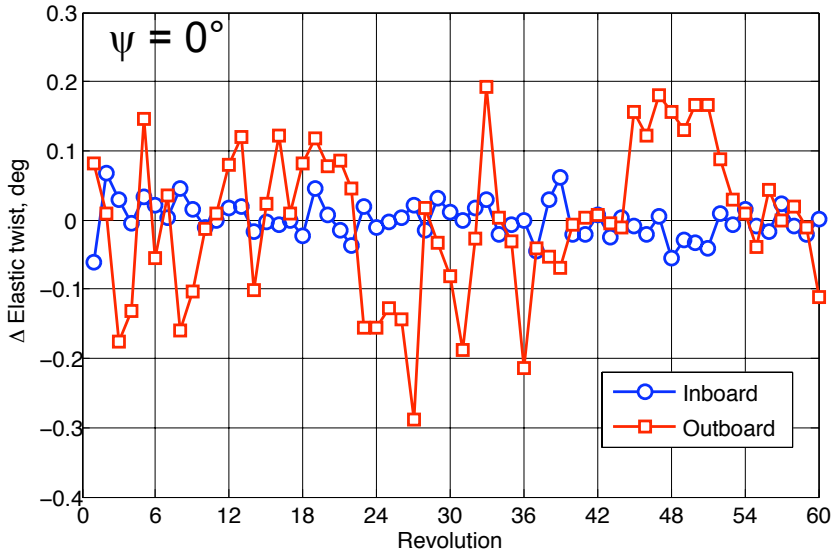


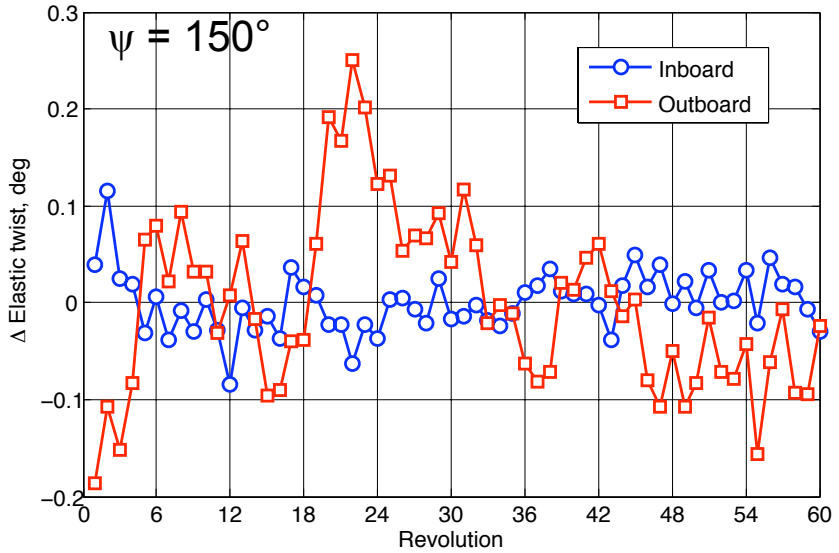


Data Reduction and Validation

Change in Elastic Twist vs Revolution

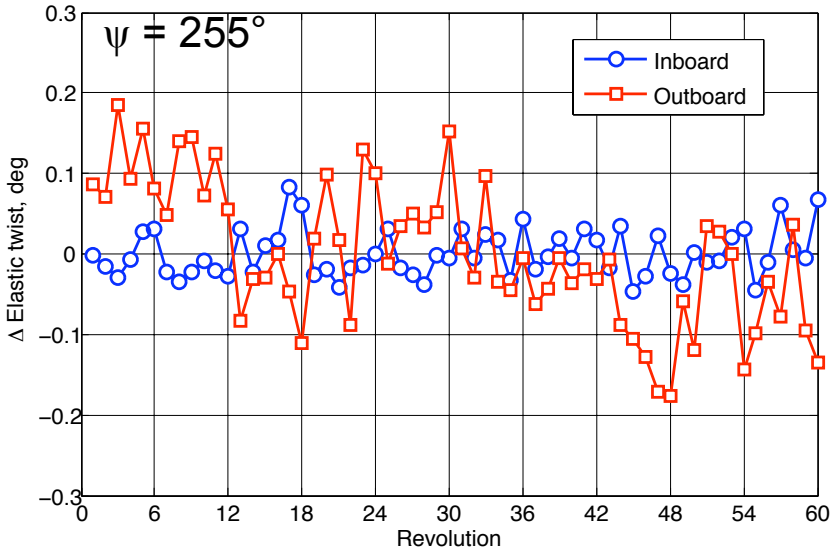
$\mu = 0.30$, $C_T/\sigma = 0.10$, $M_{tip} = 0.65$





r/R = 0.97

r/R = 0.20



Future Work

Data Processing

- Primary data point inspections
- Secondary data point processing
- Continue efforts to automate image processing and validation
- Data processing and validation improvements continue,
  - (1) optimization of camera calibrations
  - (2) alternate fish-eye corrections based on equisolid angle projection
  - (3) weighting of multiple intersection *XYZ* results by the variance to strengthen the final intersection results

Collaboration

- Comparisons with computational results will continue and assist with data validation
- Comparisons with PIV and RBOS data

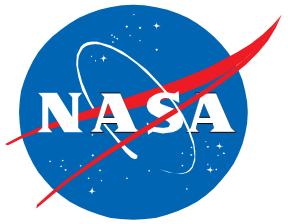
Closing Remarks

- The static precision of the photogrammetry technique for pitch, flap, lag, were found from a static azimuth sweep to be less than 0.01°.
- Bias errors over the full range of azimuth can approach 0.4°. (All values are presented in terms of one standard deviation.)
- An additional mean bias offset error of 2.25° was discovered for lag angle for the static sweep.
- The static precision for elastic bending and twist were found to be 0.002 inch and 0.012° respectively, with bias errors over the full range of azimuth of 1.2 inch and 0.30° respectively.
- Comparisons of experimental and computational results for a moderate advance ratio forward flight condition show good trend agreements, but show significant mean discrepancies for lag and elastic twist.
- The experimental values of pitch agree well with the NFAC DAS commanded pitch.

Closing Remarks

Preliminary results reported in the following publications,

- **Blade Displacement Measurements of the Full-Scale UH-60A Airloads Rotor**, American Institute of Aeronautics and Astronautics Applied Aerodynamics, June 2011.
- **Blade Displacement Measurement Technique Applied to a Full-Scale Rotor Test**, American Helicopter Society 68th Annual Forum, May 2012.


NASA