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SAND2015-0046C

Substructuring of the AmpAir 600 Wind Turbine 3-Bladed Assembly using the Transmission Simulator Method

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1/21/2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- Background
- Substructuring Overview
- Results
- Future Work

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Background

- Testing completed at Sandia National Laboratories in the Summer of 2014
- AmpAir wind turbine assembly has been frequently used for substructuring and joints research
- Several experiments and datasets are available at the substructuring wiki:

  substructure.engr.wisc.edu

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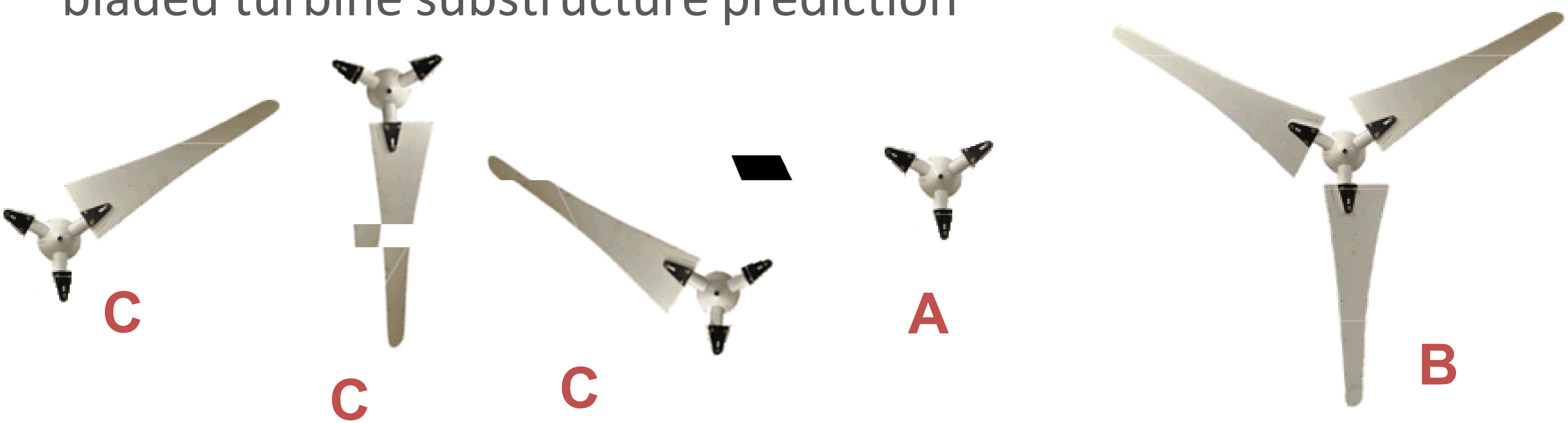
Substructuring Overview

- Modal testing completed on a single blade and hub assembly
- Hub rigid body mode shapes calculated using mass properties to act as a transmission simulator
- Three "single blade and hub" assemblies combined then two "transmission simulators" are removed to assemble a full three bladed turbine substructure prediction



C + C + C - A - A = B

Substructuring Methodology

Equations of Motion:

$$\begin{bmatrix} I_A & 0 & 0 & 0 \\ 0 & I_B & 0 & 0 \\ 0 & 0 & I_C & 0 \\ 0 & 0 & 0 & -2I_{TS} \end{bmatrix} \begin{Bmatrix} \ddot{q}_A \\ \ddot{q}_B \\ \ddot{q}_C \\ \ddot{q}_{TS} \end{Bmatrix} + \begin{bmatrix} 2\zeta_A\omega_A & 0 & 0 & 0 \\ 0 & 2\zeta_B\omega_B & 0 & 0 \\ 0 & 0 & 2\zeta_C\omega_C & 0 \\ 0 & 0 & 0 & -4\zeta_{TS}\omega_{TS} \end{bmatrix} \begin{Bmatrix} \dot{q}_A \\ \dot{q}_B \\ \dot{q}_C \\ \dot{q}_{TS} \end{Bmatrix} + \begin{bmatrix} \omega_A{}^2 & 0 & 0 & 0 \\ 0 & \omega_B{}^2 & 0 & 0 \\ 0 & 0 & \omega_C{}^2 & 0 \\ 0 & 0 & 0 & -2\omega_{TS}{}^2 \end{bmatrix} \begin{Bmatrix} q_A \\ q_B \\ q_C \\ q_{TS} \end{Bmatrix} = \begin{Bmatrix} \Phi_A^T F_A \\ \Phi_B^T F_B \\ \Phi_C^T F_C \\ 2\Phi_{TS}^T F_{TS} \end{Bmatrix}$$

Physical Constraints → Modal Coordinate Constraints

$$\begin{bmatrix} I & 0 & 0 & -I \\ 0 & I & 0 & -I \\ 0 & 0 & I & -I \end{bmatrix} \begin{Bmatrix} x_A \\ x_B \\ x_C \\ x_{TS} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \rightarrow \begin{bmatrix} \Phi_A & 0 & 0 & -\Phi_{TS} \\ 0 & \Phi_B & 0 & -\Phi_{TS} \\ 0 & 0 & \Phi_C & -\Phi_{TS} \end{bmatrix} \begin{Bmatrix} q_A \\ q_B \\ q_C \\ q_{TS} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

Premultiply by Psuedo-Inverse

$$\begin{bmatrix} \Phi_{TS}^+ & 0 & 0 \\ 0 & \Phi_{TS}^+ & 0 \\ 0 & 0 & \Phi_{TS}^+ \end{bmatrix} \begin{bmatrix} \Phi_A & 0 & 0 & -\Phi_{TS} \\ 0 & \Phi_B & 0 & -\Phi_{TS} \\ 0 & 0 & \Phi_C & -\Phi_{TS} \end{bmatrix} \begin{Bmatrix} q_A \\ q_{Bc} \\ q_C \\ q_{TS} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

Then follow standard component-mode-synthesis procedure using a transformation matrix to synthesized the system.

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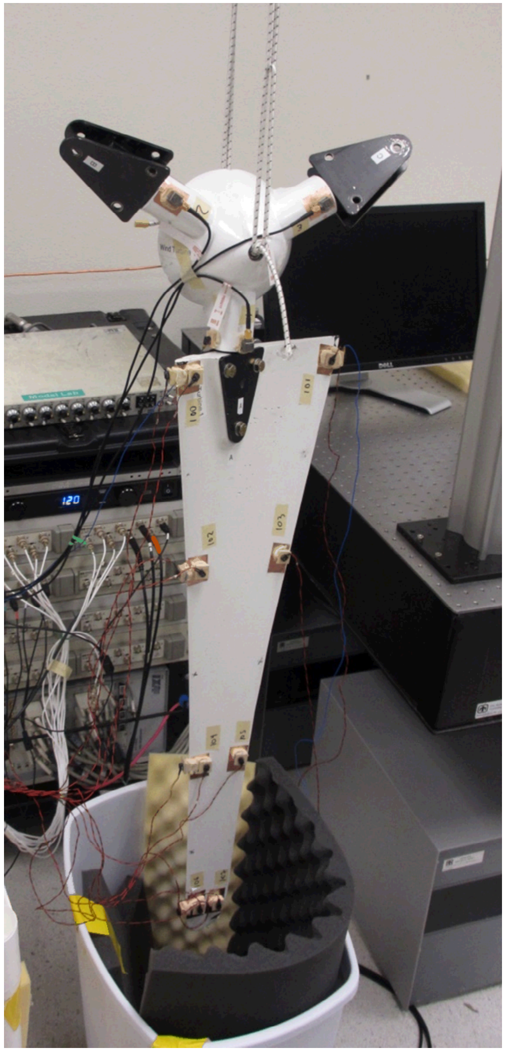
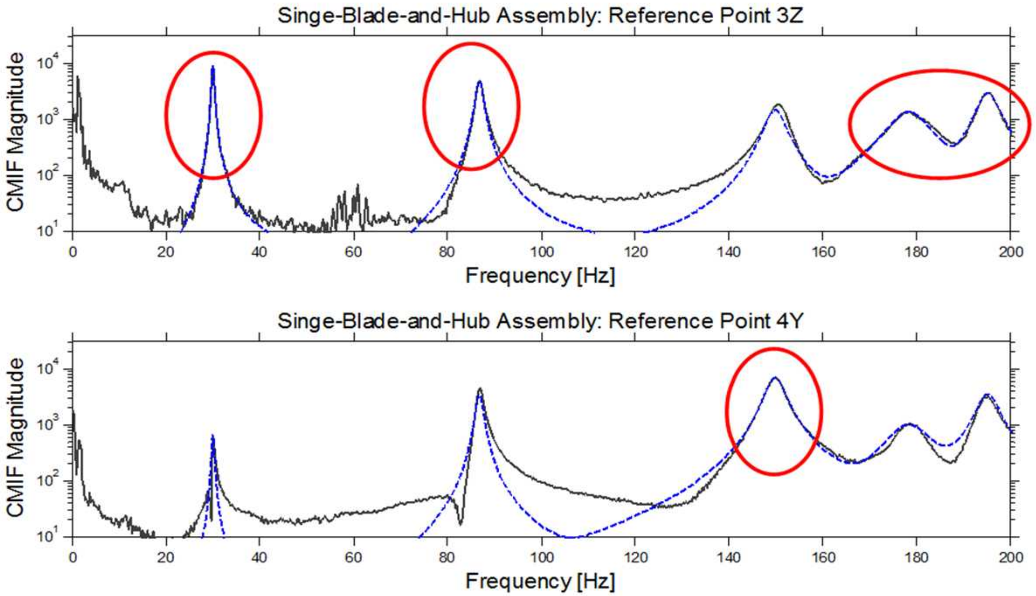
Subsystem Test (C)



- Modal test completed on subsystem (C)
- Drive points located on the hub in turbine axial and tangential directions.
- Modes considered up to 200 Hertz including 3 bending modes as well as first torsional and in plane motion



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Subsystem Test (C)

Mode*	Frequency [Hz]	Damping Ratio %	Description	Drive Direction
7	29.84	0.91%	1st Bending	Axial
8	86.75	0.92%	2nd Bending	Axial
9	149.82	1.51%	In-Plane Motion	Axial
10	178.25	2.62%	1st Torsion	Tangential
11	195.10	1.30%	3rd Bending	Axial

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*Rigid Body Modes not shown

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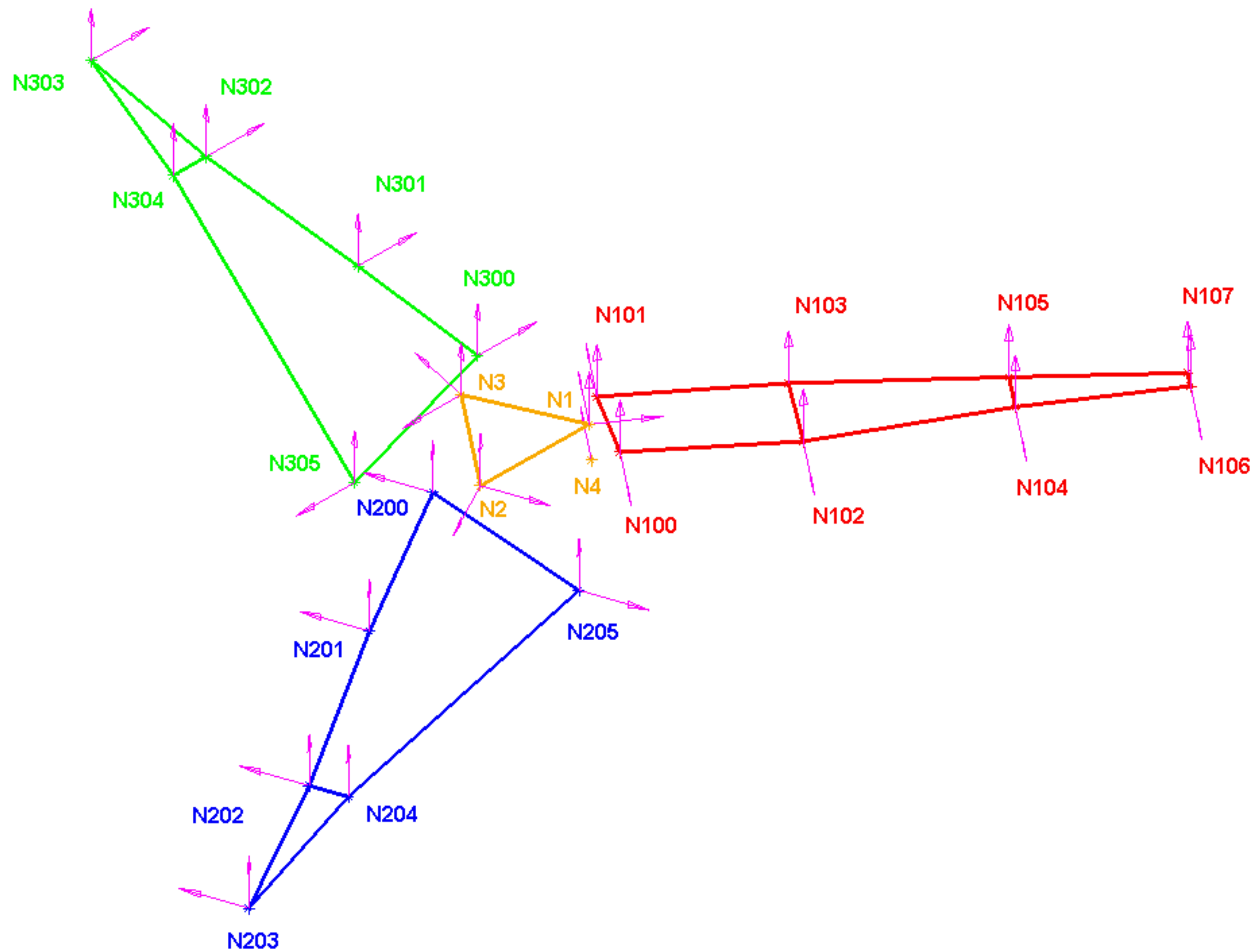
Three Blade Model



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Substructuring Predictions

Mode*	Truth Frequency [Hz]	Substr. Frequency [Hz]	Frequency Error	Truth Damping Ratio %	Substr. Damping Ratio %	Damping Ratio Error
7	20.56	23.49	14.26%	1.00%	0.73%	-27.19%
8	27.78	28.03	2.00%	0.98%	0.86%	-12.07%
9	29.03	28.33	-3.44%	0.87%	0.85%	-1.88%
10	61.10	66.53	8.91%	1.71%	0.71%	-58.31%
11	64.29	66.67	3.72%	1.27%	0.71%	-44.03%
12	70.68	77.33	9.41%	1.11%	0.84%	-23.71%
13	99.40	96.30	-1.75%	1.48%	1.00%	-32.17%
14	102.95	97.66	-6.45%	1.08%	0.99%	-8.82%
15	155.00	167.26	7.91%	1.33%	1.29%	-3.05%

*Rigid Body Modes not shown

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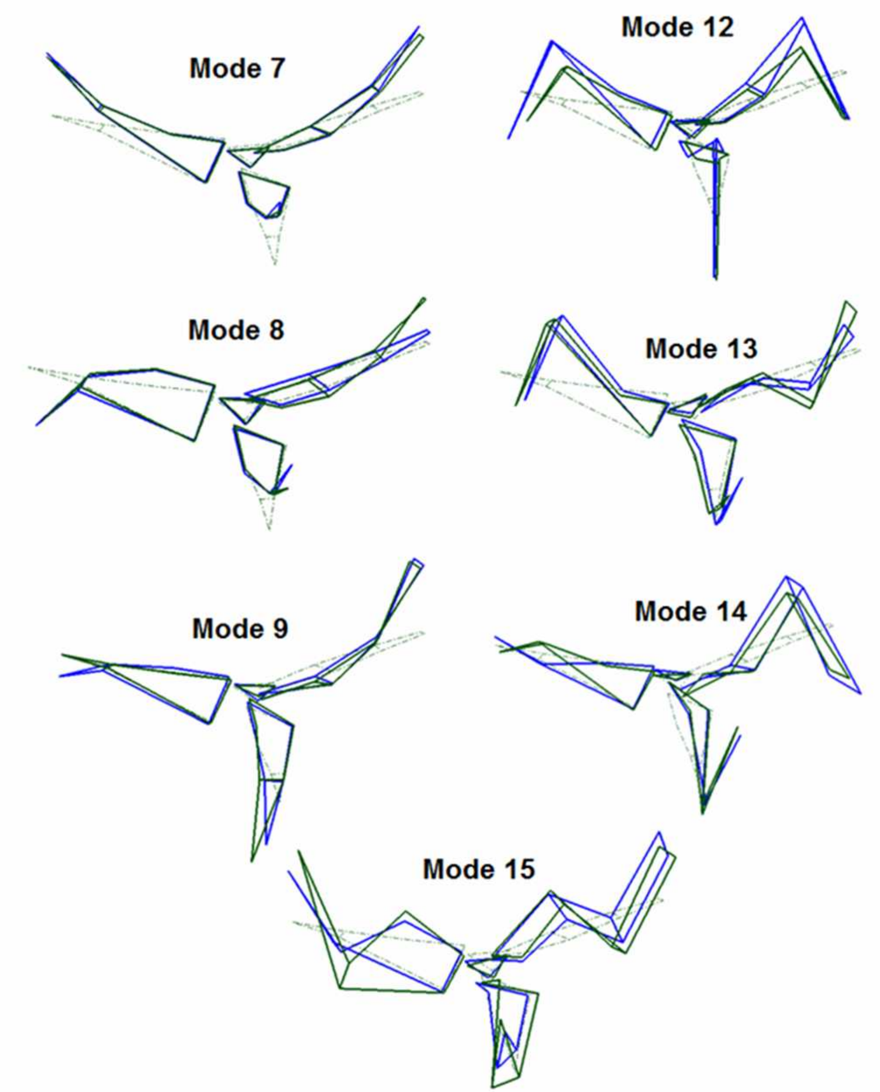
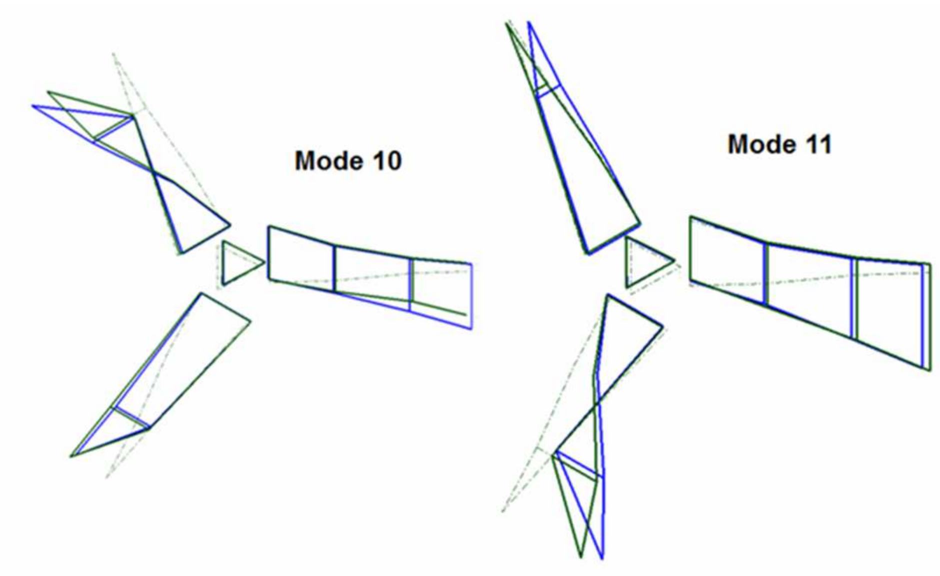
Mode Shape Comparison



Mode	MAC
7	.9912
8	.7655
9	.8808
10	.9422
11	.9787
12	.9402
13	.8618
14	.8849
15	.7850

Mode Shape Comparison



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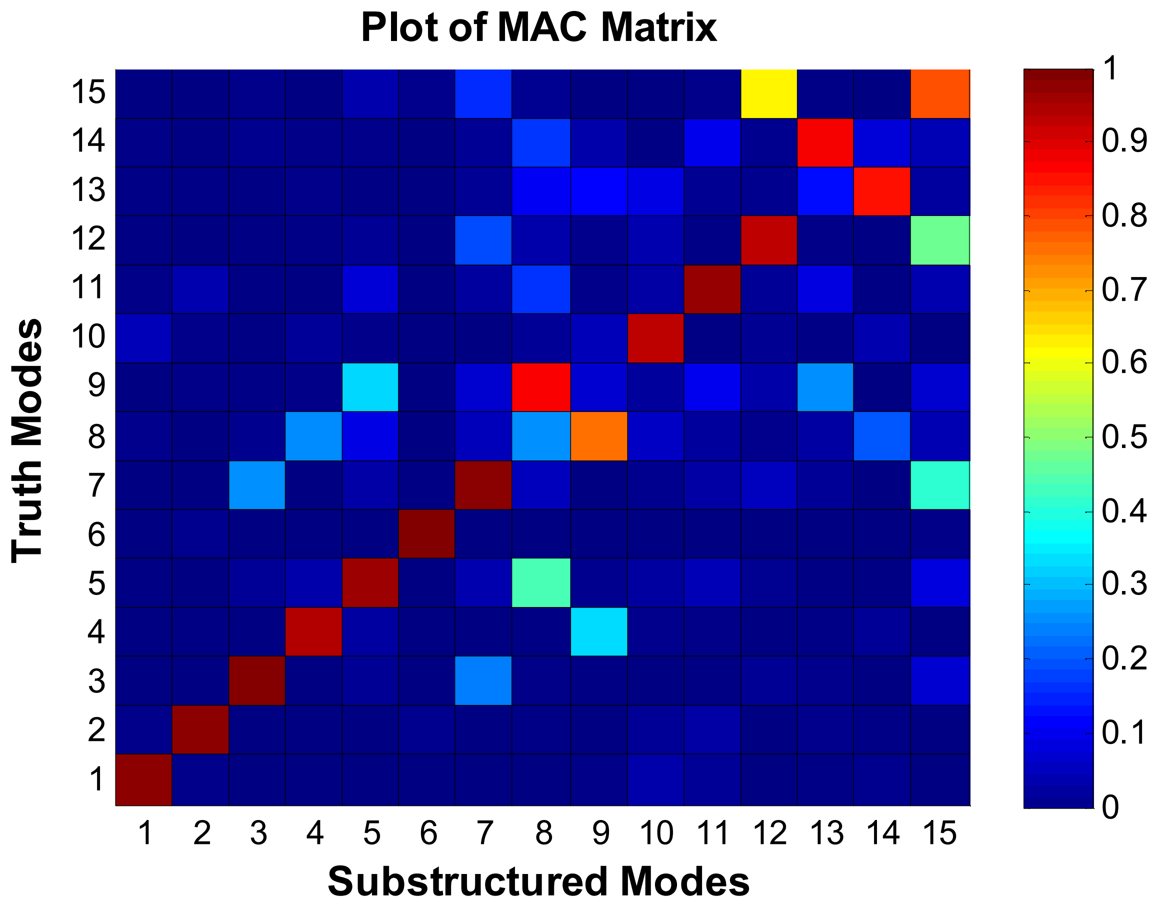
Modal Assurance Criteria



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Conclusions

- Modal testing completed on a single blade and hub assembly
- Results from this test as well as mass property derived rigid body modes were used to synthesis these results into a three bladed assembly with the hub acting as a transmission simulator
- A truth test was also completed in order to evaluate these substructuring predictions
- Frequency errors were seen as high as 15%. Damping ratio was much harder to predict with errors as high as 60%.
- Mode shapes were able to correlate well through MAC value and visual plotting with a minimum MAC value of .7850

Questions?

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