National Renewable Energy Laboratory
Innovation for Our Energy Future

Overview of MBC3 (Multiblade Coordinate Transformation Utility for 3-Bladed Turbines)

TurbSim & Design Codes Workshop

September 22 – 25, 2008

Gunjit Bir

Operated for the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy by Midwest Research Institute • Battelle

Background

- Dynamics of individual blades usually studied in rotating frames.
- The tower sees the combined effect off all blades, not the individual blades.
- Rotor also responds as a whole to excitations in a fixed frame (shaft motion, gusts, controls).
- Multi-blade Coordinate Transformation (MBC) helps us look at the cumulative blade dynamics expressed in a non-rotating (fixed) frame.
- MBC also known as Coleman transformation and Fourier Coordinate Transformation.

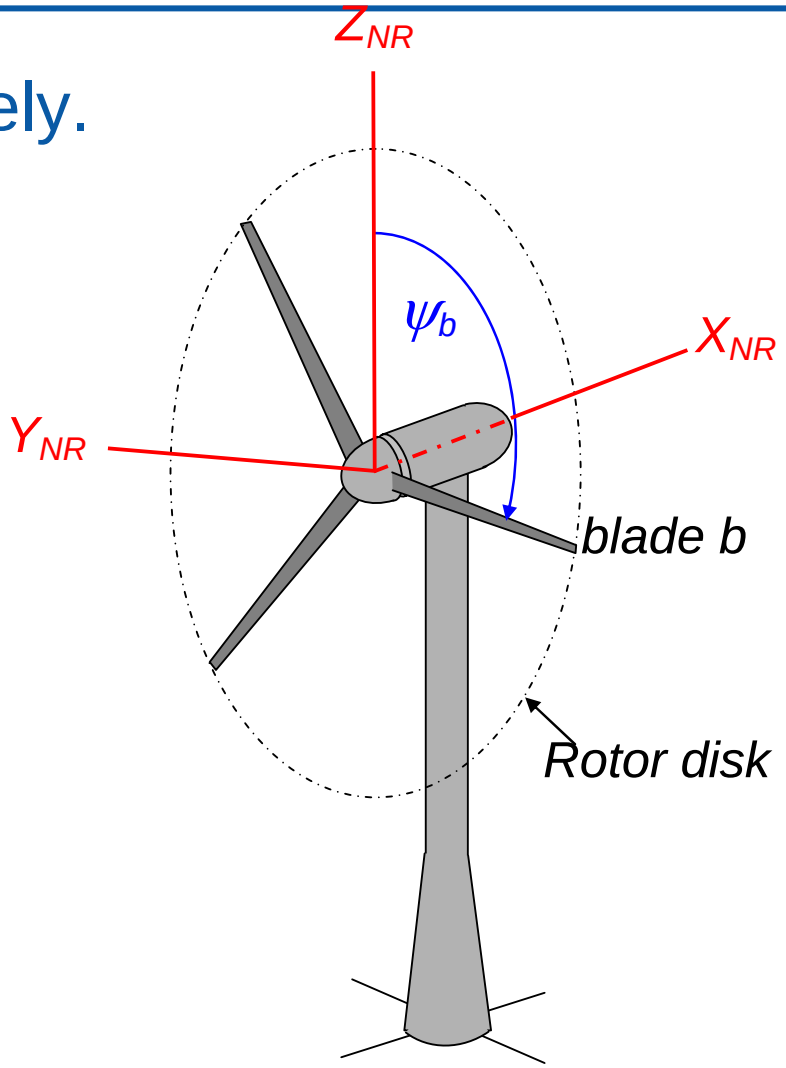
Concept of MBC

- Look at the blades collectively.
- Transform blade DOFs to rotor DOFs:

$$q_0 = \frac{1}{3}\sum_{b=1}^{3} q_b$$

$$q_c = q_{1c} = \frac{2}{3}\sum_{b=1}^{3} q_b \cos\psi_b$$

$$q_s = q_{1s} = \frac{2}{3}\sum_{b=1}^{3} q_b \sin\psi_b$$

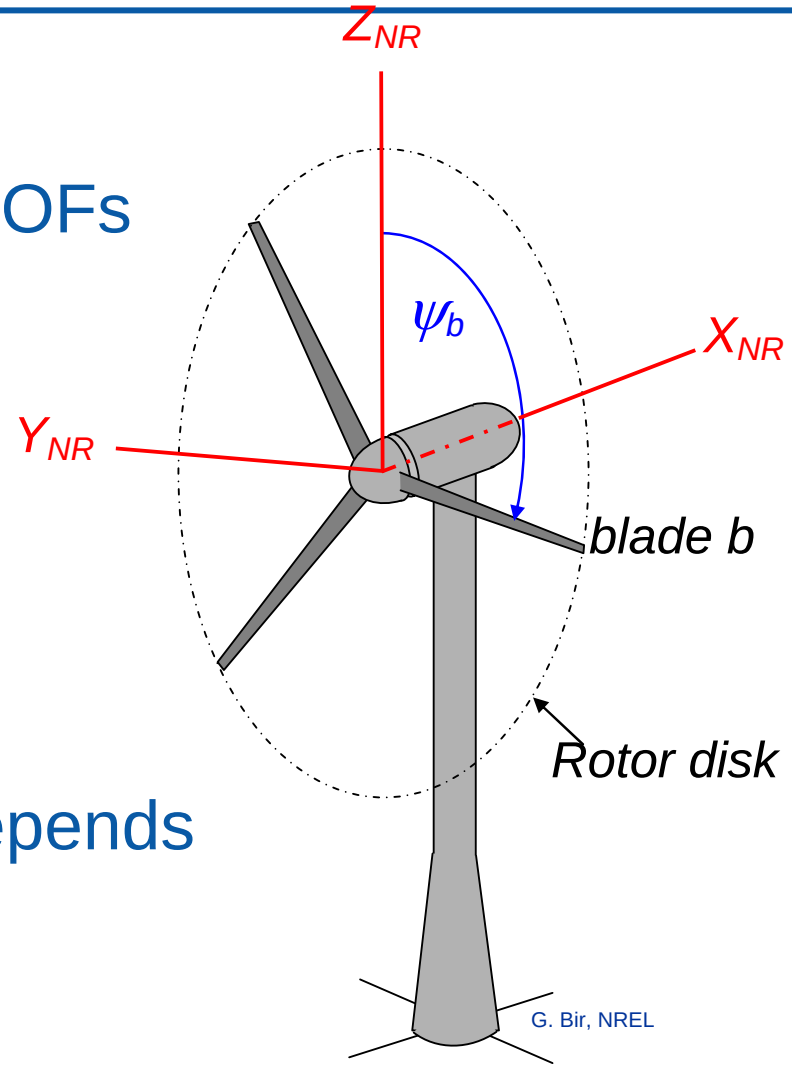


Concept of MBC (cont'd)

- q = a particular dof
- q_1, q_2, q_3 = the three blade DOFs
- q_0, q_c, q_s = rotor DOFs

q_0 = rotor collective dof
q_c = rotor cosine cyclic dof
q_s = rotor sine cyclic dof

- Interpretation of q_0, q_c, q_s depends on the dof q



G. Bir, NREL

Benefits of MBC

- Captures cumulative dynamics of blades
- Helps understand interactions of rotor and tower-nacelle subsystems
- Acts as a filter
- Well-conditions equations governing system dynamics
- Essential to stability analysis and controls design

Status

- Developed MBC scheme that transforms the full system equations (either in first or in the second-order form). The scheme covers
  - variable-speed turbines
  - dissimilar blades
  - controls, disturbances, and sensor outputs
- Demonstrated why MBC is essential to stability analysis. Presented sample result showing MBC-assisted stability analysis.

MBC of System Equations

- Two methods:
  - Operational method
  - Substitution method
- Operational method (assume 3 blades):

$$\frac{1}{3}\sum_{b=1}^{3}(rot_eqns)$$

$$\frac{2}{3}\sum_{b=1}^{3}(rot_eqns)\cos\psi_b$$

$$\frac{2}{3}\sum_{b=1}^{3}(rot_eqns)\sin\psi_b$$

Operational Method (cont'd)

- Uses the basic MBC transformation:
  blades DOFs → rotor DOFs
- Requires intensive trigonometric operations
- Applicable if system matrices are available in analytical form
- Filtering action of MBC brought out explicitly

Substitution Method

- Uses the inverse transformation:
  blades DOFs ← rotor DOFs

$$q_b = q_0 + q_c \cos\psi_b + q_s \sin\psi_b; \quad b = 1,2,3$$

- Applicable if system matrices are generated numerically (all aeroelastic codes do this)
- We use this method for both first- and second-order systems.

MBC of Second-Order System

$$M\ddot{X} + C\dot{X} + KX = Fu + F_d w$$
$$Y = C_v \dot{X} + C_d X + Du + D_d w$$

$$M_{NR}\ddot{X}_{NR} + C_{NR}\dot{X}_{NR} + K_{NR}X_{NR} = F_{NR}u_{NR} + F_{d\,NR}w$$
$$Y_{NR} = C_{v\,NR}\dot{X}_{NR} + C_{d\,NR}X_{NR} + D_{NR}u_{NR} + D_{d\,NR}w$$

- If turbine has 3 blades, all $(\ )_{NR}$ matrices contain only filtered terms (0/rev, 3/rev, 6/rev, …)

MBC of 2nd-Order System (cont'd)

- Relation between original and MBC-transformed matrices:

$$M_{NR} = MT_1$$

$$C_{NR} = 2\Omega MT_2 + CT_1$$

$$K_{NR} = \Omega^2 MT_3 + \dot{\Omega} MT_2 + \Omega CT_2 + KT_1$$

$$\vdots$$

$$C_{d\,NR} = T_{1o}^{-1}(\Omega C_v T_2 + C_d T_1)$$

$$D_{NR} = T_{1o}^{-1} D T_{1c}$$

$$D_{d\,NR} = T_{1o}^{-1} D_d$$

Variable-speed-dependent term

MBC of First-Order System

$$\dot{z} = Az + Bu + B_d w$$
$$Y = Cz + Du + D_d w$$

MBC

$$\dot{z}_{NR} = A_{NR} z_{NR} + B_{NR} u_{NR} + B_{d\,NR} w$$
$$Y_{NR} = C_{NR} z_{NR} + D_{NR} u_{NR} + D_{d\,NR} w$$

Misconceptions About MBC

- The rotor must spin at a constant speed.
- The rotor blades must have identical structural and aerodynamic properties.
- MBC transforms a time-variant system to a time-invariant one.
  Not true: MBC actually acts as a filter.

Specifications Heavily Influenced by the REpower 5M Turbine

Summary of Baseline Wind Turbine Properties

Rating	5 MW
Rotor Orientation	Upwind
Control	Variable Speed, Collective Pitch
Rotor Diameter, Hub Height	126 m, 90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 5°, 2.5°
Blade & Tower Structural Damping	1.0%

Parked (Idling) Condition

IEC Load Case 6.2a

Nacelle Yaw = 140^0

All blades feathered at 90 deg; V = 50 m/s

Analysis Steps:

- Perform trim → Ω = 0.0076 Hz
- Use FAST to obtain linearized matrices
  - Direct azimuth-averaging → eigenanalysis → stability results
  - MBC → azimuth-averaging → eigenanalysis → stability results

Parked (Idling) Turbine

IEC Design Load Case 6.2a

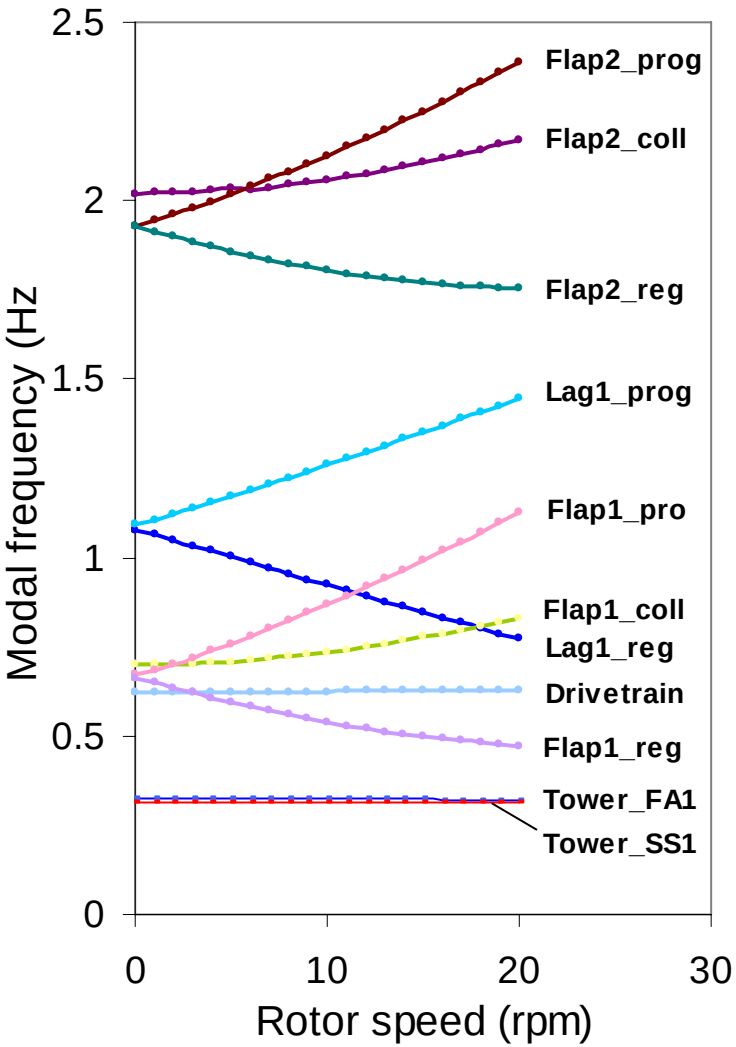
All blades feathered at 90 deg; V = 50 m/s

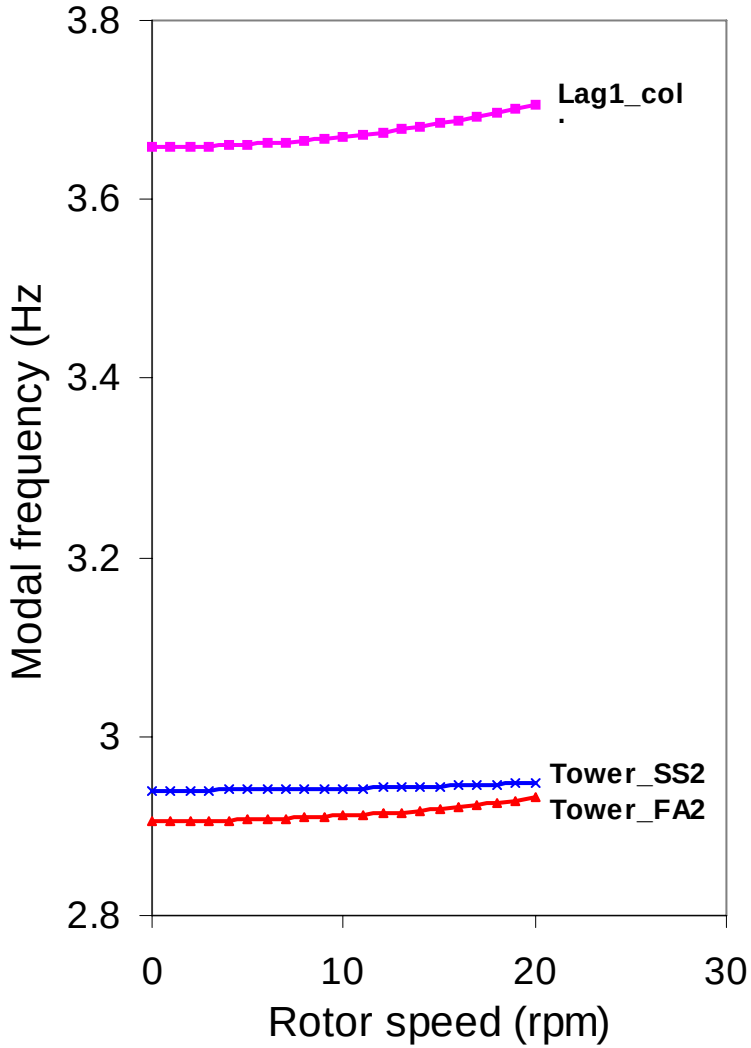
Mode	Damping ratio (%)	
	Without MBC	With MBC
1st Lag	0.18	**-1.48**
1st Flap	1.07	2.32
2nd Flap	2.28	1.71
Tower 1st Side-Side	**-1.93**	2.05
Tower 1st Fore-Aft	0.68	2.19
Tower 2nd Side-Side	3.84	2.02
Tower 2nd Fore-Aft	0.96	2.87

Modal Analysis

Modal analysis

Tower & rotor frequencies vs rotor speed



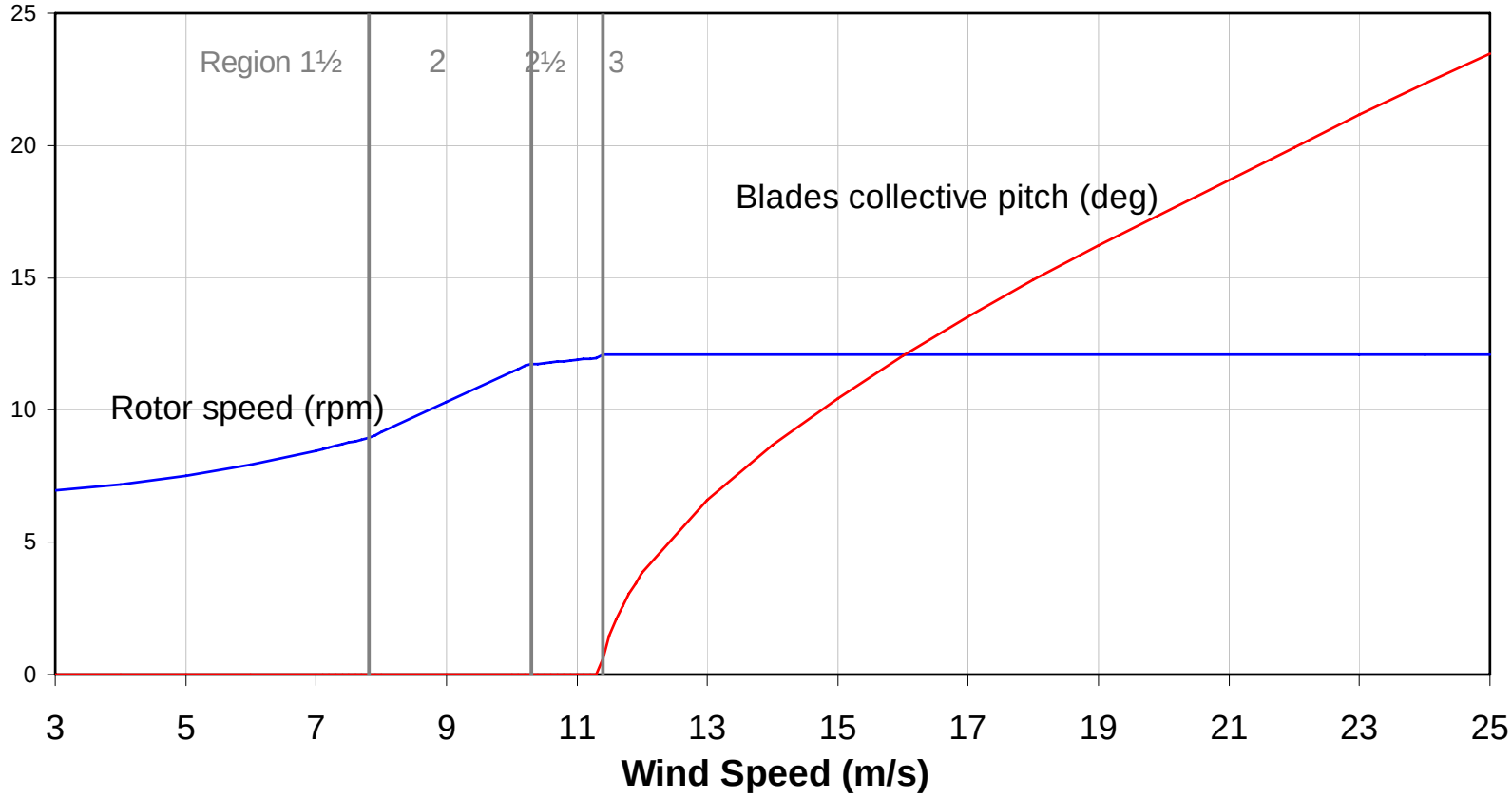


Normal Operating Condition

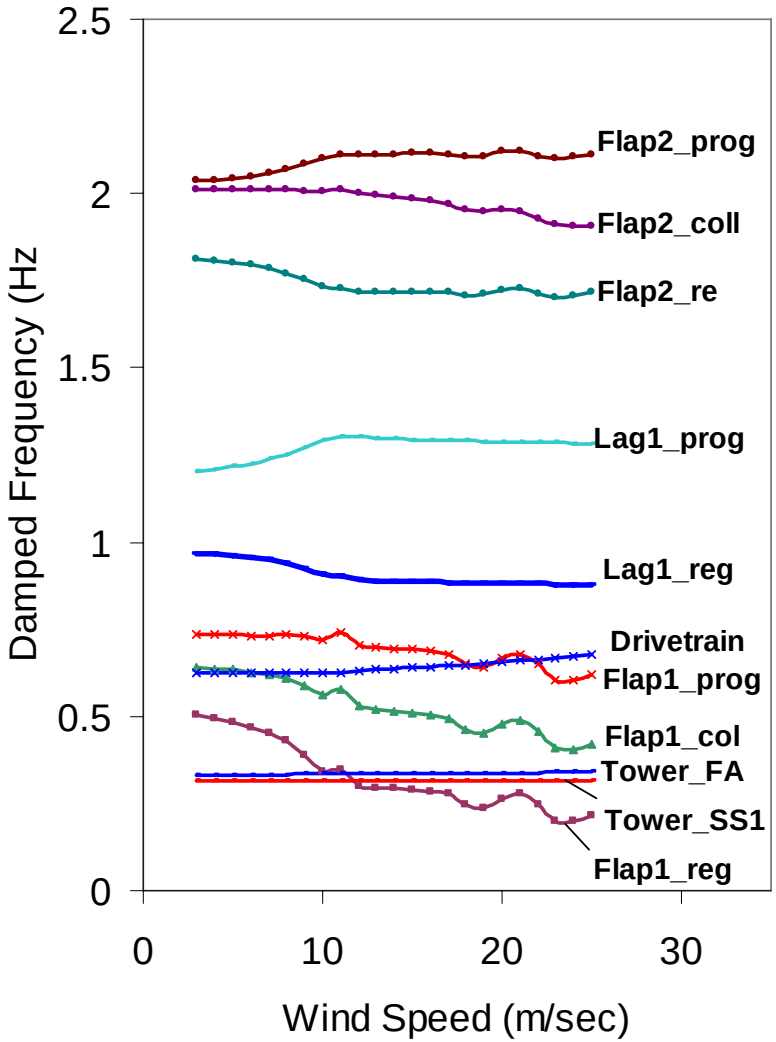
- Stability Analysis

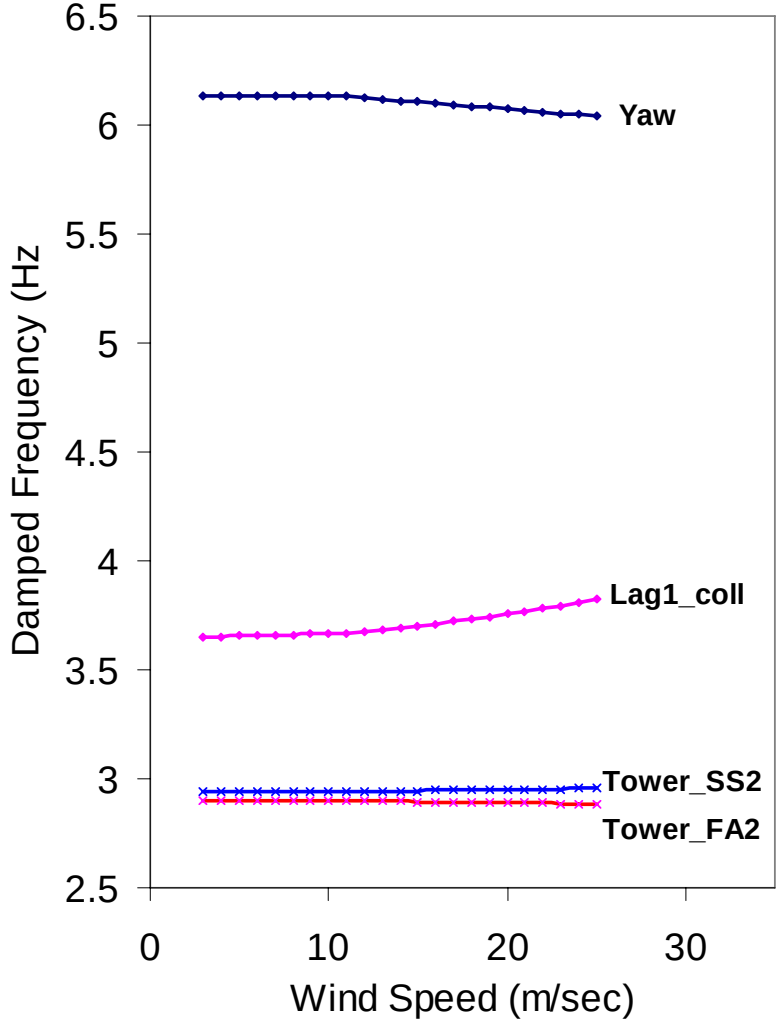
Normal Operating Condition

Relation between wind speed, rotor speed, and blade pitch

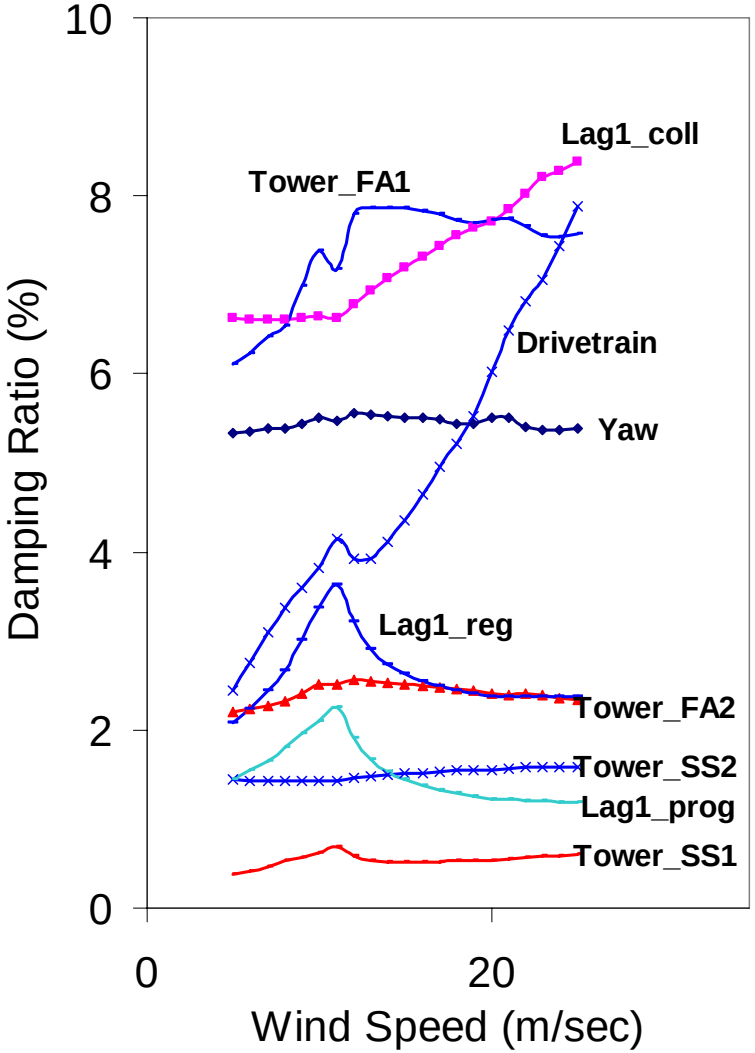


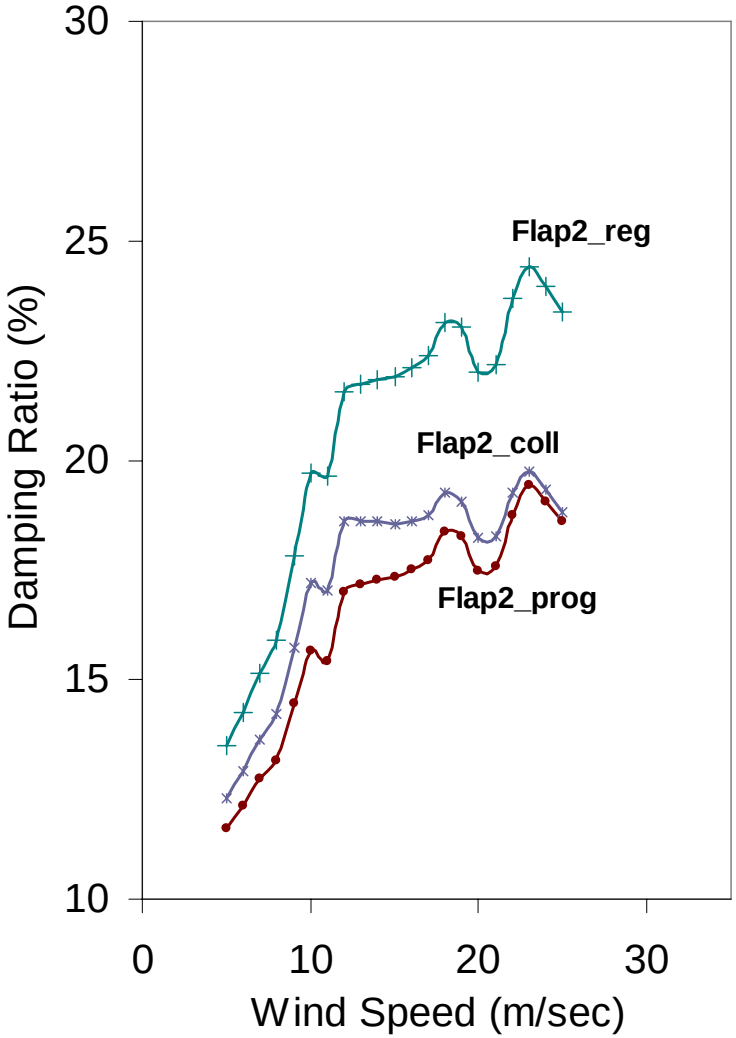
Stability Analysis
Modal damped frequencies vs wind speed





Stability Analysis
Modal damping ratios vs wind speed





Conclusions

- A new MBC scheme developed
  - applicable to both constant- and variable-speed turbines
  - allows dissimilar blades
  - covers control, disturbance, and output-related matrices, often required by control designers.
- MBC essential to stability analysis. Direct averaging eliminates all periodic terms that contribute to system dynamic. Averaging must follow MBC.
- Though the MBC formulation developed in this paper assumes three blades, it is general enough to be readily extendable to a turbine with more than three blades.

Future Work

- Show usage of MBC for improved controls design
- Demonstrate filtering actions of MBC
- Extend MBC formulation to handle arbitrary number of blades (>2)
- Show how MBC helps understand dynamic interactions amongst tower, drivetrain, and rotor.

Questions?

MBC3 Code and Manual will be posted on NWTC website by October end.

Gunjit Bir

+1 (303) 384 – 6953
Gunjit_bir@nrel.gov

Operated for the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy by Midwest Research Institute • Battelle

MBC of 2nd-Order System (cont'd)

$$X = \begin{Bmatrix} X_F \\ q_1^1 \\ q_2^1 \\ q_3^1 \\ \vdots \\ q_1^j \\ q_2^j \\ q_3^j \\ \vdots \\ q_1^m \\ q_2^m \\ q_3^m \end{Bmatrix} \xrightarrow{\text{MBC}} X_{NR} = \begin{Bmatrix} X_F \\ q_0^1 \\ q_c^1 \\ q_s^1 \\ \vdots \\ q_0^j \\ q_c^j \\ q_s^j \\ \vdots \\ q_0^m \\ q_c^m \\ q_s^m \end{Bmatrix}$$