MichiganTech
Mechanical Engineering-
Engineering Mechanics

Richard and Elizabeth Henes
Endowed Professor in Wind Energy

2018 Annual Report

Fernando Ponta

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1. Introduction

This year the Richard and Elizabeth Henes Endowed Associated Professorship in Wind Energy provided graduate student support and equipment needs for the continued development of research in the area of advanced simulation and analysis of the aeroelastic dynamics of wind turbine rotors, and their interaction with other turbine subsystems like the control system and the electromechanical devices in the drive train. These efforts have produced the first fully multi-physics simulation environment that is capable of representing simultaneously all the essential components of wind turbine dynamics, giving the MEEM Department at Michigan Tech a recognizable edge over other research institutions in the field.

2. Awards

- **2017 Journal of Aerospace Engineering Best Paper Award**, *American Society of Civil Engineers*.

3. People

Anurag Rajan

PhD Graduate - OPT Research Scholar.

Work on the flow-control dynamics aspects of the project.

Muraleekrishnan Menon

PhD Graduate - OPT Research Scholar.

Work on the fluid-structure interaction dynamics aspects of the project.

Sarah Jalal

PhD Student - Graduate Teaching Assistant.

Work on the drive-train and electromechanical dynamics aspects of the project.

Apurva Baruah

PhD Student - Graduate Research/Teaching Assistant.

Work on the drive-train and electromechanical dynamics aspects of the project.

4. Publications, Conference and Lecture Presentations

Journal Papers:

[1] M. Menon, F. Ponta (2018); "Aerodynamic Flow Control on Wind Turbine Blades using Slotted Flaps"; Submitted to *Wind and Structures*, Techno-Press; (*Under Review*).

[2] A. Rajan, F. Ponta (2018); "Aeroelastic Analysis of the 3-Dimensional Interference Patterns of Wind-Turbine Rotors: The 3-D DRD-BEM Model"; *Renewable Energy Focus*, Elsevier; *26*, 22-38.

[3] A. Otero, F. Ponta, (2018); "On The Sources of Cyclic Loads in Horizontal-Axis Wind Turbines: The Role of Blade-Section Misalignment"; *Renewable Energy*, Elsevier; *117*, 275-286.

[4] M. Menon, F. Ponta (2017). Dynamic Aeroelastic Behavior of Wind Turbine Rotors in Rapid Pitch-Control Actions. *Renewable Energy*, 107, 327-339.

[5] X. Sun, Q. Dai, M. Menon, F. Ponta (2017); "Design and Simulation of Active External Trailing-Edge Flaps for Wind Turbine Blades on Load Reduction"; *Journal of Aerospace Engineering*, ASCE; *30*, 04017062. (***2017 Journal of Aerospace Engineering Best Paper Award***).

Conference and Lecture Presentations:

[1] Ponta, F.; Menon, M.; Rajan, A. (2017). Analyzing the Aeroelastic Dynamics of Wind Turbine Rotors in Rapid Pitch-Control Actions. *Wind Energy Seminar - Okinawa Institute of Science and Technology (Okinawa, Japan)*. Invited Lecture by Fernando Ponta.

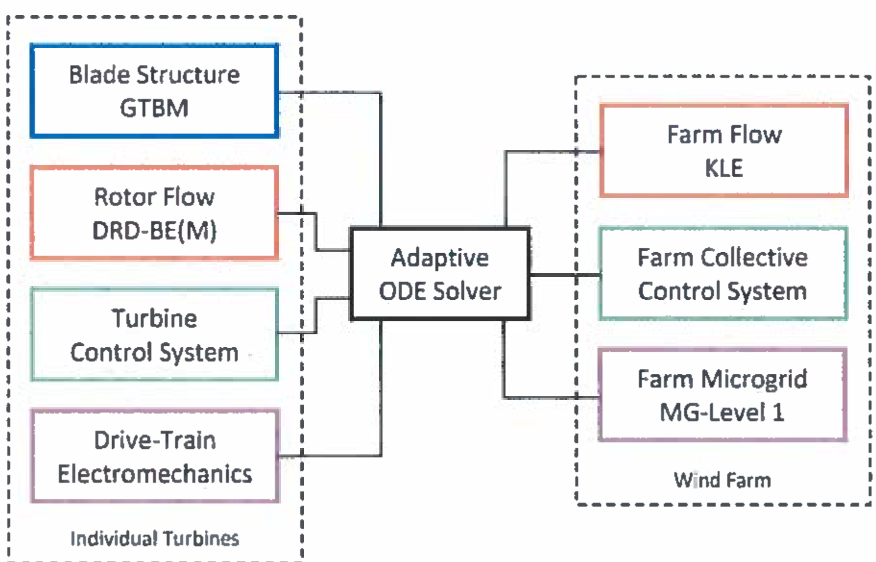
[2] Menon, M.; Ponta, F. (2017). Innovative Load Control on Utility Scale Wind Turbines Using Flow Control Devices. *ASME Power & Energy Conference (Charlotte, NC)*. Oral Presentation by Muraleekrishnan Menon.

[3] Jalal, S.; Ponta, F. (2017). Performance Analysis of Stall Controlled Variable Speed Wind Turbines Under Gust Loading Conditions. *ASME Power & Energy Conference (Charlotte, NC)*. Oral Presentation by Sarah Jalal.

5. Research

5.1 The Common ODE Framework (CODEF)

CODEF is an *Adaptive Dynamic Multiphysics* modeling technique via a Multivariable ODE Solution in time based on using non-linear adaptive variable-timestep /variable-order algorithms to solve a master ODE system that gathers together the equations associated with the different modules modeling flow, blade structure, control system, and electromechanical devices. By monitoring the local truncation error at every timestep, CODEF provides a natural way of integrating simultaneously all aspects of the multiphysics problem, improving the efficiency and ensuring the stability of the time-marching scheme.



CODEF consists of the following modules:

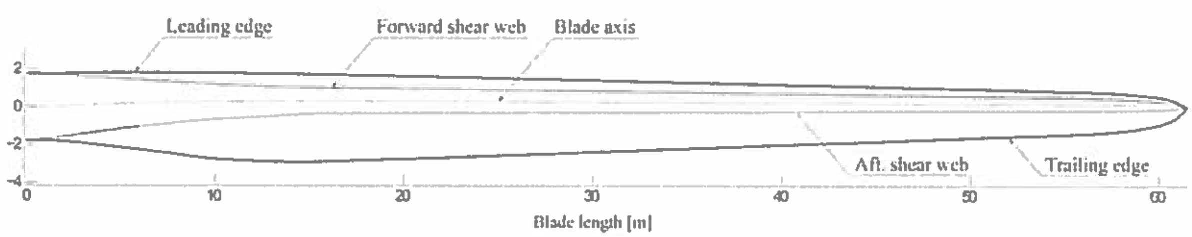
1. Reduced-Order Blade Structural Model: The GTBM technique (see detailed description on following sections) allows for a reduction of the 3D structural problem through a set of 2-D linear pre-solutions on blade sections along the span into a 1-D non-linear time-dependent solution on an equivalent beam written as an ODE system

2. Reduced-Order Rotor Flow Model: DRD–BE(M) technique provides a fully-coupled aero-elastic model based on a complete reformulation of the Blade-Element Momentum (BEM) technique including rotor deformation. It's going to be expanded to farm-scale collective flow through integration with the KLE technique via actuator-line embedded meshing: DRD-BE-KLE (detailed descriptions on the DRD-BEM and the KLE techniques will be given in following sections)

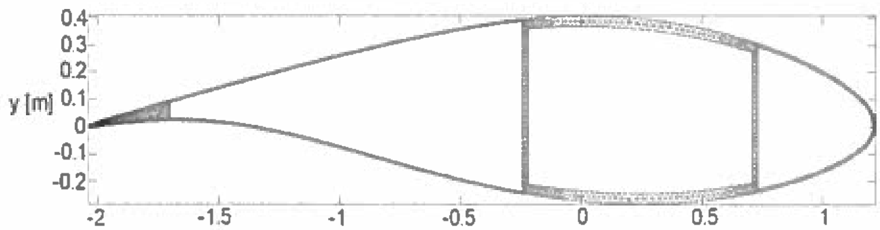
3. Modular Multiphysics Interface: CODEF is Integration-Ready with ODE modules modeling the dynamics of the electro-mechanical devices and the control system at individual-turbine scale. Master ODE system to be expanded to include ODE equations modeling wind farm microgrid (MG Level-1) and collective control system.

5.2 The Generalized Timoshenko Beam Model (GTBM)

GTBM uses the same variables of classical Timoshenko beam theory, but the hypothesis of beam sections remaining planar is abandoned. Instead, the real warping of the deformed section is interpolated by a 2-D finite-element mesh; the strain energy is rewritten in terms of the classical 1-D variables, and pre-solved.

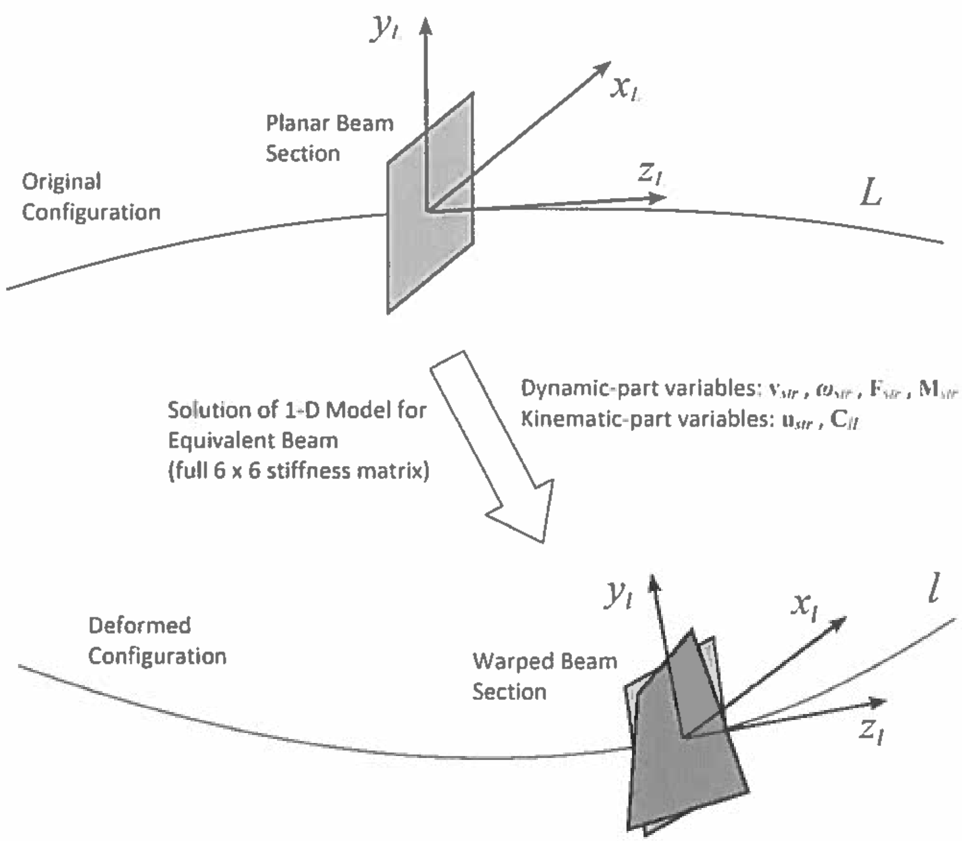


Example of a typical blade design used in current commercial turbines.



Example of finite-element 2-D meshing of the internal structure of one of the blade sections used on the dimensional-reduction computations.

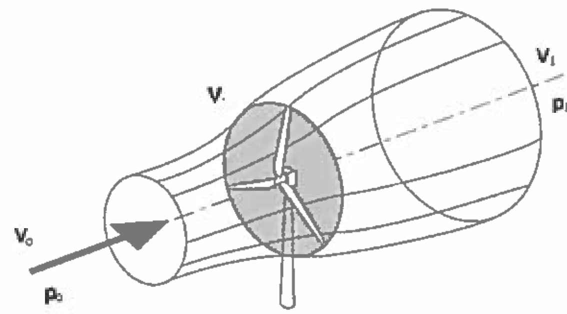
The dimensional reduction produces a fully populated 6x6 stiffness matrix for an equivalent beam, which includes all coupled-deformation modes like the bending-twist mode. It allows accurate modeling of the blade structure as a 1-D finite-element problem to be solved at each time-step of the ODE solution at a reduced computational cost.



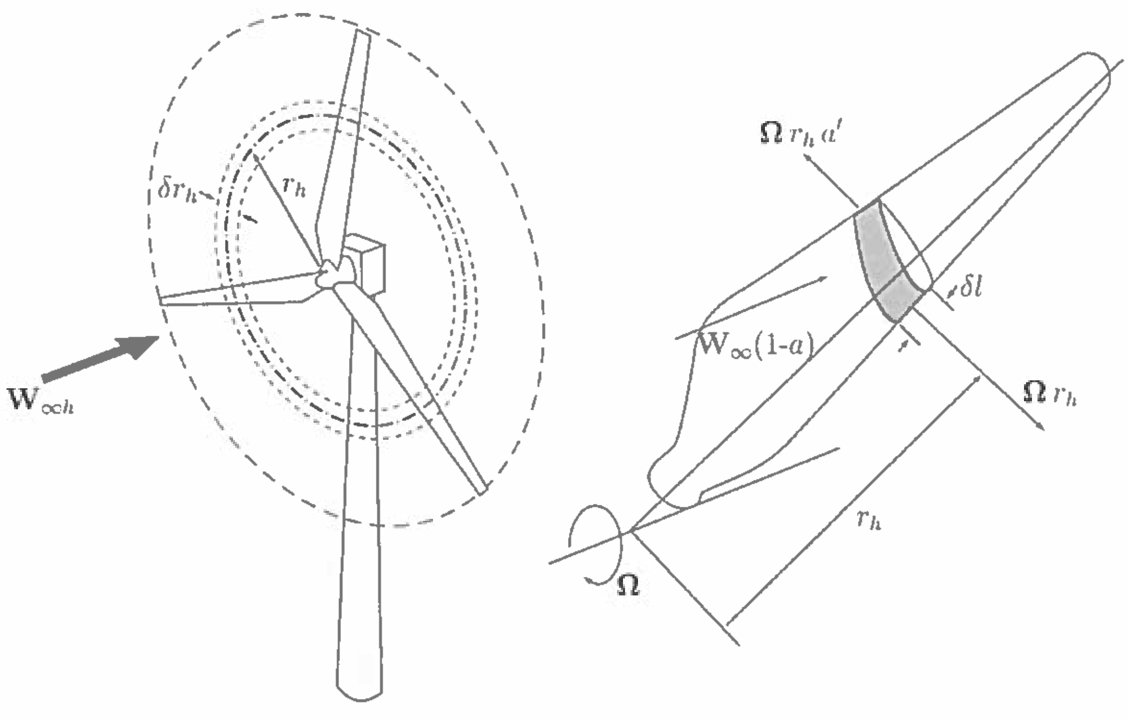
Schematic representation of the GTBM finite-element solution for the 1-D model for the equivalent beam.

5.3 The DRD-BEM model

Blade Element Momentum models (BEM) are based upon equating the forces on the blades to the change of momentum on one or more stream-tubes enclosing the swept area of the rotor. Blade action is represented by forces on one or more actuator disks placed across each stream-tube, resulting in a set of interference coefficients which modify the original wind velocity.



Schematic representation of a typical single streamtube control volume used in Blade Element Momentum models.



Schematic representation of the multiple-concentric streamtube control volume used in the DRD-BEM model, an annular actuator disk, and the Blade Element associated to it.

In the (Dynamic Rotor Deformation) DRD-BEM wind velocity is transformed through a set of orthogonal matrices into the system of coordinates of the of the blade section in its instantaneous deformed configuration. This fully includes the effects of the misalignment induced by large rotations of the airfoil sections on the computation of aerodynamic forces on the blade element. This technique includes misalignments by deformation, the action of mechanisms like yaw, pitch, main-shaft rotation, changes in wind direction, and design features like blade pre-conforming processes, rotor tilt or coning.

$$\mathbf{C}_{\theta_p} = \begin{bmatrix} \cos(-\theta_p) & \sin(-\theta_p) & 0 \\ -\sin(-\theta_p) & \cos(-\theta_p) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{W}_{\infty h} = \left(\mathbf{C}_{\theta_{az}}\mathbf{C}_{\theta_{tilt}}\mathbf{C}_{\Delta\theta_{yaw}}\mathbf{W}_{\infty wind}\right)$$

Once the wind velocity is modified to account for interference, by application of the velocity-induction coefficients a and a', and transformed into the blade element coordinates, velocity components due to structural vibration and the action of mechanisms are added. Aerodynamic forces on blade elements are computed and transformed back to the stream-tube coordinates to compute the interference.

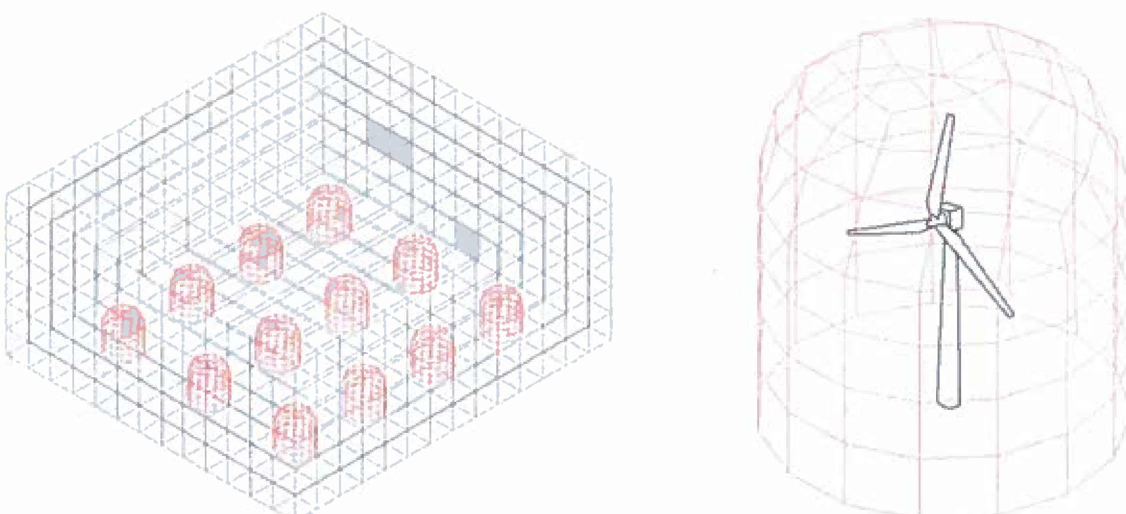
$$\mathbf{W}_h = \begin{bmatrix} W_{\infty h_x}(1-a) \\ W_{\infty h_y} + \Omega r_h a' \\ W_{\infty h_z} \end{bmatrix}$$

$$\mathbf{W}_l = \left(\mathbf{C}_{lL}\mathbf{C}_{Lb}\mathbf{C}_{\theta_p}\mathbf{C}_{\theta_{cn}}\mathbf{W}_h\right) + \mathbf{v}_{str} + \mathbf{v}_{mech}$$

$$\delta\mathbf{F}_h = \mathbf{C}_{\theta_{cn}}^T\mathbf{C}_{\theta_p}^T\mathbf{C}_{Lb}^T\mathbf{C}_{lL}^T\mathbf{C}_{Lthal}\,\mathbf{dF}_{rel}\,\delta l$$

5.4 Wind Farm Simulation by Embedded Meshing: the DRD-BE-KLE

A global mesh spanning the whole farm and following the terrain features is created where the fully unsteady flow is solved by the KLE method. High density zones of mesh are created around each turbine. The mesh is empty: the turbines are not meshed in detail. Instead, their interaction with the flow is represented by forces obtained from a DRD-BE scheme. A detailed picture of each turbine interference is provided to the global model without the prohibitive computational cost of meshing the complex geometrical details of each blade. Wind velocity conditions from an atmospheric scale model are applied on the external mesh boundary.



Schematic representation of the embedded meshing technique for the wind farm flow to be used in the KLE solution, showing the global mesh for the whole farm and the refined zone for each individual turbine.

Distributed along each blade span and applied to the corresponding cells into which they are embedded, DRD-BE forces act as actuator -lines providing a source term for the KLE solution on the flow domain of the whole wind farm. At every time step a flow field is obtained and the velocities used as input for the DRD-BE model, which provides the embedded forces to advance the solution to the next timestep.

The KLE method is based on the Vorticity-Velocity formulation of the Navier Stokes equations. It solves the time evolution of the vorticity as an ODE on each node of a spatial discretization by FEM. The right-hand side of the ODE system is evaluated from a solution of the instantaneous velocity field at each timestep, using pre-assembled matrices of derivatives of the FEM functions.

$$\frac{\partial \omega}{\partial t} = \boldsymbol{F}(\boldsymbol{\omega}, t) = \boldsymbol{\nabla} \times (\nu_{eff}\, \boldsymbol{\nabla} \cdot \boldsymbol{\nabla} \boldsymbol{v} - \boldsymbol{v} \cdot \boldsymbol{\nabla} \boldsymbol{v} + \Phi_{BE})$$

$$\boldsymbol{F}(\hat{\omega}, t) = \hat{\boldsymbol{C}}_{\boldsymbol{url}} \cdot \left(\left(\nu_{eff}\, \hat{\boldsymbol{D}}_{\boldsymbol{iv}} - \hat{\boldsymbol{V}}_{\boldsymbol{adv}} \right) \cdot \hat{\boldsymbol{G}}_{\boldsymbol{rad}} \cdot \hat{\boldsymbol{V}} + \hat{\boldsymbol{\Phi}}_{\boldsymbol{BE}} \right)$$

The instantaneous velocity field is obtained by solving a linear PDE expression in variational form called the Kinematic Laplacian Equation (KLE), using as input the vorticity distribution given by the ODE solution which is fully compatible with CODEF:

$$\nabla^2 \boldsymbol{v} = \boldsymbol{\nabla} \mathcal{D} - \boldsymbol{\nabla} \times \boldsymbol{\omega}$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{v} = \mathcal{D}$$

$$\boldsymbol{\nabla} \times \boldsymbol{v} = \boldsymbol{\omega}$$

KLE matrices could be pre-resolved and re-used at each timestep, dramatically reducing computation time. KLE may fully capture aspects of vortex-wake evolution essential to turbine interaction.

6. Funds Usage

The majority of the funds are being used in PhD student support, faculty research support, and provision of computational equipment to support the numerical simulation efforts which constitute the kernel of the activities of the MEEM Wind-Energy Research Group.

In particular they will continue supporting the PhD students Sarah Jalal and Apurva Baruah during the summer semester so they may continue their dissertation research work.

7. Concluding Remarks

The generous support provided by the Donors, Richard and Elizabeth Henes, has proved invaluable to complement other sources of funds in sustaining the research efforts of the Wind-Energy Research Group at MEEM, whose outcomes had been published in leading journals in the field and form the main component of several PhD thesis dissertations.