Hi everyone. I am Qi Wang from National Renewable Energy Laboratory. Today I am going to present a nonlinear Legendre spectral finite elements for wind turbine blade analysis. The coauthors Dr. Sprague and Dr. Jonkman are from the NREL too; and Mr. Johnson is from Colorado School of Mines.

The beam model in FAST, the flagship analysis tool for wind turbine system of NREL, is based on Euler-Bernoulli theory with shortening effect. It has two degree-of-freedom and implemented by assumed-mode method. Another popular methodology in turbine blade modeling is “multibody-formulation”. This kind of model consists of a set of linear beams; and the constraints are introduced between linear beams to describe large deflections and rotations. There are merits and drawbacks of these two methods, for example, the assumed-mode method is computationally efficient and is good for wind turbine control analysis; however, the efficiency is relatively low, especially for the composite wind turbine blade.

As the increasing size of the turbine blades, which is to reduce the cost, the geometric nonlinearity is getting more and more important in the design and analysis. Moreover, due to their excellent performance such as superior strength to weight and stiffness to weight ratios, composite materials have been introduced into the wind turbine blade design. These two pictures show the static and dynamic testing at National Wind Technical Center. Therefore the objective of the present project is to create efficient high-fidelity beam models for wind turbine blade analysis. The new beam solver should have the following features: it can capture the geometrical nonlinearity systematically; the anisotropic and heterogeneous behavior of composite materials should be captured rigorously; it should be able to modeling moving beams, both translations and rotations in 3D space; and it should achieve the speed of computational design without significant loss of accuracy comparing to the ultimate accuracy obtained by 3D finite element analysis.

The theoretical foundation of present work is the geometrically exact beam theory, which is first proposed by Reissner in 1973. Then it is extended to composite beams by Prof. Hodges at GaTech. Different numerical implementations can be found in the literature, for example, the displacement-based implementation in the famous flexible multibody dynamics code Dymore by Prof. Bauchau, and a mixed implementation by Prof. Yu at Purdue. We adopt the Legendre spectral finite element for numerical implementation. It’s a p-version high-order finite element and it has been successfully applied to simulation of fluid dynamics, geophysics, and elastodynamics. However, only limited usage can be found in structural dynamics. The result of the present project is a beam solver called “BeamDyn”, which can be used as a structural module in the new FAST modularization framework.

This slide shows the mathematical description of the Geometrically Exact Beam Theory. First is the governing equations. H and g are the linear and angular momentum, respectively; F and M are the stress and bending resultants over the cross section, respectively; u is the displacement vector; x0 is the initial position vector; lower case f and m are the distributed force and moment vector, respectively; and prime represents derivative with respect to the beam axis and dot is the derivative with respect to time. The following is the constitutive equations, which relate the 1D velocities and strains to the 1D momentems and force resultants. Here M and C are 6 by 6 sectional mass and stiffness matrices. For the most generalized case, stiffness matrices can be fully-populated so that the elastic coupling effects between all degree-of-freedoms, including 3 displacement components and 3 rotation components, can be captured by this model. Also the shear effects are included so it is a Timoshenko-like beam model. Finally, this is the kinematical equations which defined the relation between displacements and strain measures. Here u is the displacement vector and R is the rotation matrix. The phrase “geometrically exact” means the deformed beam geometry is represented exactly, or there are no approximations on the description of the 3D motions. But please note that the nonlinearity is limited to geometrically nonlinearity, the strains are still small.

NREL has put considerable effort into improving the modularity of FAST. The modules in the new framework can be coupled in one of two ways in the time domain: loose coupling and tight coupling. In the loose coupling scheme, data are exchanged between the modules at each coupling step, but each module tracks its own states and integrates its own equations with its own solver. In a tightly coupled time-integration scheme, each module sets up its own equations, but the states are tracked and integrated by a solver common to all of the modules. To enable the most flexibility, it is useful to create modules (such as BeamDyn) so that they can support both loose and tight coupling. To accommodate the tight coupling scheme in the FAST modular framework, the governing equations are recast into a state-space form. Firstly, we took out the mass terms and regroup other terms, including damping, elastic, and externally applied forces, into a function f. Next, by rewriting the variables into displacements and velocities, the governing equations are like this one, where A is a coefficient matrix, D is a matrix related to the kinematical equations, here H is the tangent matrix, and this f function is the right-hand-side term. Two new time integrators, the RK4 and AM2 are implemented into the BeamdDyn code. The implementation of RK4 is very straight forward; and this is the implementation of the second-order Adams-Moulton integrator. By the trapezoidal rule, the governing equations are discretized into this expression. This is a nonlinear equation. A linearization converts this to a system of linear algebra equations.

The Spectral Finite Element methods combine the geometric flexibility of the finite element method with the accuracy of global spectral methods. The solution improved through increased basis polynomial order, which is a kind of p-refinement. The LSFEs employ Lagrangian interpolant shape functions with nodes at Gauss-Lobatto-Legendre points which are optimum to the L 2 norm. Due to its high order nature, exponential convergence rates for the sufficiently smooth solutions can be observed. This figure shows a 2D p version refinement, where the order changes from 1 to 4. Note that here the nodes are not evenly located in this range, which is different from the Gauss-Lobatto points. The locations of these points are optimized by L2 norm.

Here are some numerical examples. The first example is a classic benchmark problem in geometrically nonlinear beam analysis. A cantilever

The second example is a validation case. Here we choose the CX-100, which is a 9-meter composite blade designed by Sandia National Lab. This figure shows the material and geometric configurations of this blade. Each color represents a material section. The sectional properties, the 6 by 6 stiffness matrix and mass matrix, are provided by Researchers from Los Alamos National Lab. There are totally 40 stations along the blade and here is a typical station at 2.2 meters from which we can see that the stiffness matrices are fully populated due to the usage of composite materials. Another feature of the realistic wind turbine blade is that there are sharp gradients of the sectional constants along the beam axial direction. This figures showed a normalized bending stiffness along the axis of CX-100. Here is a sharp change near the root and jagged noise-like distribution can be found after this jump.

This figure shows the static test configuration. The forces are applied at three locations by the crane and the deflections along the force direction are plotted in this figure. The measure data are also provided in this table. Reasonable agreement can be observed between the experimental data and the BeamDyn results. We also plotted the NLBeam, a nonlinear beam solver developed by Los Alamos National Lab, results in this plot. BeamDyn results are better, in comparison to the experimental data. One reason for this improvement could be that the initial twist has been included in our simulation.