47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition
5 - 8 January 2009, Orlando, Florida

AIAA 2009-1040

Free/Open Source Multibody and Aerodynamic Software for Aeroelastic Analysis of Wind Turbines

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This work developed a free/open source simulation software for wind turbines, based on coupling a free general-purpose multibody dynamics software developed at Politecnico di Milano, Italy, with an open-source software library for wind turbine aerodynamics developed by the National Renewable Energy Laboratory (NREL) in USA. The verification results show that this free/open source simulation software provides the capability to simulate the dynamic behavior of arbitrarily complex systems like wind turbine system with an unparalleled level of access to the source code. This also gives the wind turbine designers the flexibility to simulate their own special design cases by either modifying the source code or just combining different modules of this free/open source simulation software.

I. Introduction

The design of high-performance wind turbines requires high fidelity analysis of the system behaviour including the interaction of its aspects like structural dynamics, mechanics, aerodynamics, power generation and control. To ensure the designers to explore different architectures and design details, the analysis tools must be versatile and flexible. To ensure the designers to address different design phases, from the conceptual design to the detailed design and verification, also requires the capability to model each subsystem with an increasing level of detail. The multidisciplinary approach to modeling complex systems provided by general-purpose multibody analysis tools becomes a natural choice for solving these design problems, as testified by the increasing interest of academic, governmental and industrial research in the field.[1] The free/open source analysis tools give the designers more flexibility to solve their own special design problem by modifing the source codes.

There are some commercial softwares doing wind turbine aeroelastic simulation on the market. For example, INTEC's Simpack (`http://www.simpack.com/`) is a widely used and known multibody software which can simulate wind turbines. One of its strengths is the capability to efficiently model gearboxes. SAMTECH's Samcef (`http://www.samcef.com/`) is another well known multibody software used to simulate aeroelasticity of wind turbines with its recently released "Samcef 4 Wind Turbines" package. MSC's MSC/ADAMS (`http://www.mscsoftware.com/`) is also used to model the mechanical part of wind turbines in conjunction with the aerodynamic library AeroDyn, developed by the National Renewable Energy Laboratory (NREL)(`http://www.nrel.gov/`). NREL itself distributed open-source[a] wind turbine simulation software called FAST which does aeroelastic simulation of wind turbine but without direct multibody simulation capabilities. NREL also distributed an interface called ADAMS2AD to couple MSC/ADAMS with

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[a]For a definition of open-source software, see `http://www.opensource.org/`.

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AeroDyn (`http://wind.nrel.gov/designcodes/simulators/aerodyn/`) in order to have direct multibody simulation capability. But MSC/ADAMS is a commercial software and the designers don't have the access to modify the source codes.

There appears to be no free software with true multibody modeling capabilities that is capable of modeling wind turbines with considerable generality of topology and architecture. This work developed an interface module using C++ language linked the free[b] general-purpose multibody dynamics software MBDyn, (`http://www.aero.polimi.it/~mbdyn/`), developed by Politecnico di Milano, Italy, with the open-source wind turbine aerodynamics library AeroDyn. This will be able to fill the gap highlighted above and provide the wind turbine designers a versatile and flexible analysis tool.

A diagram of the aeroelastic simulator is shown in Figure 1. Wind turbine system properties, such as blade structural properties, geometry properties and control strategy go to input files for MBDyn. The aerodynamic properties and wind field data will go into the input files for AeroDyn. MBDyn is then executed to perform dynamic calculations. During the simulation, MBDyn calls the coupled AeroDyn library through the interface to calculate the aerodynamic forces. The outputs of the simulation are time series files of desired parameters.

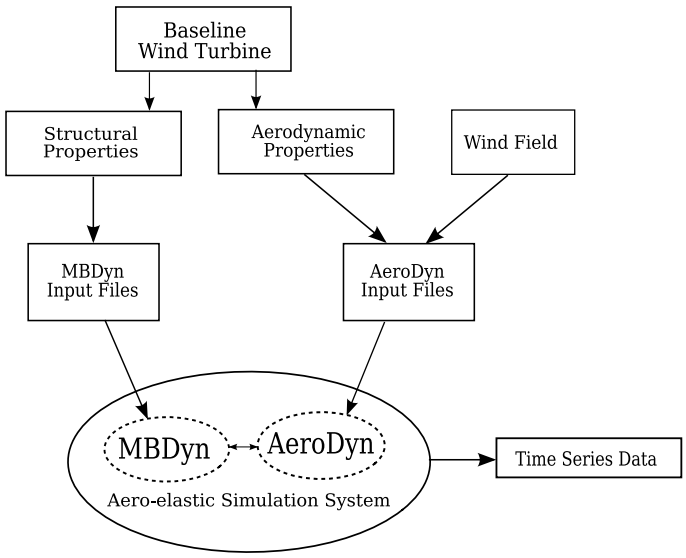


Figure 1. Aeroelastic Analysis Flow Chart.

II. Aerodynamic Model

In this aeroelastic simulation code, aerodynamic loads calculations for aeroelastic simulations of horizontal axis wind turbines are performed by AeroDyn. AeroDyn is a aerodynamic library for wind turbine simulation work which was originally developed by Craig Hansen[2] and researchers at the University of Utah and Windward Engineering. The complexity of the algorithms has gradually increased with time. Recently, researchers at the NREL have further developed these routines and changes are still ongoing.

AeroDyn use theories based on two-dimensional airflow, and the characteristics of the airfoils along the blade are represented typically by lift, drag, and pitching moment coefficients measured in wind tunnel tests. The wind field input can consist of a wide variety of atmospheric conditions: three-dimensional and time-varying atmospheric turbulence as well as discrete gusts or just steady mean wind speeds. Several different aerodynamic models are used in AeroDyn and the user has the option of selecting which of those models are most applicable to their own simulation needs. The most important of these aerodynamic models are the wake models. AeroDyn contains two wake models: the blade element momentum theory (BEM) and the generalized dynamic wake theory (GDW). AeroDyn also contains another important model for dynamic stall based on the semi-empirical Beddoes-Leishman model. This model is particularly important for yaw

[b]For a definition of free software, see `http://www.fsf.org/`.

flow cases. Finally, a tower shadow model based on a potential flow around a cylinder is also involved in AeroDyn.

II.A. Aerodynamic Load Models

As mentioned before, AeroDyn offers two different options for calculating the effect of wake on the wind turbine rotor, which are classic blade element momentum theory including some useful corrections and generalized dynamic wake model (GDW). The BEM model[3] has been the most widely used in wind turbine industry providing the aerodynamic load calculation. It has been proven to be reliable and easy to use. However, there are some limitations. One primary assumption is that this model is static. It assumes that the aerodynamic loading on each blade element is in equilibrium at any moment and the airflow accelerates instantaneously to adjust to the vorticity in the wake. So it can not model time lag effect due to vortex shed correctly. And also a static inflow model fails to capture the dynamic overshoot of thrust and torque following a collective input.

The GDW model in AeroDyn is based on the work of Peters and He.[4] This model was originally developed for the helicopter industry, and it is also known as the acceleration potential method. It is an extension of the classical Pitt and Peters dynamic inflow model,[5] with more flow states and a fully nonlinear implementation to account for turbulence and spatial variation of the inflow. An advantage of this method is that it allows for a more general distribution of pressure across a rotor plane than BEM theory. But the standard released version of AeroDyn does not include enough finite states to provide a good prediction of induced velocities at blade tip and root. When enough states are added, the calculation time increases dramatically. And also, for some unknown reasons, the GDW model can not working correctly when the AeroDyn is coupled with MBDyn.

For the reasons mentioned above, in the paper, the classical Pitt and Peters dynamic inflow has been implemented into AeroDyn to replace the original Peters-He model in the standard released version by the author. The Pitt-Peters dynamic inflow model was developed based on unsteady actuator disc theory.[6,7] The Closed-form formulas were obtained that relate transient rotor thrust and pitch and roll moments to the transient response of the rotor induced flow field. The main advantages of the classical Pitt and Peters dynamic inflow model is that it includes inherently modeling of dynamic wake effects and skewed wake aerodynamics. Another advantage of this model is that the induced velocities are determined from a set of first order differential equations, which can be solved without doing iteration. This will increase the simulation speed. And it is also very easy to be implemented into the code.

II.B. Dynamic Stall Model

The dynamic stall model of AeroDyn is base on Beddoes-Leishman dynamic stall model.[8] The model is decomposed into three distinct sub-models. One for the attached flow, where only the linear airloads are present and where viscosity is neglected. The second is the separated flow case for the non-linear airloads, where leading edge and trailing edge separation is taken into account, and, finally, one for the dynamic stall flow case, where the formation, detachment, and convection of a vortex is taken into account leading to a hysteresis in forcing.

The Beddoes-Leishman model is based on airfoil indicial response. The indicial response is the unsteady aerodynamic response as a function of time to a step change in angle of attack. The indicial response is derived from the solution of the linearized differential equations. So these step response solutions can be superimposed, using the approximation to Duhamel's integral, to construct the cumulative effect of any arbitrary time history of discrete forcing. The total indicial response in the Beddoes-Leishman model is composed of the sum of two independent parts; one for the initial impulsive (or non-circulatory) loading and another for the circulatory loading. The initial impulsive loading is the result of an instantaneous change of angle of attack or pitch rate, while the circulatory loading builds up asymptotically from zero to the steady state value. There are some modifications to the model that are necessary to make it applicable to the airfoils of wind turbines. For example, Beddoes-Leishman model considers angles of attack from approximately $-10°$ to $30°$; however wind turbine airfoils often operate outside of this range. Because of this, the model should be capable of producing aerodynamic force coefficients over the entire range of possible angles of attack, which needs some modifications to the original model.

II.C. Tower Shadow Influence

The influence of the tower on the blade aerodynamics is also considered in AeroDyn. The tower shadow model is based on a potential flow solution around a cylinder, made up of the basic flow field along with a downwind wake model dependent on tower drag coefficient, C_d, and a tower dam model for investigating the influence on the upwind turbine. The model provides the influence of the tower on the local velocity field at all points around the tower, including increases in wind speed around the sides of the tower and the cross-stream velocity component in the tower near flow field.

III. Structural Model

The modeling of the structure of the wind turbine is delegated to the free general-purpose multibody software MBDyn. The software was designed at Politecnico di Milano to support research in the field of rotorcraft aeroelasticity. The modeling of horizontal axis wind-turbines typically require proper mathematical model of the tower, the nacelle and the blades (structural model); the gearbox, the generator and the kinematics of movable parts, like blade pitch (mechanical model); the control systems (dynamical model). All these components contribute to the dynamics of the system; depending on the objective of the analysis, their modeling may need to be detailed increasingly. The use of a general-purpose multibody simulation tool allows a considerable generality in modeling the structure from a topological point of view, and a significant control on the level of detail of each component.

The dynamics of the structure are described by a set of structural nodes, which accounts for the inertia properties of the system in a lumped manner. The nodes are either connected by kinematic constraints or by deformable components, like beam elements or Component Mode Synthesis (CMS) superelements. Newton-Euler equations are written for each node; they describe the nodal force and moment equilibrium, including the contribution of the constraint reactions as functions of Lagrange multipliers. The structure of the tower and of the blades is best modeled, as a trade-off between accuracy and efficiency, by means of nonlinear, kinematically exact and composite-ready beam elements based on an original finite volume formulation.[9] Thus, it can capture the nonlinearity due to large deformation. The rest of the system is modeled in form of lumped components that represent the nacelle and hub kinematics and dynamics, which are connected by kinematic constraints. The overall wind turbine system is shown in Figure 2. It is clear that the multibody approach allows to model the exact kinematics of the system, without resorting to any unnecessary simplification.

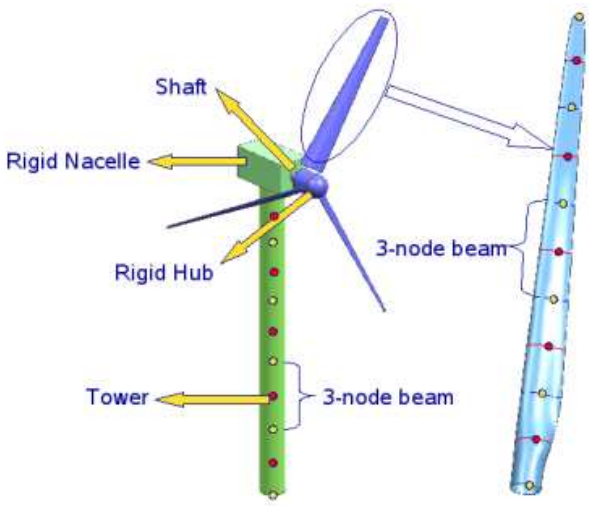


Figure 2. Structure Model of Wind Turbine.

The typical analysis consists in solving an Initial Value Problem (IVP): the dynamics equations are integrated in time starting from a set of initial conditions, resulting in time series that describe the motion of the system. The performances of the wind-turbine are evaluated by letting the system converge to a steady solution, if any. The stability properties of steady solutions are evaluated by analyzing the time series

of the response, using a technique based on system identification of the signals resulting from the application of the Proper Orthogonal Decomposition (POD) to free-response transients.[10]

IV. MBDyn-AeroDyn Interface Module

In this paper, an seperated interface code between the free general-purpose multibody dynamics software MBDyn and the open source wind-turbine aerodynamic library AeroDyn has been made by the author using C++ language, in order to exploit the advantages of both codes. For example, MBDyn can model wind turbines with considerable generality of topology and architecture, and it also allows to model controllers, while AeroDyn is a specialized aerodynamics library which contains some state-of-the-art models like the GDW model,[11] a modified Beddoes-Leishman dynamic stall model,[8] and a tower shadow model. Furthermore, AeroDyn has been validated by Germanischer Lloyd WindEnergie GmbH.[12]

Figure 3 shows the detailed description about how does this interface work. When the aeroelastic simulation starts, the interface gathers information about the wind turbine geometry, operating condition, blade element velocities and positions and wind field data,etc. from AeroDyn and MBDyn input files. AeroDyn uses this information to calculate the force and moment contributions for each segment of blade, which are passed to MBDyn to compute the forces and moments that load on the structure model of the turbine blades. During the simulation, at each time step the interface calls the function `AeroFrcIntrface` to get the force contributions for each segment from AeroDyn. MBDyn calculates the deflections and the velocities at each blade element, which are need by AeroDyn to compute the forces in the following time step. Typically, the AeroDyn library is called by MBDyn through the interface once per time step for each blade element to compute the aerodynamic forces. As a consequence, the aerodynamic forces affect the wind turbine deflections and vice versa, resulting in a coupled aeroelastic simulation procedure.

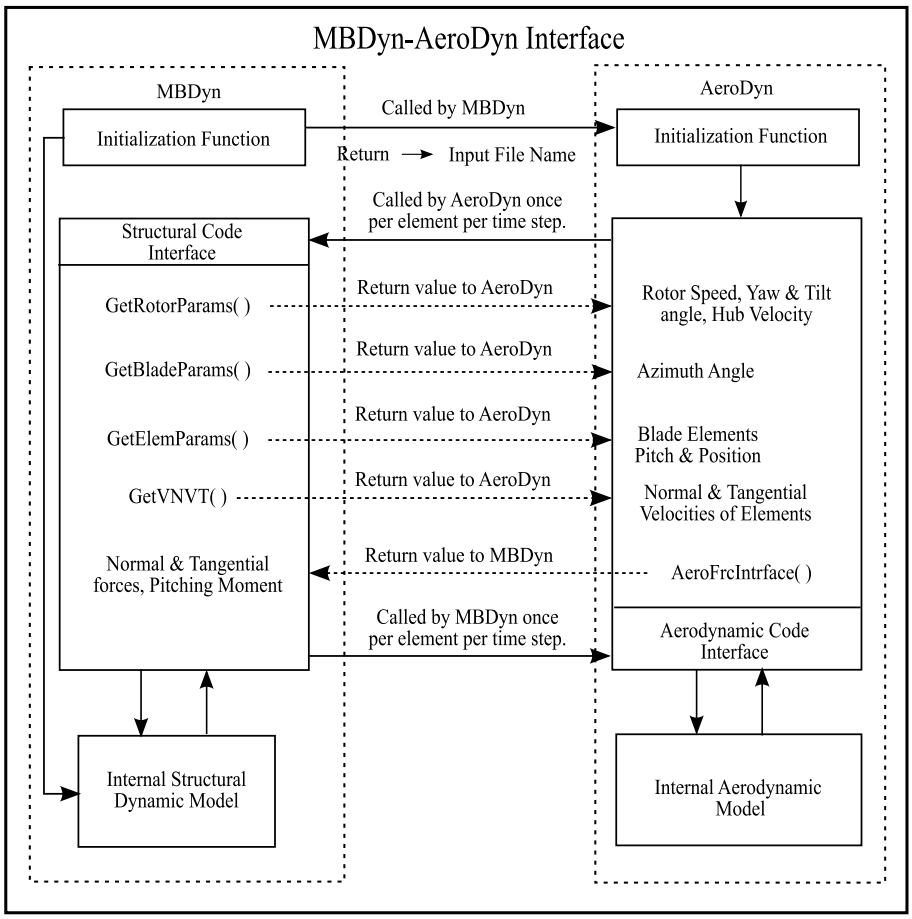


Figure 3. MBDyn - AeroDyn Interface Flow Chart.

V. Software Verification

This aeroelastic simulation system presented in the previous sections has been verified with FAST developed by the National Renewable Energy Laboratory (`http://wind.nrel.gov/designcodes/simulators/aerodyn/`) based on a reference wind turbine (RWT) developed for the UPWIND project [c]. FAST was evaluated by Germanischer Lloyd WindEnergie and found suitable for "the calculation of onshore wind turbine loads for design and certification". The thrust, torque, power output, flap-wise tip deflection and edge-wise tip deflection at several different wind speed have been compared in order to verify this aeroelastic simulation system. This will give us confidence to apply this code in real applications on wind turbine aeroelastic simulation.

V.A. Simulation Input Parameters

In this aeroelastic simulation, both uniform inflow and vertical shear inflow (8m/s, 10m/s, 18m/s) are used. The vertical wind shear is defined by the hub height wind speed conformed with the power law shear profile shown in equation 1. It is used to determine the wind speed V_z at any height,z,based on the hub height, z_{hub}, and hub height wind speed,V_{hub}.

$$V_z = V_{hub}(\frac{z}{z_{hub}})^{\alpha} \tag{1}$$

Typically, the value of α is 0.14 representing a $\frac{1}{7}^{th}$ power law profile. Figure2 also represents the layout of the reference wind turbine. It is a three blades turbine. The length of the blade is 61.5 meters, which is model by five three-nodes beams. The tower is 107.5 meters long also being modeled by five three-nodes beams. The hub, nacelle and shaft are modeled by lumped mass and connected by joints. In table 1, the detailed input parameters for both of the two aeroelastic simulation tools are shown.

Table 1. Aeroelastic Simulation Input Options

Simulation Tools / Input Options	MBDyn-AeroDyn	FAST
Aerodynamic Option	Classical Pitt-Peters dynamic inflow. Dynamic stall. (on) Tower shade. (off) Tip and hub loss correction.	Extended Pitt-Peters dynamic inflow. Dynamic stall. (on) Tower shade. (off) None
Structural Dynamic Option	Multibody dynamics with Finite volume beam.	Assumed mode shape.
Control Option	Torque Controller (on) No pitch controller	Torque Controller (on) Pitch Controller (off)

In FAST, torque controller is switched on and pitch controller has been turned off. The initial blade pitch angles for all blades are set to 0.0 degree when running at 8m/s and 10m/s, and 13.8 degrees when running at 18m/s, and the initial rotor speed is 7.0rpm. In MBDyn-AeroDyn, only the torque controller is implemented in the model at this moment. There is no pitch controller yet in the model to regulate the power output when running above rated power. For this reason, a fixed and tuned blade initial pitch angle equaling to 13.8 degrees is set when the wind turbine is operating above rated power. The initial rotor speed is also set to 7.0rpm so as to make the comparison easier. The total simulation time was set for both codes to 120 seconds. As the results show, both of the simulations will eventually converge to an equilibrium state.

V.B. Simulation Results

Fig.4 to Fig.6 show the results for a constant and uniform wind field at 8m/s, 10m/s and 18m/s. All the figures show the time period between 0 second and 120 seconds.

[c] An EU 6th framework programme, Contract No.:019945

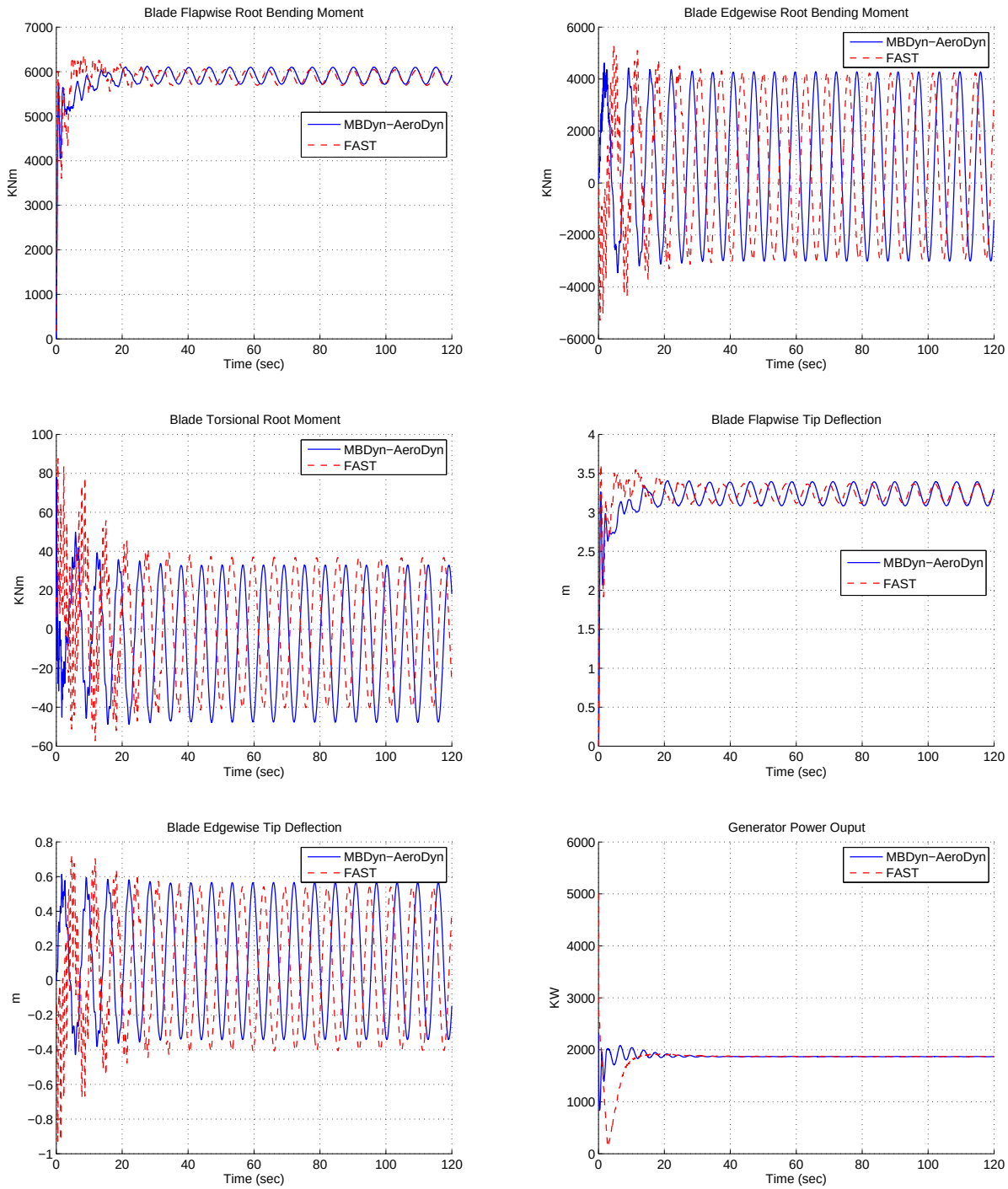


Figure 4. Constant and uniform wind field at 8m/s.

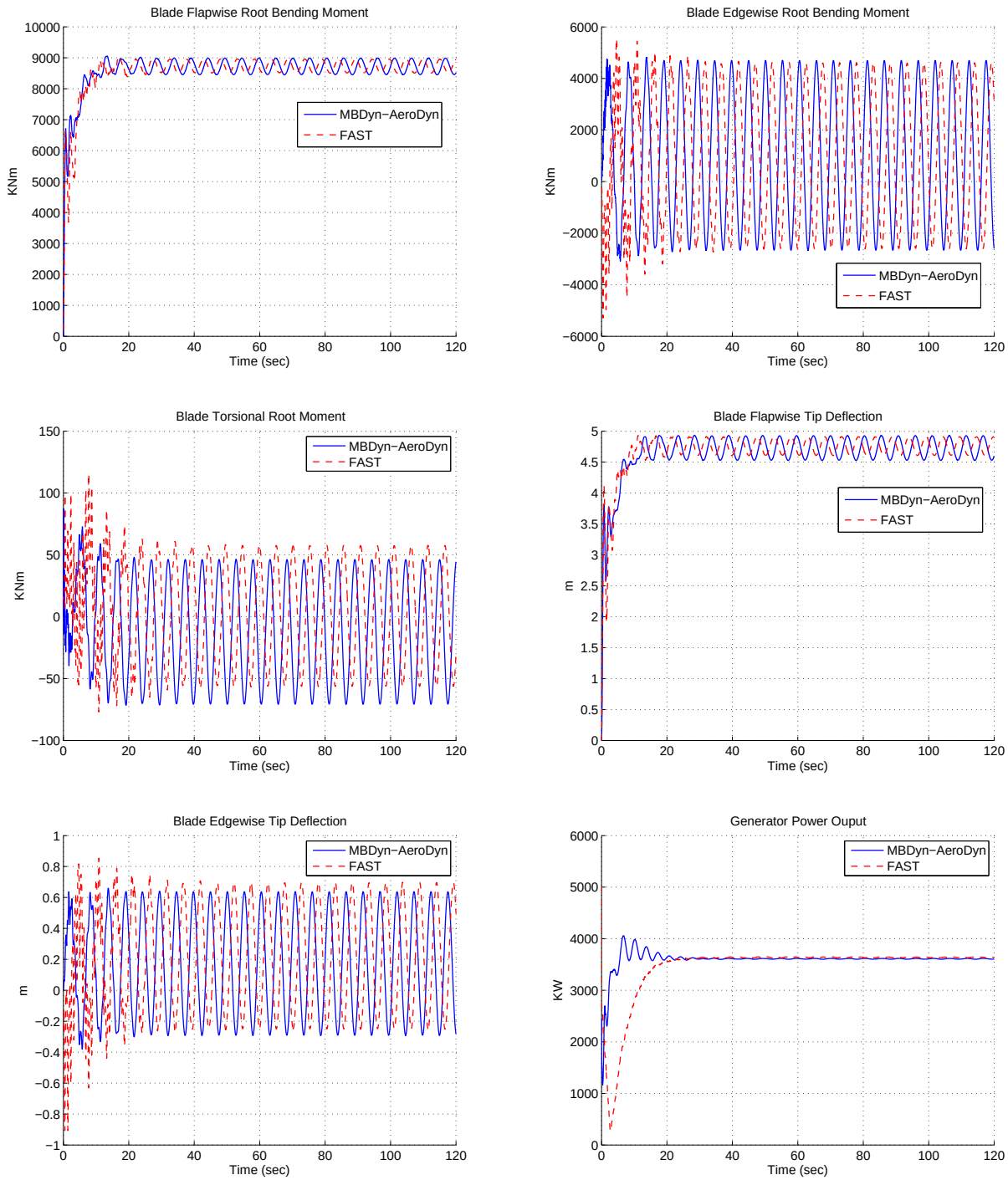


Figure 5. Constant and uniform wind field at 10m/s.

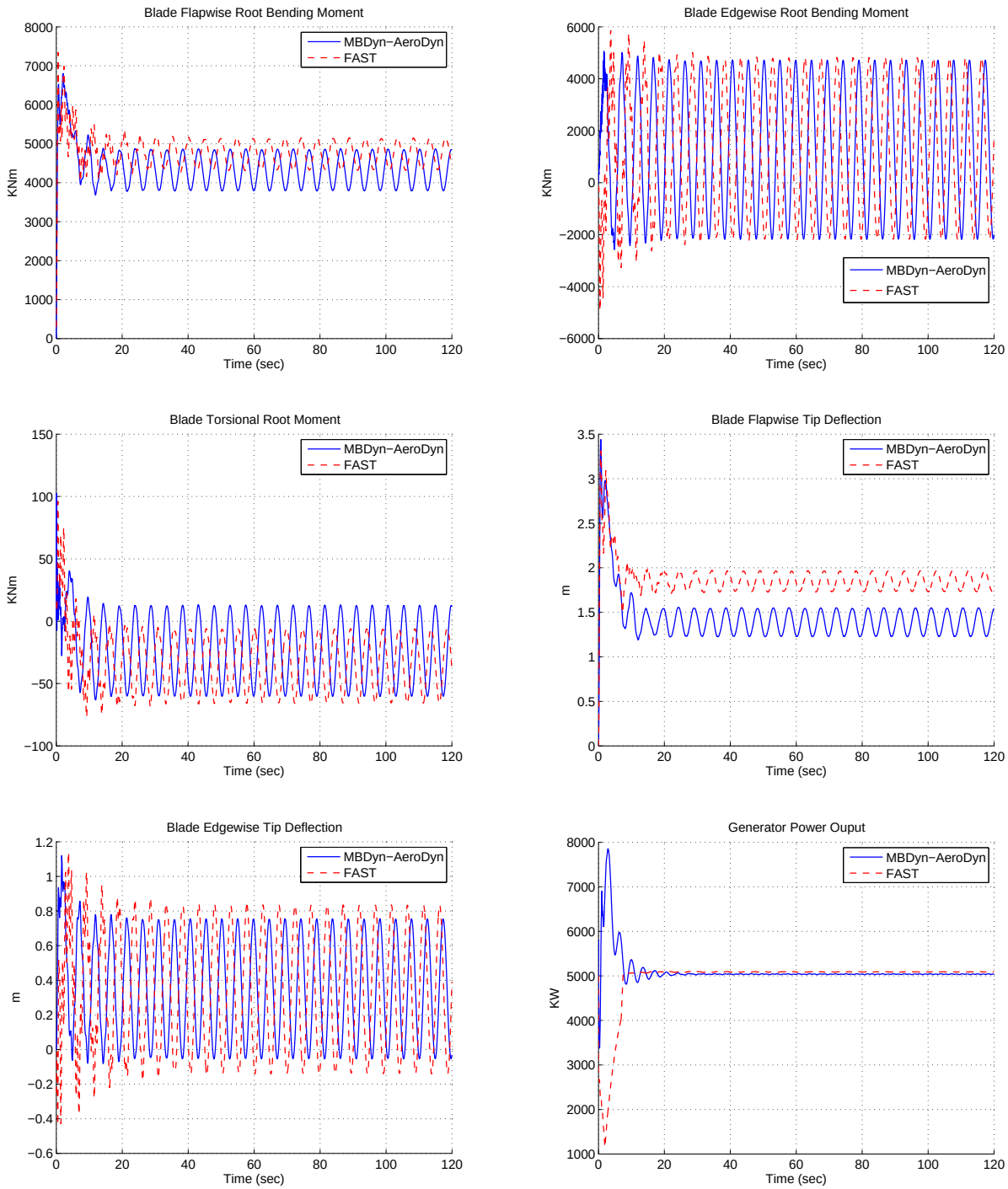
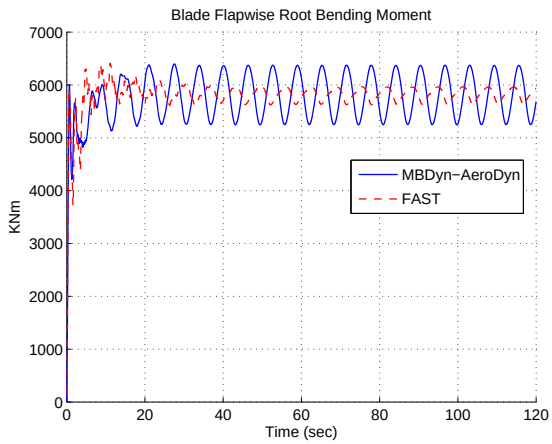
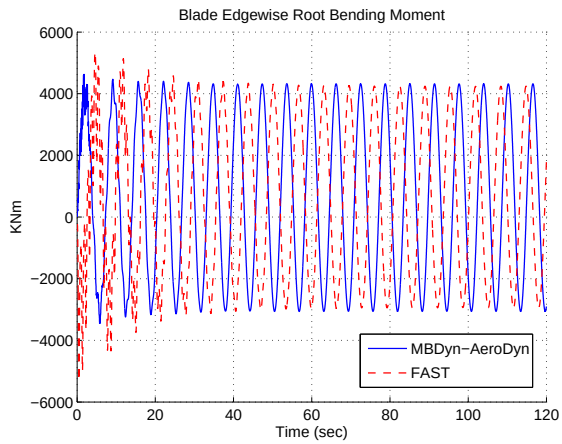


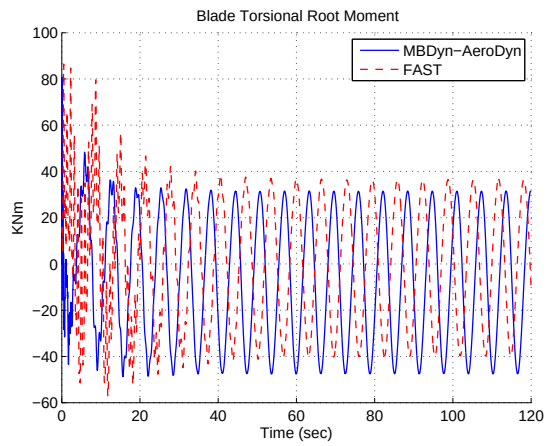
Figure 6. Constant and uniform wind field at 18m/s.

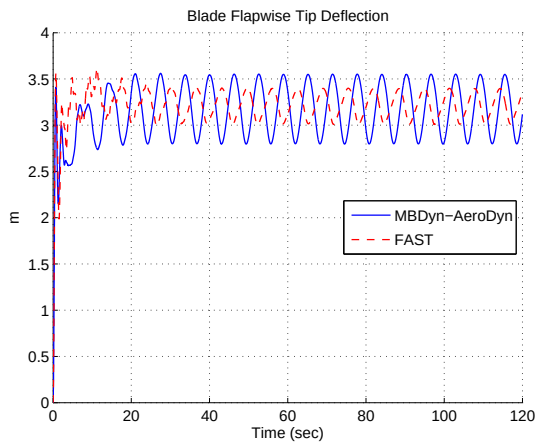
Fig.4 and Fig.5 show the aeroelastic responses calculated by both codes. They agree on each other quite well at 8m/s and 10m/s. There are some small discrepancy in blade edgewise tip deflection and blade torsional root moment. But, when the wind speed goes to 18m/s, the differences of the aeroelastic responses calculated by both codes become bigger especially for the blade flapwise root bending moment and blade flapwise tip deflection. This is probably due to different structure dynamic models used in these two codes. In FAST, assumed mode shape method has been used and in flapwise direction only tow flapwise bending modes have been taken into account, while in MBDyn-AeroDyn, the blade is modeled by finite volume beam theory, so it allows more degrees-of-freedom and can capture large deformations. In general, FAST predicts larger blade flapwise and edgewise tip deflection than MBDyn-AeroDyn, this is because the extended Pitt-Peters dynamic inflow model in the standard released version of FAST does not include enough finite states to provide a good tip and root loss correction. So FAST over predicts the magnitude of aerodynamic forces. This has also been proved in Fig.10, which shows the comparison of the average rotor thrust calculated by three difference codes at different wind speeds. FAST also predicts larger rotor thrust than MBDyn-AeroDyn and BLADMODE from Energy research Centre of the Netherlands(ECN).

Fig7, Fig8 and Fig9 are the results for a constant wind field with a power law wind shear profile at 8m/s, 10m/s and 18m/s. Again, both of the codes have a good agreement at 8m/s and 10m/s. When the wind speed reaches to 18m/s, the difference between the codes becomes big. The figures indicate that MBDyn-AeroDyn can capture more wind shear effect than FAST does. It can be found that the oscillation amplitude of blade flapwise root bending moment and flapwise tip deflection calculated by MBDyn-AeroDyn is much bigger than in the no wind shear case. This is because the finite volume beam theory used in MBDyn-AeroDyn is nonlinear and more flexible than assumed mode shape theory. So MBDyn-AeroDyn can better capture large deformation than FAST.









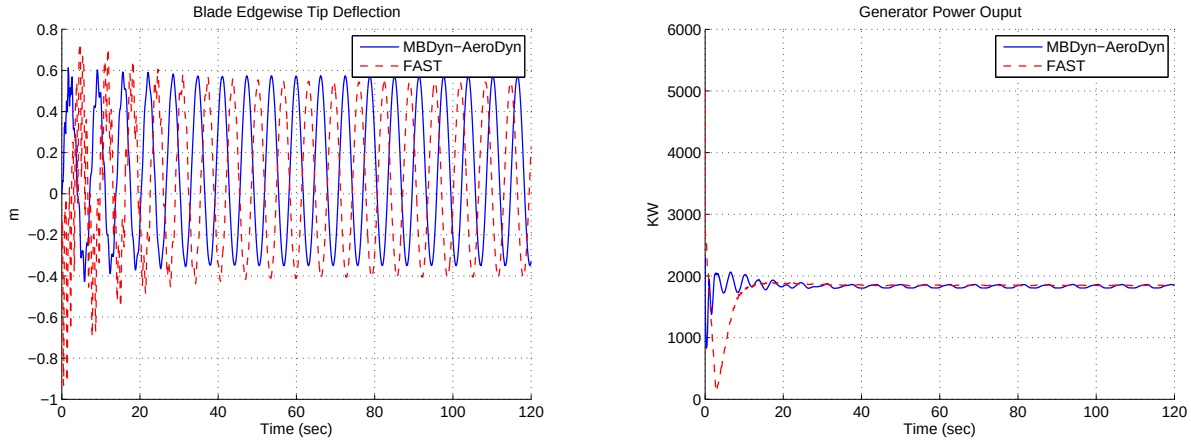
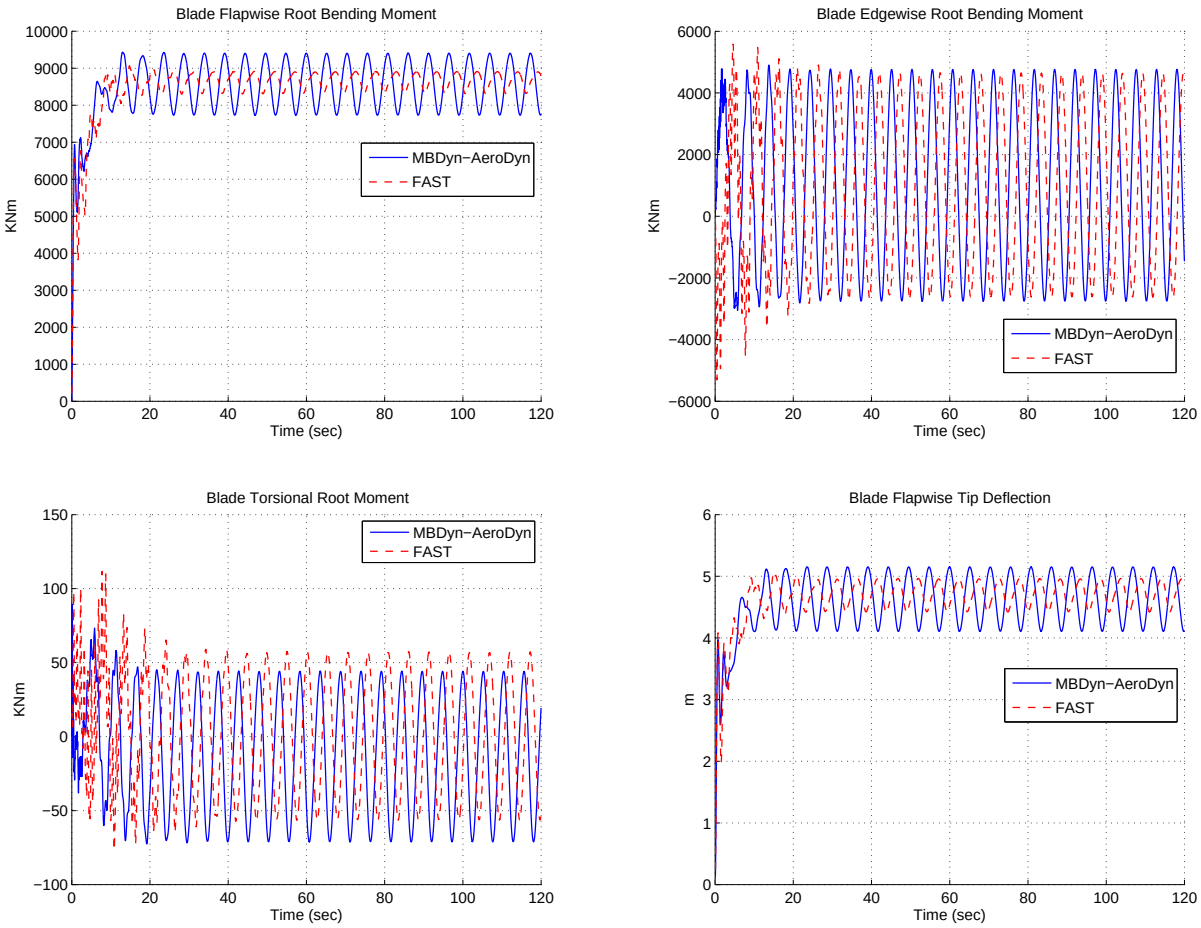


Figure 7. Constant wind field with shear at 8m/s.



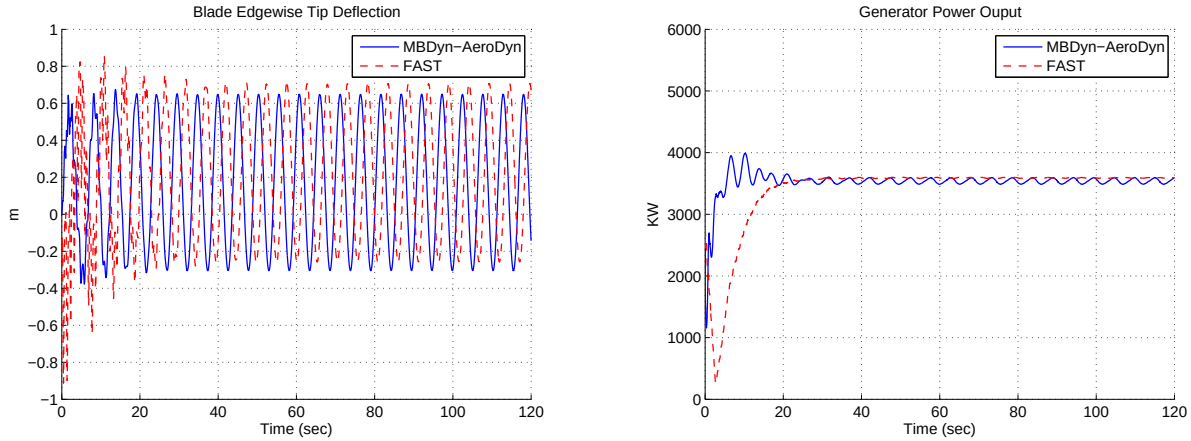
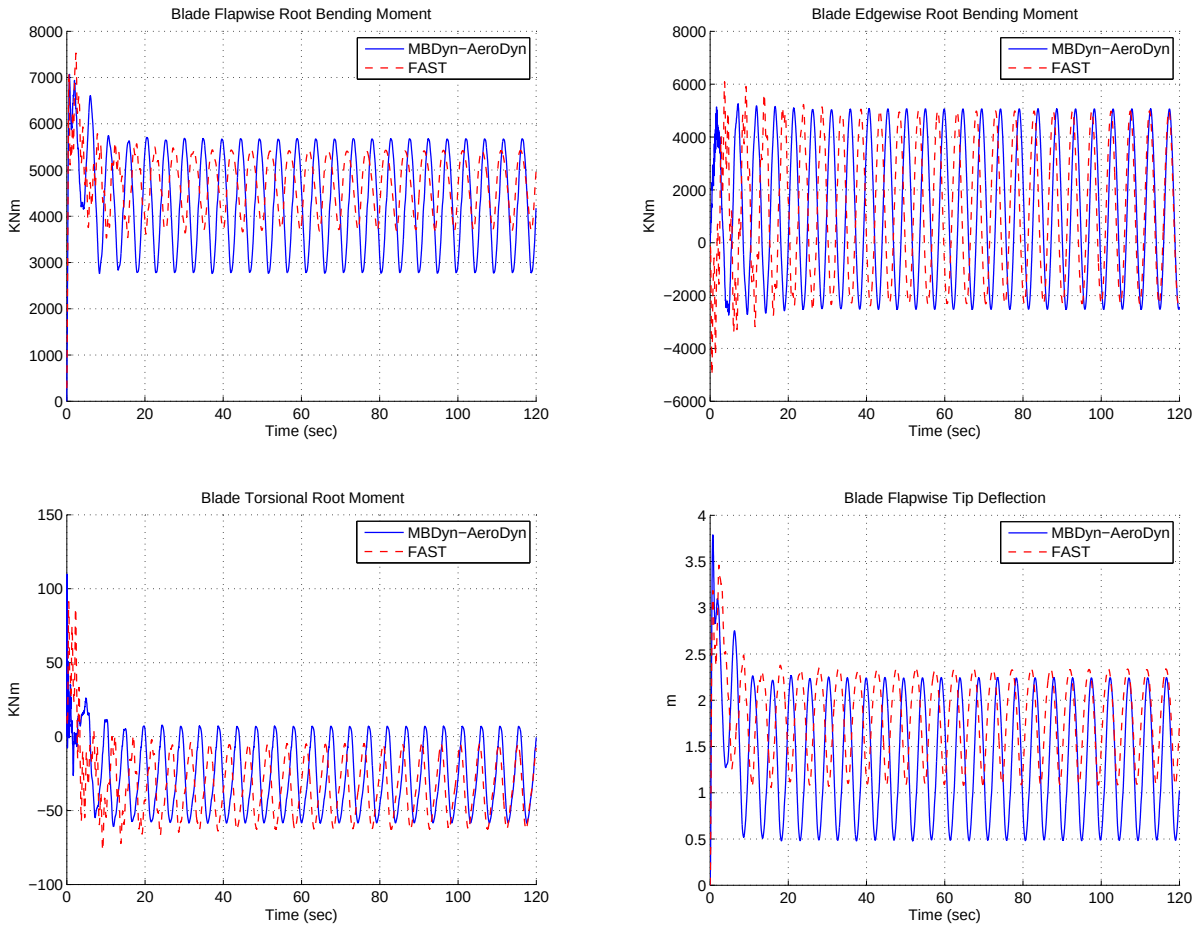


Figure 8. Constant wind field with shear at 10m/s.



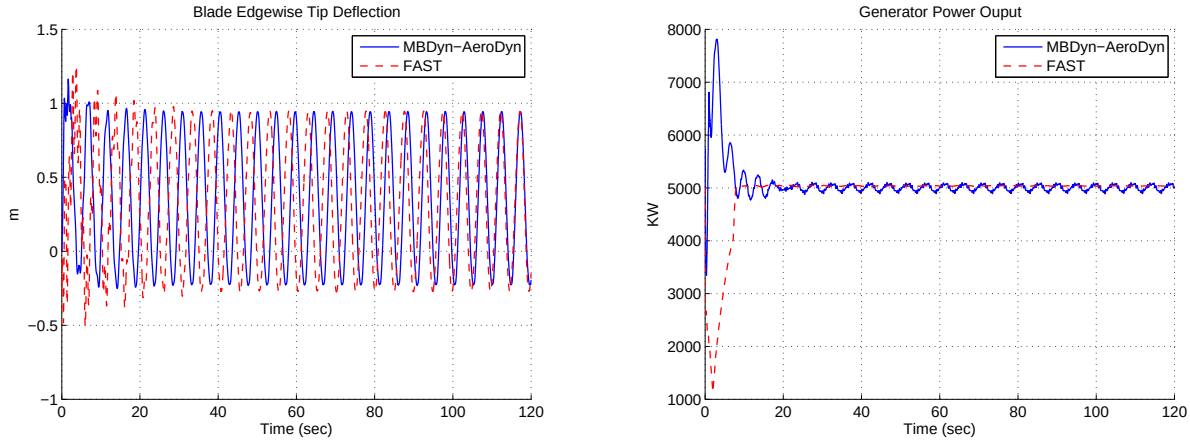


Figure 9. Constant wind field with shear at 18m/s.

All the results being shown in the above figures have very strong time phase error although all the responses are compared based on the same blade, for example, blade number one; and the starting azimuth angle is the same. This is because that the output data by the two codes are not synchronized according to the azimuthal position of the blade. The difference of the aeroelastic frequencies being predicted will also cause this time phase error with the time marching.

Further more, another simple comparison has been made between MBDyn-AeroDyn, FAST and BLADMODE to support the above results. It compares the static operational rotor thrust. As it is mentioned above, in standard released version of FAST, the extended Pitt-Peters dynamic inflow model does not contain enough states to well predict the tip and hub loss. Because of this, FAST predicts bigger rotor thrust than MBDyn-AeroDyn and BLADMODE does. From the wind turbine designer's point of view, better predicting the tip and hub loss is very important to make a good design. On the other hand, to calculate fatigue of the blade in order to estimate the wind turbine lifetime, FAST will give a more conservative choice.

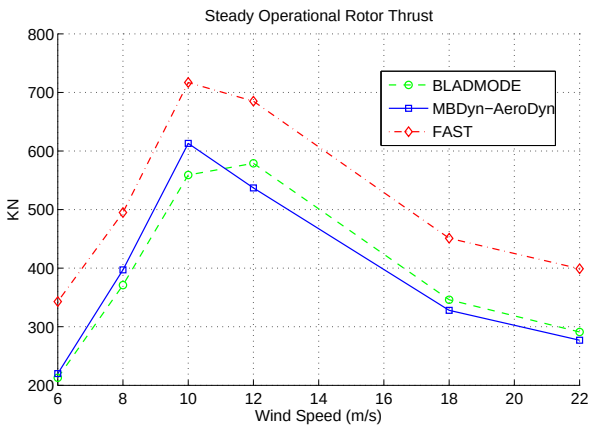


Figure 10. Steady Operational Rotor Thrust.

VI. Conclusions

This simulation tool is made by two simulation code linked by a separate interface code, and it is open-source code. The designers can easily access to the source code and make some modifications on their own special requirements. So the resulting simulation tool provides the capability to simulate the aeroelastic behavior of large wind turbine systems with an unparalleled level of access to the underlying code. The simulation results show that this aeroelastic simulation system has good agreement with FAST and BLADMODE. It can better capture the wind shear effect than FAST. This is also an important aspect for simulating the future large and flexible wind turbines. It provides us a good aeroelastic simulation tool

which has the ability to capture some of the nonlinearities of large and flexible wind turbines.

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