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Unified approach for modelling of wind turbine power train using bond graph

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Abstract

A Wind turbine is a nonlinear and multidisciplinary system (mechanics, aeronautics, electrical and magnetics) which deals with various energy domain to extract electricity from wind. A unified approach based on bond graph for robust multi-physics modelling and reliable simulation is used for understanding, design and simulation of wind turbine system. NREL 5MW reference turbine is modeled and eigenfrequencies as well as blade deformations are verified. Results are showing good agreement with published values. Effect of gravity and eccentricity is considered in transient rotordynamic analysis in order to show chosen approach capability..

Objectives

Development of parametric wind turbine model using bond graph approach for multiphysic domain modelling is main objective. Rotordynamic system simulation and analysis of wind turbine power train under steady-state loading conditions is performed using electrical, magnetic and structural domain at once. Eigenfrequencies of the complex system have to be determined properly to avoid resonance in all points of operation. Torsional, translational and bending vibrations of shaft considering structural damping need to be calculated for further damage and fatigue prediction. The transient orbital displacement behavior of the power train due to eccentricity and gravity load on hub has to be observed for advanced bearing design. For optimization purposes electric and magnetic domain of induction machine is modelled to analyze starting behavior and power output.

Methods

Bond graph methodology is used to model complete wind turbine system where every element is attached to next element by half arrows called as power bond considering causality of system. Wind turbines having several important components like the blades, hub, shaft, planetary gearbox, bearings and generator and they exchange power between them as shown in Fig.1. To model Blade, it is divided in seven flexible beam elements having six degrees of freedom. Steady state or unsteady state fluid forces can be mapped from CFD or any other source to blade nodes. Complete shaft is divided into number of small elements and each element is modelled as Raleigh beam (acc. to [1]). Every element is having five degree of freedom including gyroscopic effect, spinning and gravity. Main bearing is considered as ball bearing where stiffness and damping is considered in term of geometrical description like number of ball, diameter of ball, diameter of inner race and outer race and many more. Gear box is modelled as transfer function including moment of inertia of gear and translational bearing stiffness. Squirrel cage generator is modelled considering sinusoidal distribution of stator winding voltage from electrical network. Magnetic losses, air gap loss and core losses are considered while modeling [2]. NREL 5MW Reference turbine is used for determination of input parameters and validation of results [3].

Results

Phase I - system modelling and parametric model creation

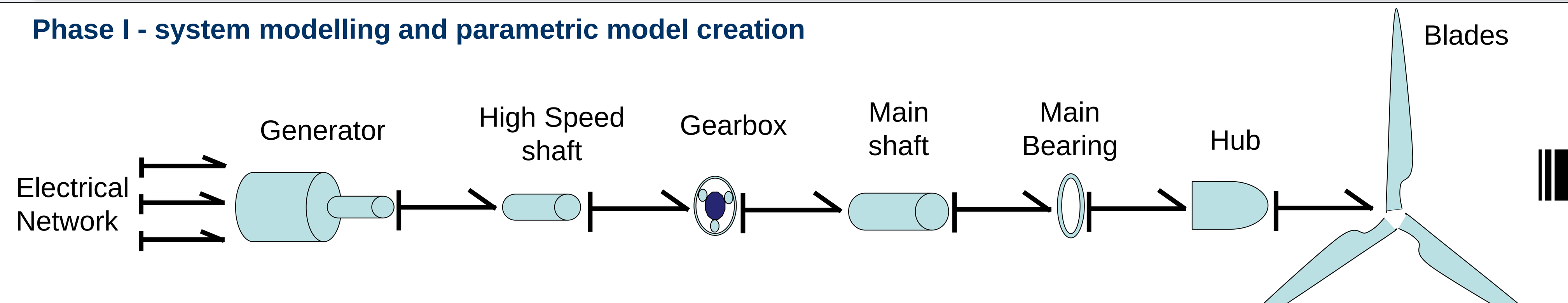


Fig.1. schematic wind turbine model

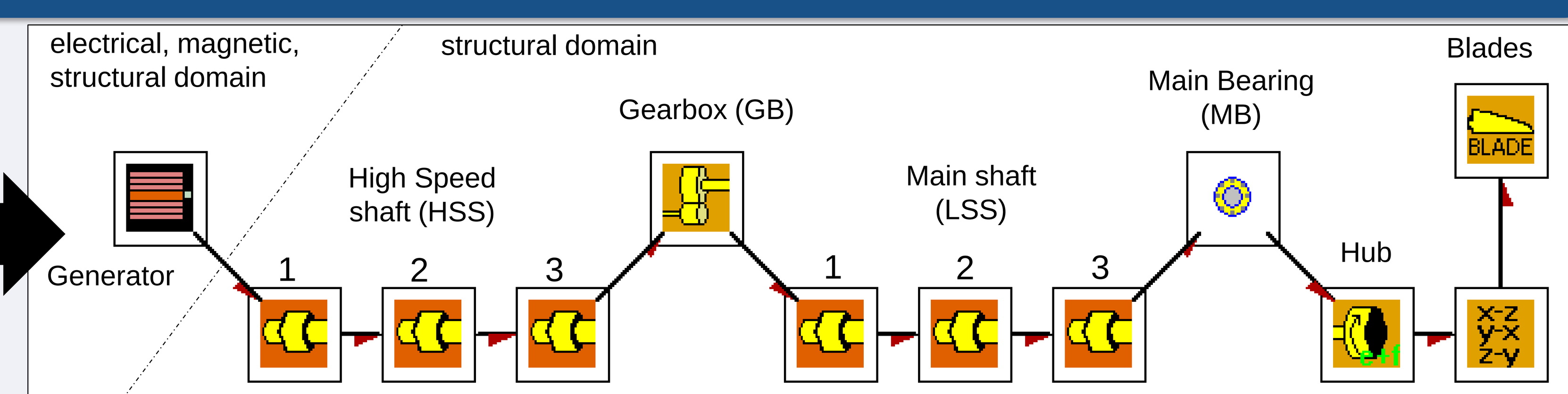


Fig.2. parametric wind turbine model using bond graph submodel capsules in SYMBOLS Sonata

Phase II - system analysis and load determination

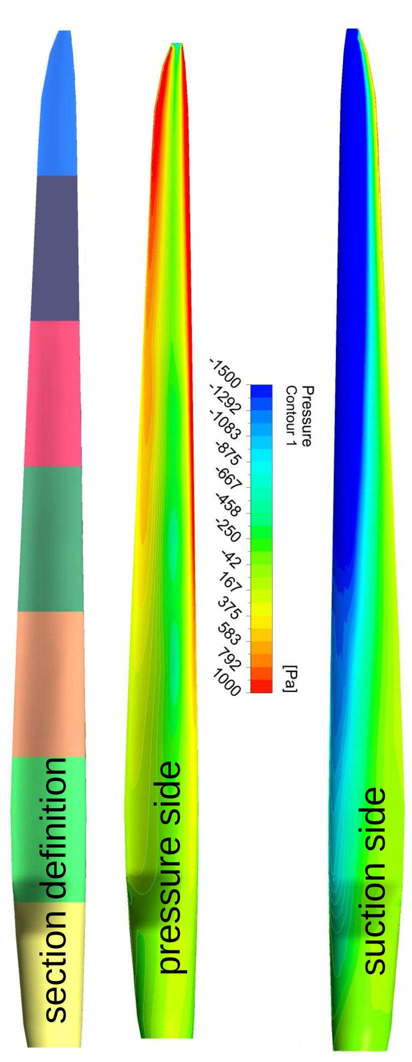
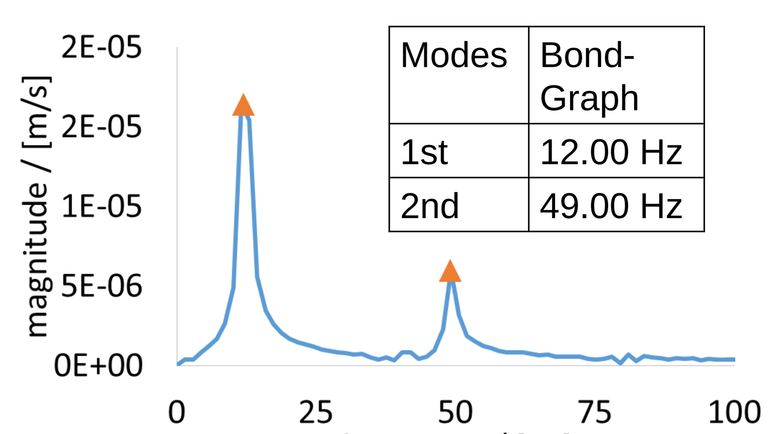
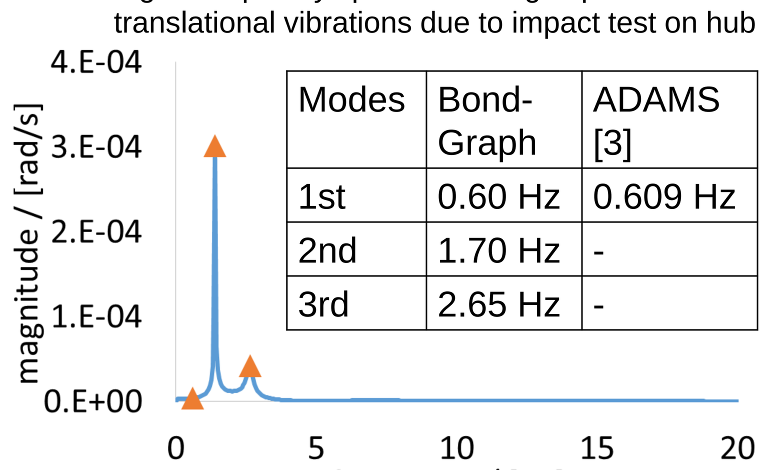


Fig.3. NREL 5MW reference turbine blade. CFD-Results for pressure load and section definition using Ansys CFX



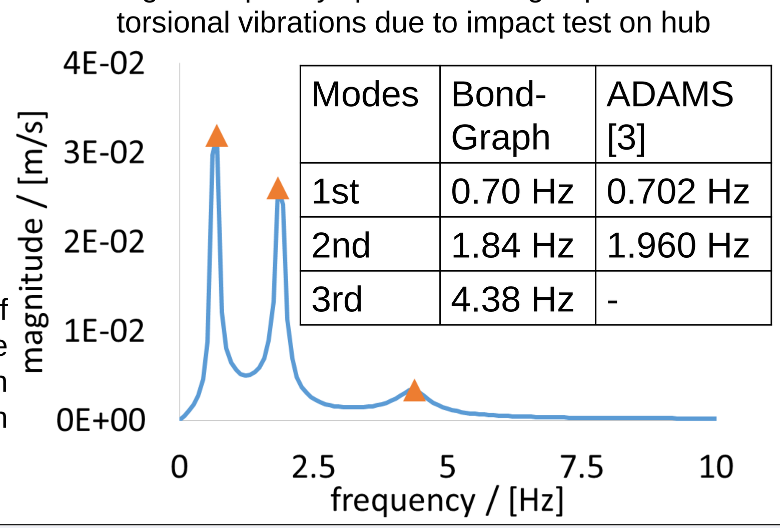
Modes	Bond-Graph
1st	12.00 Hz
2nd	49.00 Hz

Fig.4. frequency spectrum of high speed shaft translational vibrations due to impact test on hub



Modes	Bond-Graph	ADAMS [3]
1st	0.60 Hz	0.609 Hz
2nd	1.70 Hz	-
3rd	2.65 Hz	-

Fig.5. frequency spectrum of high speed shaft torsional vibrations due to impact test on hub



Modes	Bond-Graph	ADAMS [3]
1st	0.70 Hz	0.702 Hz
2nd	1.84 Hz	1.960 Hz
3rd	4.38 Hz	-

Fig.6. frequency spectrum of blade tip axial out-of-plane vibrations due to impact test on blade middle section

Phase III - initialization of rotary movement due to electrical grid connection of induction machine and CFD – loads on blades sections

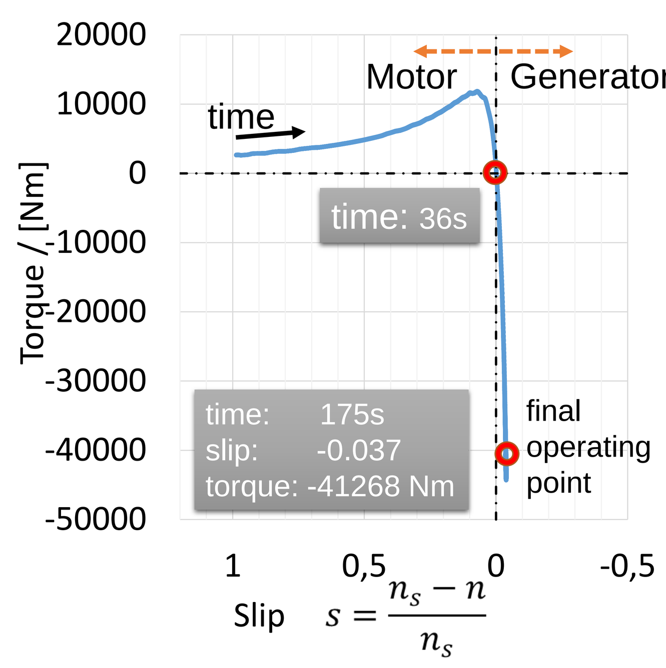


Fig.7. starting behavior of induction machine connected to an electrical network

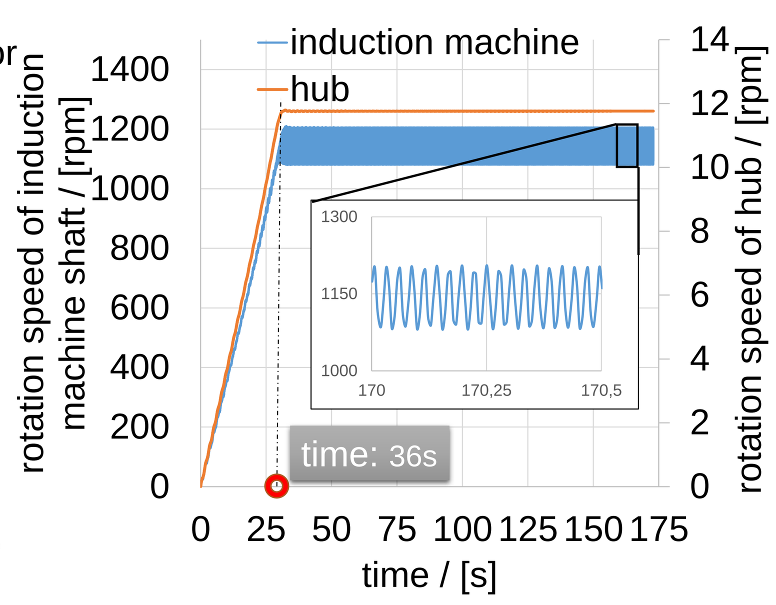


Fig.8. rotation speed and torsional vibration of induction machine shaft while initialization and during operation

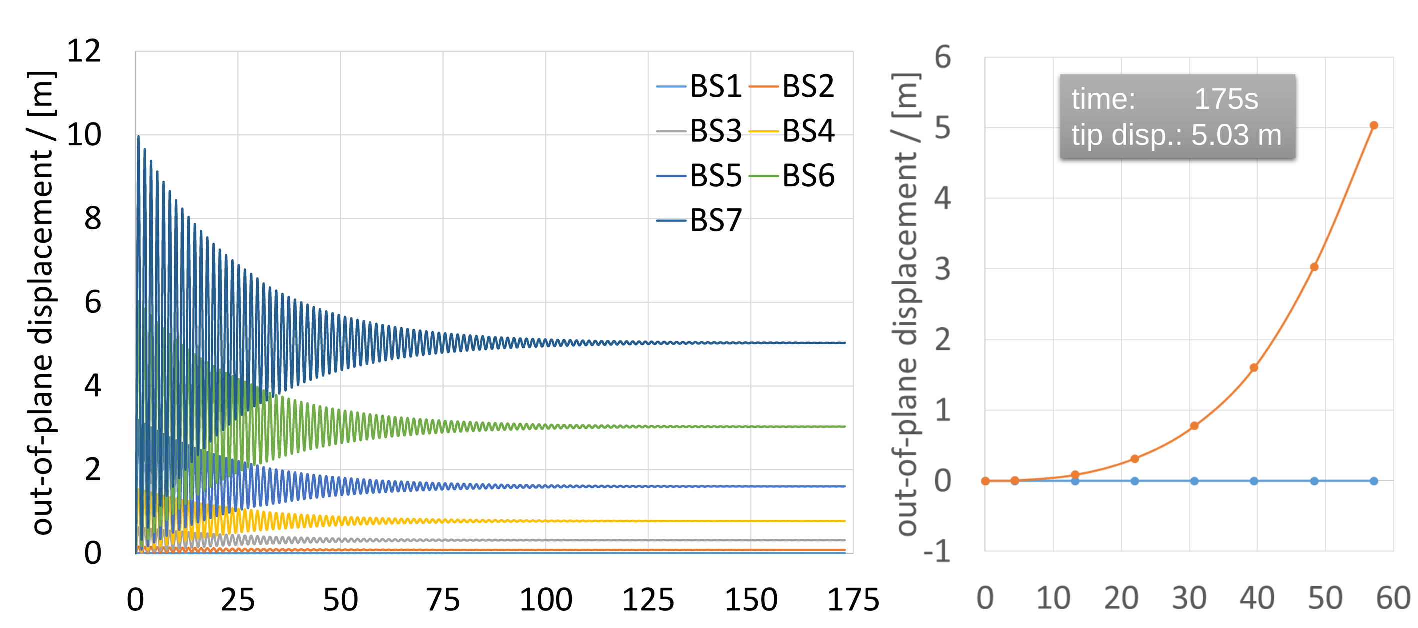


Fig.9. transient out-of-plane displacement of blades sections due to steady state CFD-loads and final converged displacement after 175 s

Phase IV – complex system dynamic analysis considering gravitation, eccentricity and gyroscopic effects

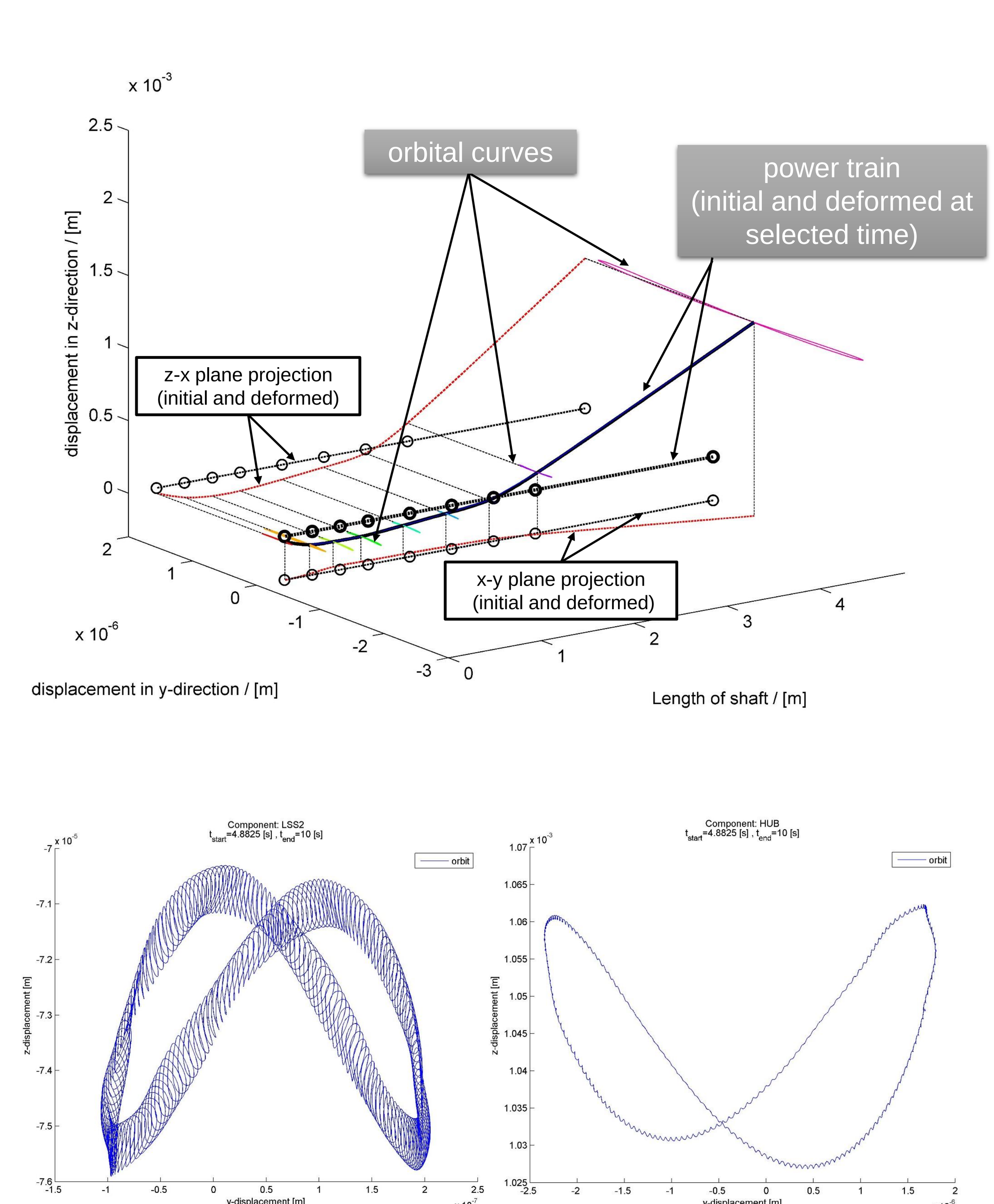


Fig.10. Orbital displacement of power trains and selected components due to gravity load in positive z-direction and eccentricity of hub mass considering torsional vibrations and gyroscopic effects

PHASE I: Parametric model of NREL 5MW reference turbine has been developed using bond graph approach (fig. 1-2). Input parameters have been selected according to [3].

PHASE II: Steady state loads are derived from CFD-Simulation at center of gravity for each pre-defined blade section (fig. 3) using rated rotor and wind speed (12.1rpm;11.4m/s). Impact test in translational and rotational direction is conducted on hub. Fast Fourier Transformation is applied to corresponding velocity-time signal of high speed shaft center for determination of system eigenfrequencies (fig. 4-6). 1st blade and 1st torsional powertrain natural frequencies are in very good agreement to published results [3].

PHASE III: System is being initialized using electrical grid connected induction machine (650V,3 pole pairs, 50Hz net frequency) and derived CFD-loads (mapped to the blade sections). System is simulated for 175s. Up to 36s the induction machine is acting as motor and adding power to the shaft because rotational velocity of high speed shaft is below synchronous speed. Here slip is decreasing from 1 to 0 (fig. 7). After 36s it can be observed that torque at high speed shaft is getting negative value due to superior aerodynamic load on rotor. Rotor speed is converging to a constant mean value above synchronous speed (fig. 8). Therefor slip is negative and the induction machine is acting as a generator as it is expected. Furthermore CFD-loads are causing out-of-rotor-plane-deflections of the blade (fig. 9). Observed vibrations are damped out slowly and after 175s a converged steady-state displacement can be obtained (fig. 9 right). Final blade deformation at rated load is in good agreement to published values [4].

PHASE IV: Within this phase the initialized rotating, quasi-stationary system is charged with gravity load in positive z-direction, perpendicular to the power train. Moreover eccentricity of hub mass from its rotational axis is set. This leads to a transient periodic load at hub center. This complex system is simulated for 10s. As a result the system is leaving balanced state and lumped masses of all components are orbiting. The orbital shape is determined by rotational speed, torsional vibration, gyroscopic effect and gravity load of interconnected components (fig. 10).

Conclusions

Bond graph methodology can be used to achieve robust and reliable tool, which is capable of describing the dynamic behavior of rotating components in diverse energy domains for industry applications. Parametric and generic model of wind turbine can be used for any size of wind turbine to estimate system eigenfrequencies and predict real time behavior of different component for various boundary conditions. This method empowers the engineer to observe losses in different power domains, which allows optimization and pre-design of all components. Level of detail can easily be adjusted to fit engineering needs.

References

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