Time domain response of a 3 blade HAWT considering fluid-structure interaction

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Long Abstract

Introduction

Wind turbines are non-linear structures consisting of both rotating and non-rotating substructures made of different materials. Designs of large scale horizontal axis wind turbines are optimized for weight and strength making them very flexible dynamically. Wind turbines are subjected to periodic loads due to blade rotation, change in wind velocities with height, influence of tower and turbulent wind gusts. Wind turbine blades are made of aerofoil cross sections to generate aerodynamic forces when wind blows over their sections. These forces turn the wind turbine rotor which is connected to a generator to produce electricity. Wind is a random phenomenon which changes in both space and time. Wind velocity can be regarded as a mean value with superimposed random fluctuations and gusts, this mean value also changes with height which is known as wind shear. In case of horizontal axis wind turbines (HAWT), different cross-sections of the blade experience different wind velocities based on the height and due to the rotation of the blade, periodic wind velocities are experienced at each blade section. Blades experience periodic aerodynamic loads due to wind shear with frequency equal to rotational speed, generally denoted by 1P. In case of upwind wind turbines, when the blade is in front of the tower during the rotation, tower creates an obstruction to wind to flow over the blade. This reduces wind velocity blowing on the blade which is known as tower shadow effect. Each blade passes the tower once per one turbine revolution. Torque and power characteristics in case of a typical 3 blade HAWT will be periodic with frequencies 1P and 3P. Wind shear contributes to the 1P frequency and tower shadow contributes to 3P frequency (known as blade passing frequency). Large scale HAWT operate at very low rotational speeds and are subjected to excitations of frequencies 1P, 3P. The blades of HAWT are generally designed to have their first natural frequency above these excitation frequencies. Fundamental vibration modes of all the substructures contribute more to the vibration response at low rotational speeds of the wind turbine than the other higher vibration modes. In order to perform a dynamic analysis of wind turbines, we need a detailed structural model and loads predicted from the aerodynamic analysis of blades. Wind is a dynamic phenomenon and forces flexible blades to vibrate. Rotation of the blades and vibrations of the blades changes effective wind velocity generating aerodynamic forces. Thus structural and aerodynamic analyses of the wind turbine are coupled to each other and dynamic behavior of the structure can be accurately predicted considering this coupling. Finite element methods (FEM) are used to model structural behavior and computational fluid dynamic (CFD) techniques are used for predicting aerodynamic loads. Coupled analysis using detailed FEM and CFD models is computationally expensive for parametric studies in the design stage. To determine the influence of this coupling on the dynamic behavior, simple models for structure and aerodynamic calculations are used in this study.

1. Method

In this study, 10 degree of freedom (DOF) model of a wind turbine structure (shown in Fig.1) is derived considering fundamental vibration modes of all the substructures. Non-linear coupled differential equations are linearized by assuming small angle oscillations for all the DOF. Blade element momentum (BEM) theory is used for calculating quasi-steady aerodynamic loads acting on the blades. Wind shear is modeled using power law for a mean wind speed at nacelle height. Tower shadow is modeled using potential theory of flow around a cylinder for calculating wind velocity near the tower. Simple models for structure considering first vibration modes of the substructures and aerodynamic model considering wind velocity changes due to height, tower shadow and blade vibrations are used to perform coupled dynamic analysis of the wind turbine. NREL 5 MW model wind turbine data (Ref. [1]) is considered as an example for this study. This wind turbine is designed to operate at a constant speed; pitch angles of the turbine blades are changed using control systems to produce its rated power. Wind turbine rotating at its rated speed 12.1 rpm is analyzed for various wind speeds, and vibrations of the wind turbine structure are obtained. Results are compared for cases with and without considering coupling between structural and aerodynamic analysis. Tangential forces acting on the blades and mechanical power generated in the wind turbine obtained from an uncoupled aerodynamic analysis are plotted in Fig. 2. Vibration behavior of tower fore-aft and blade in-plane DOF are plotted in Fig. 3 which are obtained from an uncoupled structural analysis of 10 DOF model.

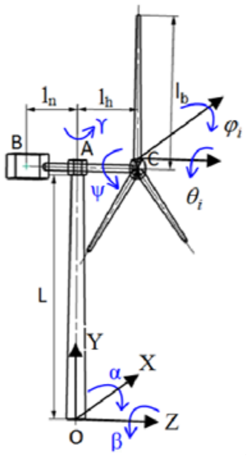

Figure 1. Wind turbine model

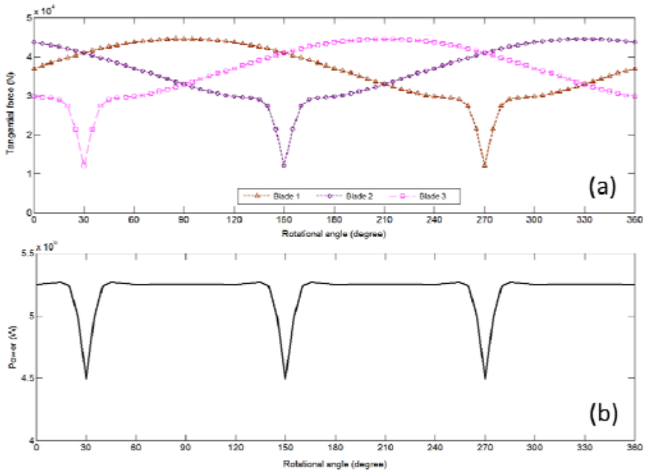

Figure 2. **(a)** Blade tangential forces, **(b)** Power curve

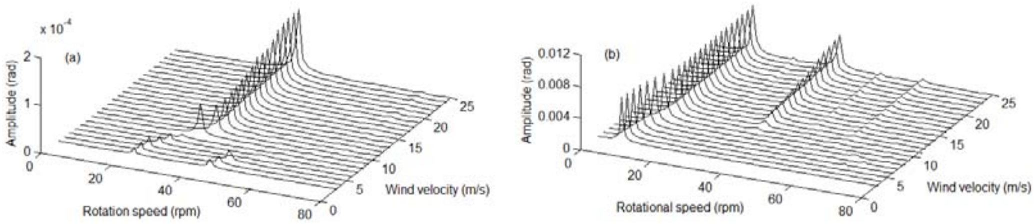

Figure 3. **(a)** Tower oscillations (α DOF), **(b)** Blade in-plane oscillations (θ_i DOF)

References

[1] Jonkman, J., Butterfield, V., Musial, W. and Scott, G., 2009, “Definition of a 5-MW Reference Wind Turbine for Offshore System Development”, National Renewable Energy laboratory, Technical report, NREL/TP-500-38060.