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Vibration-based structural health monitoring of a wind turbine system. Part I: Resonance phenomenon

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ABSTRACT

This paper is focused on a resonance phenomenon of a wind turbine system in 5 MW class, on the basis of dynamic signals acquired continuously from the tubular tower under normal operational conditions during two years.

Firstly, technique specifications of the wind turbine system are introduced and a finite element model is developed to characterize the structural dynamic properties. The following part describes the continuous dynamic monitoring system integrated with an automated operational modal analysis procedure using the poly-reference Least Squares Complex Frequency domain (p-LSCF) method. Subsequently, variations and mutual relationships of environmental/operational factors such as vibration amplitude, temperature, wind speed, rotation speed of blades, pitch angle and nacelle direction are also presented. Finally, significant resonance is observed due to the fundamental frequency of the tower matching with the harmonic frequency induced by the rotation of three blades. As the rotation speed of rotor approaches to 8 rpm, the vibration amplitude of the tower increases significantly and the corresponding damping value decreases. With the further rising wind velocity, the rotation speed of blades stops increasing and the input energy just contribute to accumulate the vibration amplitude of tower. Such observation indicates the Sommerfeld effect that aggravates the resonance phenomenon. A vibration control device is necessary to minimize the excessive structural responses.

A companion paper will further discuss the environmental/operational effects on dynamic properties of the wind turbine system under the operational conditions.

1. Introduction

This paper describes the significant resonance phenomenon of a wind turbine system under normal operational conditions, on the basis of the automated operational modal analysis (OMA) of the acceleration signals recorded continuously by the Structural Health Monitoring (SHM) system implemented on the wind tower.

The continuous aging and subsequent deterioration of a large number of existing structures, together with the general social concern about the safety of vital infrastructures and the demand to validate the predictions provided by numerical models of new structures with increasing complexity have encouraged the theoretical, methodological and technological developments of vibration-based SHM technology for the evaluation of civil infrastructures. Successful implementation and operation of SHM system for civil infrastructure have been widely reported in [1–7].

Recently, SHM technology has been receiving considerable interest in the field of wind power generation. Implementation of an SHM system not only provides an efficient health indicator for early damage detection, but also assists in understanding the dynamic behaviors of a wind turbine system under normal operational conditions. With the increasing size of the wind turbine system for harvesting more energy, the dynamic interaction between the different structural components is still not sufficient, though such issue has attracted considerable research attention. Theoretically, Gasch and Twele suggest that the significant resonance phenomenon of the wind turbine system will be observed when the structural frequencies agree with the frequency resulting from mass unbalance of blades and the harmonic frequencies due to blade passage of tower [8]. In [9], Brasil et al. simplify a wind turbine system as an unbalanced rotor on a supporting tower and so-called Sommerfeld effect is addressed. Murtagh et al. perform a time-domain forced vibration analysis of the wind tower considering the dynamic interaction between the tower and the blades

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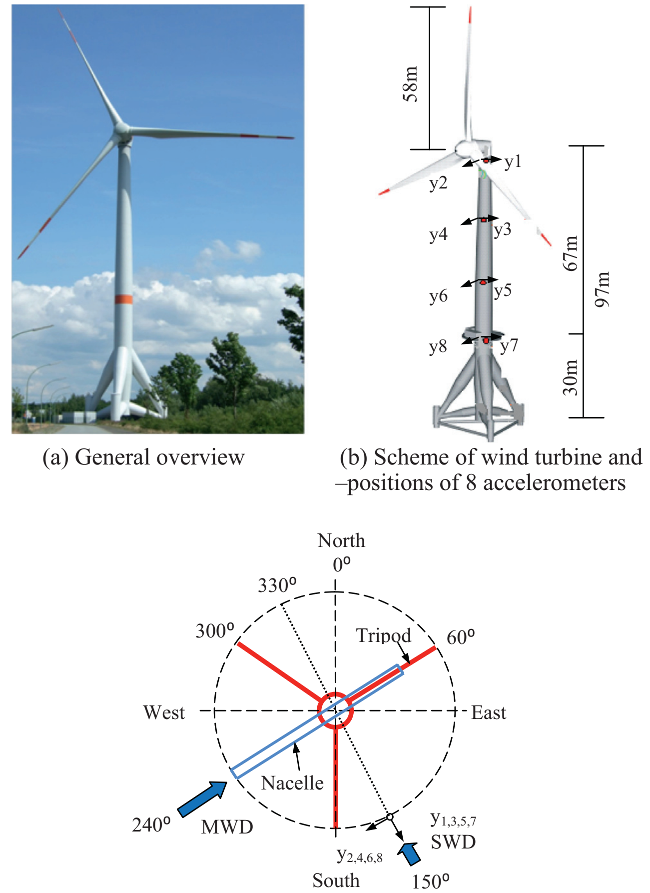
[10]. Recently, Liu performed a numerical vibration analysis by further considering the wind turbine system as a blade–carbin-tower coupling system [11]. Staino and Basu proposed a muti-modal mathematical model describing the dynamics of flexible rotor blades and their interaction with the turbine tower, taking the variable rotor speed into account [12]. Nevertheless, hardly any prior works focus on experimental research of the dynamic interaction between the tower and the blades under normal environmental/operational conditions using actual measurements within several years, though they are critically important for design verification, optimization and structural operation maintenance.

These companion papers focus on the experimental research on the dynamic behaviors of the wind turbine system with the purpose of building a health monitoring system. In the current paper, the resonance phenomenon is discussed in detail and the reasonable explanations of such phenomenon are presented based on the Sommerfeld effect theory. It is divided into four main parts: The first part generally introduces the wind turbine system in 5-MW class and a finite element model. The second part presents a continuous dynamic monitoring system integrated with automatic operational modal analysis algorithm on the basis of the poly-reference Least Square Complex Frequency domain (p-LSCF) method. Variations and corresponding statistical analysis of different environmental/operational factors acquired in two years are also illustrated. The interaction between wind speed, rotation speed of the blade, the pitch angle and the nacelle direction are presented in order to describe the operational status of the wind turbine. Subsequently, the analytical and experimental Campbell diagrams are presented. It is observed that the harmonic frequencies due to the blades passing the tower cross the various frequencies involved with the fundamental bending mode of the tower and the vibration modes of blades. Especially, resonance occurs when the rotation speed of blades approaches 8 rpm that matches the tower's fundamental frequency. The vibration amplitude of the tower increases significantly and the identified damping value decreases due to the variation of the aerodynamic damping. At the same time, the rotation speed of blades stops rising and input energy only contributes toward increasing the vibration amplitude, until the rotation speed jumps to a higher value and passes the resonance when enough energy is available. It indicates the Sommerfeld effect makes the wind tower always get stuck in the resonance state [9,13–15]. Finally, the discussion of the experimental results and conclusion are presented.

2. Prototype of Areva Multibrid M5000

A prototype of a 5-MW wind turbine system, Areva Multibrid M5000 (Fig. 1), was built and tested from 2007 in the first German offshore wind energy test field in the North Sea, preparing for the production of the commercial offshore wind power system. Table 1 lists the main characteristics of the wind turbine [16]. The ideal relationship between electrical power and wind speed measured in the Hub is shown in Fig. 2. In the design phase, it is assumed that the generation of electrical power increases gradually when the wind speed ranges from 4 m/s to 12.5 m/s and is stable around 5000 kW as the wind velocities are larger than 12.5 m/s. When the wind velocities are above 25 m/s, the rotor blades will stop working in order to avoid potential damage caused by excessive wind loads. Under normal operational conditions, the direction of nacelle changes automatically with the wind direction in order to produce the maximum rotation speed of rotor blades. According to statistical analysis in the design phase, the main wind direction (MWD) is along the Southwest direction and the secondary wind direction (SWD) is mainly distributed perpendicular to the MWD, as shown in Fig. 1(c).



(a) General overview

(b) Scheme of wind turbine and –positions of 8 accelerometers

(c) Plane view of the wind turbine and wind direction

Fig. 1. The prototype of wind turbine M-5000_2, positions of 8 accelerometers on the tower and wind directions.

Table 1
Technical specifications of the prototype of Areva Multibrid M5000.

General		*Rotor*	
Rated power	5000 kW	Rotor diameter	116 m
Design life time	20 years	Number of blades	3
Cut-in wind speed	4 m/s	Lowest rotation speed	4.5 rpm
Rated wind speed	12.5 m/s	Rated rotation speed	14.8 rpm
Cut-out wind speed	25 m/s	Highest rotation speed	14.8 rpm ± 10%
Tower		*Support foundation*	
Type	Tubular tower	Type	Tripods
Height	67 m	Height	30 m

3. Finite element modeling

In order to characterize the dynamic properties of the wind turbine, a three-dimensional numerical model was developed as shown in Fig. 3 [17], representing the wind turbine in an idle state.

The support structure of the wind turbine comprises a tubular tower, a tripod and foundations. The tower is divided into three segments by ring flanges. The tripod consists of upper braces, lower braces and pile guides. The pile guides contain reinforced concrete and shear connectors that are welded to the internal surface of the pile guide. The foundation consists of circular reinforced concrete slabs attached to a pile group. The reinforced concrete slabs and pile groups were explicitly modeled and in this way