ARTICLE IN PRESS

ISA Transactions xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Practice article

Output-only modal analysis of wind turbine tower based on vibration response under emergency stop

Aijun Hu, Jun Zhao, Ling Xiang*

Department of Mechanical Engineering, North China Electric Power University, Baoding 071003, Hebei Province, China

ARTICLE INFO

Keywords:
Output-only modal analysis
Vibration response
Wind turbine tower
Emergency stop
VMD

ABSTRACT

The identification technique of output-only modal parameters is proposed for the large wind turbine tower under emergency stop. Compared with the response of regular operating conditions, the immediate tower structural response under emergency stop much more resembles a state of free vibration, which is more appropriate for the modal identification of the wind turbine tower. The vibration response is measured in the nacelle, which is easy to perform in the field modal test. The variational mode decomposition (VMD) is applied to decompose the vibration response into several band-limited intrinsic mode functions. The free responses of decomposed functions are extracted by applying the random decrement technique (RDT). Finally, the modal damping ratio and natural frequency are identified from each free modal response by using the Hilbert transform method. Simulations and a 1.5 MW wind turbine field modal test results verify the effectiveness of the proposed identification method. The main modal parameters of wind turbine, including weak modes, are effectively extracted by using output-only vibration responses under emergency stop. The modal parameter identification method is provided for the large wind turbine structure under the engineering condition.

1. Introduction

Over the decades, wind energy has recently gained much attention from researchers [1]. With the sizes of modern wind turbines increasing, their dynamic behaviors get more complicated. Analyzing and experimentally measuring the modal parameters, natural frequency and modal damping, for instance, of wind turbine structures became more important to successful design and operation. The traditional Experimental Modal Analysis (EMA) techniques have been widely developed and employed in wind turbine structures, which extract modal parameters from input and output data. The different methods such as impact hammer modal testing, single-input multiple-output (SIMO) and multiple-input multiple-output (MIMO) measurement were used to extract modal parameters of the wind turbine [2]. A 600 kW wind turbine with 40 m hub-height is excited by shakers connected with cables in EMA [3]. Structural response characteristics and modal parameters are reported using shake table test on a full-scale 65-kW wind turbine with 22.6-m hub height [4]. Step-relaxation excitation method is used by Carne [5] in the field modal test of a 110 m Darrieus bladed vertical axis wind turbine (VAWT). The step-relaxation forces are applied to the wind turbine with a high strength cable and a diesel winch, which is located on the ground 100 m from the base of the turbine. As the sizes of modern wind turbines increase, it is usually a hard work to perform excitation in field testing of large wind turbines.

It is a substantial challenge to carrying out modal tests on large wind turbine structures. The operational modal analysis (OMA) is regarded as a key technique for the large and flexible structures. The approach was formally documented for modal testing in 1986 [5]. The OMA of structures subject to environment and natural excitations under operational states has attracted a lot of attention in engineering since 1990s [6]. The OMA method extracts modal parameters from mechanical system responses only, so it is also called output-only modal analysis [7]. Several ambient excitations are considered in OMA test of the wind turbine. Carne et al. have a series of study on modal parameter extraction from operating turbines with wind excitation, for example, the cross spectra analysis for a 110 m Darrieus bladed vertical axis wind turbine (VAWT) [5], the natural excitation technique (NExT) for a 34 m Darrieus VAWT [8] and a two-bladed upwind horizontal axis wind turbine (HAWT) [9]. Wind excitation is also adopted in the OMA of a 600 kW wind turbine with 40 m tall hub [3], a two blade 11 kW downwind turbine with 18 m tubular steel tower [10], a 40 kW wind turbine with 21 m steel tower height [11]. Human power is also utilized to pull the structure and excite the free vibration response of a 21 m tall steel tower [11]. It is reported that sometimes a few modes cannot be well excited by the wind [3]. Ambient excitation (wave and wind) and overspeed stop test are performed in the modal analysis for a 3 MW

* Corresponding author.
E-mail address: ncepuxl@163.com (L. Xiang).

https://doi.org/10.1016/j.isatra.2018.07.035
Received 30 November 2017; Received in revised form 24 July 2018; Accepted 26 July 2018

offshore wind turbine with 72 m with hub height [12]. The first natural frequency and modal damping are obtained in the condition measurement [12]. The damping ratios at different tower level are identified [13]. "Rotor-stop" tests are also used to obtain the natural frequency and modal damping of offshore wind turbines at four offshore wind parks [14]. Rotor-stop condition can cause obvious decay process of the wind turbine.

Emergency stop is an ambient operating condition of wind turbine. It is can be triggered by many events, a fault within the control system, high grid loading or manually triggered by the emergency stop buttons [15], for instance. The global motion and dynamic structural response of the wind turbine can be activated during emergency stop. Compared with the response of regular operating conditions, the emergency stop can be treated as a step-relaxation. The large amount energy can be input to the wind turbine. The immediate tower responses represent a wider frequency range of high signal energy. So the response data can be used to identify the wind turbine structures. In this paper, the output-only responses under emergency stops are proposed for the modal parameters identification of a 1.5 MW onshore wind turbine with 70 m tower height.

Frequency domain and time domain technique still are the critical groups of output-only system identification methods. For example, Brincker et al. [16] used frequency domain decomposition (FDD) to practice modal identification from ambient responses. In next year, Brincker et al. [17] enhanced frequency domain decomposition to identify damping. However, frequency domain methods are based on Fourier transform, which is adapted to the time-period vibration signals, so the local characteristics for identification of time-varying system may be erased. Because of the limitation, the time domain methods have further progressed. Some classical methods such as Ibrahim time domain (ITD) method, its upgrade method and other methods are illustrated and applied in literature [18–25]. The time domain methods can directly use the measured vibration responses from time-varying system, therefore, the disadvantages of the frequency domain methods, such as errors caused by aliasing, leakage and other reasons could be avoided. Yang et al. [26,27] performed the modal identification of linear structures through adopting Hilbert-huang transform (HHT) method. Subsequently, the identification method of the instantaneous characteristics of the nonlinear multi-degree of freedom (MDOF) structures based on the Hilbert transform (HT) and the empirical mode decomposition (EMD) was presented by Huang and Lou [28]. On the basis of EMD, Pines and Salvino [29] extracted phase information from transient signals in structural health monitoring. However, some deficiencies related to the EMD process is found in Ref. [30]. Bao et al. [31] provided a novel improved Hilbert-Huang transform (HHT) algorithm for identification of time-varying systems and analysis of nonlinear structural response with closely spaced modes. The RDT-AMD (analytical mode decomposition, AMD) is reported for building system identification [32]. The effectiveness of variational mode decomposition (VMD) is validated by Abdollah et al. for shear frame and footbridge system identification [33].

Based on the researches, this paper presents a new system identification routine that uses output-only vibration responses under emergency stop to identify the parameters of the wind turbine tower. The VMD [34] is used to decompose the measured responses in time domain, which consists of a series of modal responses. Then, the random decrement technique (RDT) is used to acquire the free responses from each modal response. Finally, the natural frequency and the modal damping ratio can be recognized from each modal free response by using the Hilbert transform (HT) method. The field modal test can easily be performed using accelerometer in the nacelle under emergency stop condition. The large amount energy can be supplied by the emergency stop, which makes it suitable for the field test of large wind turbine structure with low modal frequencies. The modal parameters of the dominant mode and weak modes of the wind turbine tower are identified by VMD-RDT method. The remainder of this paper is organized as follow: Section 2 introduces the VMD algorithm, random decrement technique (RDT) and Hilbert transform. Section 3 presents the numerical analysis results of two responses, which are damped free vibration response without noise and with white Gaussian noise of a MDOF system. Section 4 dedicates the implementation procedure of the proposed identification routine of the wind turbine tower, and the modal analysis results are showed in this section. In the end, in section 5, the conclusions are demonstrated and some further study direction proposals are discussed.

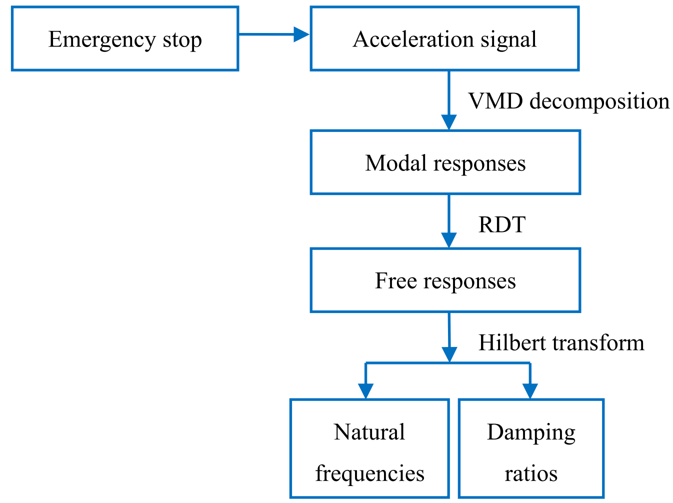

Fig. 1. Schematic diagram of the proposed method.

2. Identification algorithms

Fig. 1 illustrates the schematic diagram for the modal parameter identification using VMD-RDT method under emergency stop. The method consists of four main steps: 1) The vibration signal under emergency stop is acquired by accelerometers mounted in the nacelle. 2) VMD is used to decompose the measured responses in time domain. 3) The random decrement technique (RDT) is used to obtain the free responses from each modal response. Finally, the natural frequency and the modal damping ratio can be recognized from each modal free response by using the Hilbert transform (HT) method. Each of these steps is described in the following sub-sections.

2.1. Variational mode decomposition (VMD) method

EMD is widely used in non-stationary signal process. However, as a recursive decomposition model, EMD is known for limitations like mode mixing, end effect and sensitivity to sampling and noise. Recently, Dragomiretskiy and Zosso proposed a novel and non-recursively adaptive time-frequency analysis method, the variational mode decomposition (VMD). VMD can decompose a complex and real valued multi-component signal into a discrete number of sub-signals whose bandwidths are estimated using the H1 Gaussian smoothness of the demodulation signal.

The decomposition process of VMD is the process of solving variational problems, which makes the sum of estimation bandwidth of each mode minimum. The resulting constrained variational problem for any given non-stationary input signal *x(t)* in VMD is written as

$$\begin{cases}\min\limits_{\{u_k\},\{\omega_k\}}\left\{\sum_k \left\|\partial_t\left[\left(\delta(t)+\frac{j}{\pi t}\right)*u_k(t)\right]e^{-j\omega_k t}\right\|_2^2\right\}\\ \text{s.t.}\ \ \sum_k u_k = f\end{cases} \tag{1}$$

Where $\omega_k = \{\omega_1, \omega_2, \cdots, \omega_K\}$ is the center frequency of each intrinsic mode components, $u_k = \{u_1, u_2, \cdots, u_K\}$ is the corresponding all intrinsic