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Discrepancy study of modal parameters of a scale jacket-type supporting structure of 3.0-MW offshore wind turbine in water and in air

Fushun Liu [a, b, *], Qi Yang [a], Huajun Li [a, b], Wei Li [c], Bin Wang [c]

[a] College of Engineering, Ocean University of China, Qingdao 266100, China
[b] Shandong Province Key Laboratory of Ocean Engineering, Ocean University of China, Qingdao 266100, China
[c] Powerchina Huadong Engineering Corporation Limited, Hangzhou 310014, China

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ABSTRACT

The discrepancy of modal parameters of a scale offshore wind turbine is studied by using the proposed assessment method. One theoretical development is that weak genuine modes can be separated from strong noisy modes; and the other is the size of the reconstructed Hankel matrix will not be changed to ensure the comparability of modal parameters from different scenarios. A numerical signal is synthesized to demonstrate the proposed method. Numerical results indicate that the approach can isolate the two genuine modal parameters respectively, by applying estimated pass band with a 2 by 2 Hankel matrix of the Eigensystem Realization Algorithm, which means it can be used as a criterion to assess modal parameters from different scenarios. An experiment with model scale 15 from a 3.0-MW offshore wind turbine is tested. Experimental results indicate that natural frequencies are considerably reduced and damping ratios are increased, with the rate of frequency change varies from 15.33% to 17.97%. The modal parameters obtained in water with waves are close to those obtained in still water even if the structure is excited by a hammer or waves. The modal parameters estimated from the reconstructed responses of different accelerometers are in excellent agreement.

1. Introduction

Structural Health Monitoring (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. During the implementation of the SHM, a key step is the accurate estimation of modal parameters. Considering the fact that the true dynamic behavior of the structure are represented better through real response measurements, tests in laboratory scale have been conducted as an attempt to assess the dynamic behavior of the structure, usually from modal parameters such as frequencies, damping ratios and even mode shapes [1,2].

Theoretically, the modal parameter estimation problem of an offshore wind turbine, is no different than other types of offshore structures, like platforms or wave energy devices. Because the offshore structures are usually surrounded by water, modal analysis techniques for ambient excitations are generally employed and called operational modal analysis (OMA), and they can be classified by signal processing domain (time, frequency or time-frequency) or by model-based methods (parametric or non-parametric), such as the autoregressive moving average [3,4], eigensystem realization algorithm (ERA) [5], stochastic subspace identification [6], enhanced frequency domain decomposition method [7,8], and continuous wavelet transform [9–11]. Lindholm et al. [12] experimentally investigated the vibration of cantilever plates in air and in water, their results have been the benchmark for later investigations. Hu et al. [13] described the significant resonance phenomenon of a wind turbine system under normal operational conditions, on the basis of the automated OMA of the acceleration signals recorded continuously by the SHM system implemented on the wind tower. Du and He et al. [14,15] developed a method to

* Corresponding author. College of Engineering, Ocean University of China, Qingdao 266100, China.
E-mail addresses: percyliu@ouc.edu.cn (F. Liu), yqmessi@sina.com (Q. Yang), huajun@ouc.edu.cn (H. Li), weili018@163.com (W. Li), wangbindut@gmail.com (B. Wang).

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consider the water effect on the turbine runner by importing the added mass into the structural dynamic theory. They performed a simulation with mesh that included both fluid and structure, which produced several mode shapes and their corresponding frequencies. However, these references conclude that several operational modal analysis techniques should be used to process ambient vibration because there are always several discrepancies in the identified results.

Many researchers have also focused on developing the methods to predict natural frequencies accurately of offshore wind turbines, and the target could be the whole structure or just part of it, such as blades, gearbox, and supporting structure. An analytical method to calculate the natural frequencies of a rotating blade was presented by Southwell and Gough [16]. They proposed an equation which related the natural frequency to thee rotating frequency of a beam. Choi et al. [17] proposed the basic formulation to predict modal characteristics for mechanical systems including rotating blades. Park et al. [18] proposed a systematic formulation method to investigate natural frequency variations. Their work showed that the method was useful to predict the vibratory behavior of the rotating blade. About researches on gearbox, Helsen et al. [19] experimentally investigated a grid loss event on the Gearbox Reliability Collaborative drive train mounted on the NREL nacelle test rig. The driving torsional resonance is identified by means of a polyreference least-squares complex frequency-domain modal identification estimator. They also confronted the challenge of accurate modal parameter estimation. Feng et al. [20] proposed a time-frequency analysis method based on the Vold-Kalman filter and higher order energy separation to extract fault symptoms. The method is illustrated and validated by analyzing simulated and experimental signals of a planetary gearbox in a wind turbine test rig under nonstationary running conditions. The results have shown that the method is effective in detecting both distributed and localized gear faults. Related researches, such as the dynamic characterization testing of a turbine implemented by the National Renewable Energy Laboratory [21]. The tower was struck with a hammer and the resulting vibrations were measured with accelerometers. Liu et al. [22] used real measurements from a steel jacket-type offshore wind turbine experiment conducted in a water tank of Ocean University of China for modal parameters identification, and then an improved modal strain energy indicator was defined for damage localization. Recently, Liu et al. [23] proposed an improved modal parameter identification method by reconstructing a response consisting of only lower-order frequencies and applied this method to a real offshore jacket platform located in the northern region of Liaodong Bay, China. While how to assess these modal parameters using a same criterion was not discussed. In theory, a critical issue is the optimum determination for the dimensions of the block Hankel matrix (Juang 1994) [24]. Common procedure to obtain modal parameters is to choose different model orders intentionally in the modal parameter estimation process for different scenarios, and then a problem caused is that how to employ an unchangeable criterion to maintain the estimated modal parameters comparable in different scenarios, which means not only the same algorithm, but also the identical setting parameters.

The purpose of this study is to develop a universal method for identifying modal parameters and then they can be assessed by using a same criterion, when measured data of different sea states of offshore wind turbines are available. Firstly, a numerical signal with four components is synthesized to demonstrate the performance and illustrate the procedure of the proposed scheme. And then a scale jacket-type supporting structure of the 3.0-MW wind turbine experiment will be tested in air and in a water tank at the Ocean University of China, respectively, to study the discrepancies of the modal parameters using the proposed approach.

2. Preliminaries

2.1. Fourier transform

A periodic function $y(t)$ with period T can be represented in terms of complex exponentials [25] by

$$y(t) = \sum_{n=-\infty}^{\infty} c_n e^{i\omega_n t} \tag{1}$$

and

$$c_n = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} y(t)e^{-i\omega_n t}dt \tag{2}$$

where c_n are the complex Fourier coefficients of $y(t)$, and $i = -1$.

When $y(t)$ is given only in terms of values at finitely many points $y_k = y(t_k)$, $k = 0, 1, 2\cdots N-1$, where N is the number of sampled points, then Eqs. (1) and (2) could be rewritten

$$y_k = \sum_{n=0}^{N-1} c_n e^{i\frac{2\pi nk}{N}} \tag{3}$$

$$c_n = \frac{1}{N}\sum_{k=0}^{N-1} y_k e^{-i\frac{2\pi nk}{N}} \tag{4}$$

2.2. Traditional eigensystem realization algorithm

A time-invariant system can be described by

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}_c\mathbf{x} + \mathbf{B}_c\mathbf{u}\\ \mathbf{y} &= \mathbf{C}\mathbf{x}\end{aligned} \tag{5}$$

where $\mathbf{x}$, $\mathbf{u}$ and $\mathbf{y}$ are the state, input, and output vectors, respectively; and matrices $\mathbf{A}_c$, $\mathbf{B}_c$, $\mathbf{C}$ with appropriate dimensions represent the internal operation of the linear system.

The discrete-time version of the state-space representation is expressed as:

$$\begin{aligned}\mathbf{x}(k+1) &= \mathbf{A}\mathbf{x}(k) + \mathbf{B}\mathbf{u}(k)\\ \mathbf{y}(k) &= \mathbf{C}\mathbf{x}(k)\end{aligned} \tag{6}$$

where k is the time index, and constant matrices $\mathbf{A}$ and $\mathbf{B}$ are derivable from $\mathbf{A}_c$ and $\mathbf{B}_c$.

The traditional eigensystem realization algorithm (ERA) begins by forming the generalized Hankel matrix

$$\mathbf{H}(k-1) = \begin{bmatrix} \mathbf{Y}_k & \mathbf{Y}_{k+1}\cdots & \mathbf{Y}_{k+\beta-1}\\ \mathbf{Y}_{k+1} & \mathbf{Y}_{k+2}\cdots & \mathbf{Y}_{k+\beta}\\ \vdots & \ddots & \vdots\\ \mathbf{Y}_{k+\alpha-1} & \mathbf{Y}_{k+\alpha}\cdots & \mathbf{Y}_{k+\alpha+\beta-1}\end{bmatrix} \tag{7}$$

where $\mathbf{Y}_k = \mathbf{C}\mathbf{A}^{k-1}\mathbf{B}$, and α and β are the number of rows and columns of $\mathbf{H}$ respectively.

3. Modal parameters assessment for different experimental scenarios

Assume a measured response $y(t)$ from any experimental scenario can be decomposed into N_m components,