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Experimental study of improved modal strain energy method for damage localisation in jacket-type offshore wind turbines

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ABSTRACT

An improved modal strain energy method is proposed for damage localisation in jacket-type offshore wind turbines by defining a series of stiffness-correction factors that can be employed to calculate the modal strain energy (MSE) of the measured model without utilising the stiffness matrix of the finite element model (FEM) as an approximation. The theoretical contribution of this article is that the MSE of the measured model could be estimated with better accuracy, and the advantage of the proposed indicator is that it is more sensitive to damage locations than the traditional MSE method. Numerical studies on a tripod offshore jacket wind turbine reveal that the proposed method could locate the damage positions for jacket-type offshore wind turbines when limited number of lower-order modes is available, even when these modes are spatially incomplete. The performance of the proposed method is also investigated using real measurements from a steel jacket-type offshore wind turbine experiment conducted in a water tank of Ocean University of China. The experimental results demonstrated that the proposed method outperforms the traditional MSE method, and damages in jacket-type offshore wind turbines could be properly located utilising the first two measured modes excited by environmental loadings, such as waves, currents, or the vibration of the wind turbine.

1. Introduction

Over the past three decades, wind energy has become an attractive source of renewable energy and experienced a rapid development, especially offshore wind energy. Compared with onshore wind energy, the offshore wind energy provides better wind conditions with less turbulence and no visual or auditory annoyances. The global offshore cumulative capacity reached 2946 MW at the end of 2010 [1].

To date, most wind turbines have been installed on monopile or gravity foundations in shallow water. With the development of technology in offshore oil and gas industries, jacket foundations are regarded as an alternative for the intermediate water depths (30–80 m). The first offshore wind farm in the world with jacket foundations was installed in the Alpha Ventus Wind Farm (30 m water depth) in Germany in 2009. Using jacket foundations for offshore wind turbines has the advantages of having lower ultimate loads and employing mature technologies from the offshore and gas industries, as discussed by Shi et al. [2], who compared three types of foundation in a water depth of 50 m. Moll et al. [3] studied the added mass effect on the local jacket eigen frequencies using a fully coupled simulation under several design load cases. Shi et al. [4] designed and analysed a three-bladed NREL 5-MW offshore upwind variable speed, pitch collective control wind turbine on two different jacket support structures. The natural frequencies and significant loads of different jacket members obtained for the two models are expected to provide useful information for the construction of large-scale offshore wind turbines in Korea in intermediate water depths.

Jacket-type offshore structures are exposed to all kinds of external loads, such as waves, wind, earthquakes, ship-berthing impacts, and operational loads. Moreover, the maintenance and repair of offshore structures are much more difficult than those of large land-based infrastructures due to the difficulty of accessing the structures and the inherent characteristics of offshore environments. Therefore, structural health monitoring (SHM) systems with multiple sensors plays an important role in the operation of offshore wind turbine. In

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practice, there are almost no publicly available sources of long-term monitoring data for real utility-scale offshore structures; instead, numerical and/or lab-scale experimental studies are common. Hartnett et al. [5] presented a numerical simulation study for Kinsale Head Gas Production Platform Alpha, located off the southern coast of Ireland. They also identified five lower natural frequencies with acceleration data measured on top of the platform and compared them with calculated frequencies and investigated the effects of hydrodynamic mass on natural frequencies. Mangal et al. [6,7] proposed neural-network-based damage detection for jacket-type offshore structures and verified its performance using lab test results with a 1/35-scale model. Shi et al. [8] proposed the use of the change in the modal strain energy (MSE) of each element as a damage indicator, which was proven effective in locating structural damage. However, because the damage elements are unknown, the undamaged elemental stiffness matrix is used instead of the damaged matrix as an approximation during the calculation of the change of the modal strain energy (MSE). Li et al. [9] developed an effective damage localisation method for three-dimensional frame structures: the modal strain energy decomposition (MSED) method. The MSED method defines two damage indicators, the axial and transverse damage indicators, for each member. Analysing the joint information obtained from the two damage indicators greatly improves the accuracy of localising damage elements. However, the MSED method cannot satisfactorily estimate the corresponding damage severity. Li et al. (2008) [10] extended the Cross Model Cross Mode (CMCM) method to the damped systems for damage detection using spatially incomplete complex modes. A cantilever beam structure was used to demonstrate this method [11]. Recent researches on the beam and offshore platforms in water can be found in Refs. [12–13]. However, further studies have indicated that the method is sensitive to noise; thus, a more robust indicator is expected based on the CMCM method for damage localisation.

It is worthy of noting that the dynamic characteristics of jacket-type structures containing rotational machinery (wind turbines) are very important for evaluating the possibility of resonance and avoiding excessive resonant vibrations. In this paper, we will propose an improved modal strain energy method for locating damages in jacket-type supporting structures, aiming at providing good knowledge of the integrity of offshore wind turbines, by utilising dynamic responses from a number of sensors with the excitation of waves, currents, or wind turbines. A numerical jacket structure will be used to investigate the performance of the proposed method, and a steel physical model with a 1/15-scale will be tested in a water tank of Ocean University of China.

2. Preliminary: modal strain energy method

Shi et al. (1998) [8] employed the change of modal strain energy in each structural element before and after the occurrence of damage for locating damage in a structure, which were defined as.

$$\mathrm{MSE}_{ij} = (\boldsymbol{\Phi}_i)^t \boldsymbol{K}_j \boldsymbol{\Phi}_i \tag{1}$$

$$\mathrm{MSE}_{ij}^d = (\boldsymbol{\Phi}_{di})^t \boldsymbol{K}_j \boldsymbol{\Phi}_{di} \tag{2}$$

where MSE_{ij} and MSE_{ij}^d are the undamaged and damaged MSEs, respectively, which are functions of the jth undamaged element stiffness matrix $\boldsymbol{K}_j$, and the ith mode shape of the undamaged and damaged state, i.e., $\boldsymbol{\Phi}_i$ and $\boldsymbol{\Phi}_{di}$ respectively; subscript t represents transpose of a matrix. Because the location of the damage is unknown, the undamaged stiffness matrix is used in the damaged state as an approximation. Damage is assumed to cause a local stiffness reduction affecting the mode shapes nearby. Eq. (2) shows that when damage occurs in an element of a system, the MSEs will change little in the undamaged elements but significantly in the damaged elements. Thus, the modal strain energy change ratio (MSECR) could be a meaningful indicator for damage localisation, defined as

$$\mathrm{MSECR}_j^i = \frac{\left|\mathrm{MSE}_{ij}^d - \mathrm{MSE}_{ij}\right|}{\mathrm{MSE}_{ij}} \tag{3}$$

If the MSEs for several modes are considered together, the MSECR_j of the jth element is defined as an average of the summation of MSECR_j^i for all the modes normalised with respect to the largest value $\mathrm{MSECR}_{\max}^i$ of each mode.

$$\mathrm{MSECR}_j = \frac{1}{m} \sum_{i=1}^{m} \frac{\mathrm{MSECR}_j^i}{\mathrm{MSECR}_{\max}^i} \tag{4}$$

where m is the number of measured or used modes.

3. Improved damage localisation method for jacket offshore wind turbines

For the nth element, the ith mode for the baseline model or finite element model (FEM), and the jth mode for the damaged model, the MSE is given as.

$$\mathrm{MSE}_{ni} = (\boldsymbol{\Phi}_i)^t \boldsymbol{K}_n \boldsymbol{\Phi}_i \tag{5}$$

$$\mathrm{MSE}'_{nj} = \left(\boldsymbol{\Phi}'_j\right)^t \boldsymbol{K}'_n \boldsymbol{\Phi}'_j \tag{6}$$

where $\boldsymbol{K}_n$ and $\boldsymbol{K}'_n$ are a pre-selected stiffness matrix for the baseline and measured models, respectively. The stiffness matrix $\boldsymbol{K}'_n$ of the measured model is a modification of $\boldsymbol{K}_n$ via

$$\boldsymbol{K}'_n = \boldsymbol{K}_n + \alpha_n \boldsymbol{K}_n \tag{7}$$

where α_n are unknown stiffness correction factors to be determined, with $\alpha_n = 0$ in traditional MSE. To obtain α_n in Eq. (7), we assume that the jth eigenvalues λ'_j and eigenvectors $\boldsymbol{\Phi}'_j$ associated with $\boldsymbol{K}'$ and $\boldsymbol{M}'$ could be obtained based on modal analysis techniques, such as Eigensystem Realization Algorithm (ERA) or Stochastic Subspace Identification (SSI). Then, we can write

$$\boldsymbol{K}'\boldsymbol{\Phi}'_j = \lambda'_j \boldsymbol{M}'\boldsymbol{\Phi}'_j \tag{8}$$

Substituting Eq. (7) into Eq. (8) and pre-multiplying Eq. (8) by $\boldsymbol{\Phi}_i^T$ yields.

$$\boldsymbol{\Phi}_i^T \boldsymbol{K} \boldsymbol{\Phi}'_j + \sum_{n=1}^{N_e} \alpha_n \boldsymbol{\Phi}_i^T \boldsymbol{K}_n \boldsymbol{\Phi}'_j = \lambda'_j \boldsymbol{\Phi}_i^T \boldsymbol{M} \boldsymbol{\Phi}'_j \tag{9}$$

In Eq. (9), we assume $\boldsymbol{M}' = \boldsymbol{M}$ based on the fact that mass terms can usually be properly modelled and are unlikely to change significantly, even when severe damage occurs.

Rearranging Eq. (9), one obtains.

$$\sum_{n=1}^{N_e} \alpha_n \boldsymbol{\Phi}_i^T \boldsymbol{K}_n \boldsymbol{\Phi}'_j = \lambda'_j \boldsymbol{\Phi}_i^T \boldsymbol{M} \boldsymbol{\Phi}'_j - \boldsymbol{\Phi}_i^T \boldsymbol{K} \boldsymbol{\Phi}'_j \tag{10}$$

And Eq. (10) can be rewritten in matrix form as

$$\boldsymbol{S}_{(N_i \times N_j) \times n} \boldsymbol{\Gamma}_{(n \times 1)} = \boldsymbol{b}_{(N_i \times N_j) \times 1} \tag{11}$$

where N_i, N_j are mode numbers from baseline and measured model; N_e is the number of elements need to be corrected; and