Marine Structures 49 (2016) 163–179

Contents lists available at ScienceDirect

Marine Structures

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

Damage detection and localization method based on a frequency spectrum change in a scaled tripod model with strain rosettes

S. Opoka [a], R. Soman [a,*], M. Mieloszyk [a], W. Ostachowicz [a,b]

[a] *Institute of Fluid Flow Machinery PASci, Fiszera 14, 80-952 Gdansk, Poland*
[b] *Warsaw University of Technology, Narbutta 84, 02-524 Warsaw, Poland*

ARTICLE INFO

Article history:
Received 20 August 2015
Received in revised form 15 March 2016
Accepted 24 May 2016

Keywords:
Damage detection
Offshore support structure
Strain
FBG sensor
Integrity monitoring
Output-only

ABSTRACT

A method for detection and localization of a damage in a model of an offshore support structure is addressed in this paper. The damage has been simulated as a dismantled flange located in one of the upper braces of a tripod model. The strain measurements have been obtained from a network of Fibre Bragg Grating (FBG) sensors bonded to the model. The root mean square deviation (RMSD) estimator applied to a chosen part of averaged and smoothed frequency spectrum of the strain data has been considered here as a damage indicator. A capability of the method has been checked for the freely hanging model as well as for the tripod fixed to a table. Experimental results have been supported by numerical modal analysis using Abaqus software. The results show that additional peaks have appeared in some frequency regions revealing vibration modes which are associated with damage in the structure. Applying the RMSD estimator to the regions where new peak has emerged it is possible to detect the damage by comparing the same part of an averaged frequency spectrum of the same rosette before and after the damage or by comparing the spectra of two rosettes for model with the damage without referencing to the healthy state. The good localization performance of the RMSD estimator for some new frequency peaks can be justified by analysing the corresponding localized numerical maximal in-plane principal strain modes. The determination of damaged structural member is understood as the correct damage localization.

1. Introduction

Wind Energy is recognized as one of the most promising solutions to man's ever increasing demands of clean source of energy. Due to the limited availability of land, aesthetic reasons, the negative impact of onshore wind farms on human settlements and better wind characteristics the number of offshore installations is steadily increasing. The major hindrance of offshore wind energy is the relatively high cost of energy as compared to the conventional energy sources. In order to reduce this cost, the present trend is to build bigger wind turbines in deeper areas in order to harness the massive potential of the unfettered winds in the sea regions.

* Corresponding author.
E-mail addresses: szop@imp.gda.pl (S. Opoka), rohan.soman@imp.gda.pl (R. Soman).

http://dx.doi.org/10.1016/j.marstruc.2016.05.010
0951-8339/

The first offshore wind farm was constructed in 1991, in Denmark at 2.5 km from the coast at sea depths of 2.5–5 m [1]. With the advancements in science and technology next farms have been moved into deeper sea locations. The planned Kriegers Flak project is 30 km from the shore at a depth ranging from 20 to 40 m [2]. For the increased depth different designs of the support structures emerged in the last two decades. At the beginning in lower depths (<5 m) the gravity based foundation was the low cost solution fulfilling the structural requirements. For depths of up to 20 m the monopile foundation has become the offshore industry standard. The advantages of monopile are the comparatively easy design and production procedures, and as a consequence the comparatively low unit price per ton. For depths >20 m it is believed that more complex foundation types like a tripod become more competitive against the monopile due to the increased structural demands [3,4].

In addition to produce more electrical energy using bigger wind turbines, further savings can be gained by the reduction of the downtime periods and the optimal maintenance planning. The more efficient and cheaper maintenance devoted to structural part of the wind turbine can be obtained using the additional information about the condition of the structure from structural health monitoring (SHM) systems. The SHM applications based on passive and active measurement techniques are described in Refs. [5–8].

A low cost methodology for the assessment of the condition of the structure is through the analysis of its dynamic properties. The modal analysis is the procedure which reduces the complex information about structural vibrations to finite sets of vibration modes. In order to properly map FRF peaks to vibration modes the information regarding frequency spectrum of the excitation must be known. But in operational modal analysis [9,10], the lack of information about excitation is considered as more realistic assumption which also should be used in damage detection experiments. If the experiment on output-only system is performed a correct indication of the vibration peaks can be performed comparing the experimental results with the accurate finite element (FE) numerical model.

There are different definitions of deformation measures: natural strain, covariant strain, contravariant strain and engineering strain. All these measures can be unified into single measure for small deformations [11]. The measurement strain is based on the notion of the Lagrangian engineering strain where the reference length of the strain sensor (or reference wavelength of FBG sensor) must be specified. Strain sensors have been traditionally used for the fatigue lifetime monitoring [12]. Furthermore, the development of FBG strain sensors which offer advantages in comparison with conventional strain gauges like small size and weight, multiplexing capabilities, immunity to electromagnetic fields, high corrosion resistance [13] have made their use more desirable for permanent installation on offshore structures [14].

The conventional modal analysis is mainly based on acceleration measurements and the theory devoted to this method is strongly established [15]. This method was used for a tripod tower platform model in Ref. [16]. The comparison between modal analysis based on acceleration measurements and the strain modal analysis can be found in Refs. [17,18]. The use of strain modal analysis encounters theoretical problems like non-symmetrical form of matrices and hence has not been investigated in detail. Furthermore, the in-plane displacements (the engineering strain can be interpreted as the dimensionless normalized displacement or as the spatial derivative of the in-plane displacement) are of one order of magnitude less than the out-of-plane displacement (the direction most frequently used in acceleration measurements) especially for thin shells and plates. Thus, for obtaining good quality of strain data higher levels of excitation are required. But with the maturing sensor technology, and the advent of FBG sensors capable for underwater measurements, the measurement of strains for damage detection and localization purposes has been applied in the presented research. The paper proposes damage indicator based only on the analysis of sensors' frequency spectrum and shows its validity under different boundary conditions for the scaled model of a tripod structure.

The paper is organized as follows. In Section 2 tripod geometry, strain sensing network, experiments performed on the (un)damaged tripod model and a numerical approach for vibration analysis are described. In Section 3 results concerning damage detection and localization capability of the rosette network as well as numerical vibration modes for the tripod with free support conditions and for the tripod with fixed legs to the antivibration table are shown. The root mean square deviation (RMSD) estimator as a damage indicator is used here twofold. It compares parts of averaged frequency spectrum of the same rosette before and after damage or it is used for comparing corresponding parts of averaged frequency spectrum of two rosettes for damaged tripod without referencing to undamaged state. The initially flat part of the frequency spectrum must contain one new peak after the occurrence of damage. The conclusions are provided at the end of the paper.

2. Experiments and numerical simulations performed on a tripod structure

The first step in the proposed method is to ensure that new peak which appeared in experimental frequency spectrum is caused by the damage. For that purpose the comparison between the frequencies determined experimentally with those achieved from numerical FE simulations is performed. Next, the damage indicator is applied to the verified new peaks. The method is capable of detecting damage from every new peak. Additionally, if the strain mode shape is highly localized on the member with damage then damage localization can be performed if any sensor responds to this strain field. The localization of damage is understood as the localization of damaged member (upper brace, lower brace, pile guide etc.) rather than the exact location of damage on particular structural member. Some error originating from differences between the localization of sensors and damage is inherent feature of the method.