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Experimental study of strain prediction on wave induced structures using modal decomposition and quasi static Ritz vectors

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ABSTRACT

Offshore structures are continuously subjected to dynamic loading from wind and waves which makes fatigue an important parameter for the structures expected lifetime. Monitoring the vibrations of the structure using real time operating data enables an assessment of the general health state of the structure.

This paper proposes a method for an accurate full-field prediction of the strain history. Experimental mode shapes are found by the use of operational modal analysis and expanded to strain modes using a well correlated finite element model. The measured response from the structure is divided into two parts using complementary filters: Low frequency response caused by the quasi-static effect of the waves acting on the structure, and the high frequency response given by the modal properties of the structure. The high frequency response is then decomposed into modal coordinates using the experimental mode shapes. Strain histories are predicted by multiplying the modal coordinates with the expanded strain mode shapes. The low frequency response is decomposed using Ritz-vectors corresponding to the shapes that the structure vibrates with due to the wave loading. Strain Ritz-vectors are then extracted from the finite element model by applying a load corresponding to a representative wave and the strain history for the low frequency response is found by multiplying the decomposed signal with the strain Ritz-vectors. Finally the combined strain history is found by adding the strain histories from the low and high frequency responses.

To validate the theory tests were performed on a scaled model of an offshore structure where the strain history was predicted using only the response from the accelerometers.

1. Introduction

Measuring systems are increasingly being installed on offshore structures with the purpose of monitoring the current health of the structure. Offshore structures are often placed in rough environments and the continuous dynamic loading from the wind and waves makes the structures sensitive to accumulated fatigue. A weakening of the materials or development of cracks can be critical to the safety of the structure and a precise estimation of the dynamic behavior can therefore be of high value.

During the past couple of decades many researchers have been working within the area of damage detection and Structural Health Monitoring (SHM) [1]. One of the occurring problems is that many offshore structures are reaching the age originally planned in the design stage, but their current health state is unknown. Structures like these are very expensive and any increase of their lifetime could prove significant savings for the owners. One of the governed design parameters is accumulated fatigue which is calculated using conservative norms and standards. Fatigue calculations are based on the structures strain history, which is predicted using simulations of the platforms with expected wind and wave loadings. The framework for these simulations is defined by current norms and standards which are known to be conservative to some extent. The actual lifetime of offshore structures therefore might be higher than the lifetime the structures are designed for.

The strain history can be measured using resistance based strain gauges or fiber optic sensors. But the number of points where the strains can be measured will be limited due to the high cost of installing sensors. Furthermore most hotspots are placed below the water level making it challenging to install sensors on

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existing platform. A methodology for a full field strain estimation using a limited number of vibration sensors could prove valuable for civil structures subjected to continuous dynamic loading.

In recent years a number of researchers have taken an interest in the ability to estimate the dynamic response of advanced structures induced with wind and wave loading. In [2] the authors are investigating the response of a scaled jacket structure mounted with accelerometers and strain gauges. The experiments are carried out with the model being in air and in water, and the responses are compared with an analytical model.

The theory of modal decomposition is one of the most widely used techniques within strain estimation [3–6], and also play a large part in the proposed technique. Basically the response of a structure is measured using accelerometers, from which experimental mode shapes can be identified. The mode shapes are then expanded to strain coordinates using a well correlated FE model, and the strain histories can be obtained by multiplying the expanded mode shapes with the estimated modal coordinates. In recent years the use of no contact measurement systems has gained more and more attention. In [7] the response is measured using 3D point tracking and in [8] using stereophotogrammetry, both with the purpose of estimating strain histories.

An alternative to the modal decomposition technique for predicting strains is the use of Kalman filtering where the measured response in limited points of the structure is used as input. In [9,10] this technique is used to estimate the strains on an offshore wind turbine using measured accelerations. In [11] the authors use a similar technique to estimate the strain in an offshore truss structure.

In [12,13] the authors introduce a methodology for estimating strain in beams combining experimentally identified modes shapes and the Bernoulli-Euler beam theory. An analytical expression for the deflection of the beam between the measuring points is derived, and by differentiating the expression twice the strain can be predicted. The methodology is further developed to cover plates. The same methodology is presented in [14] where the authors use it to estimate the strain history of a monopole offshore wind turbine using measured accelerations.

In [15] the authors present a method for strain prediction, familiar to the method presented in this paper. Here the measured signal of an offshore wind turbine is divided into 3 different frequency regions: Near static, low frequency and high frequency regions. Response from the near static region is expanded using measured strains, since the accelerometers are too polluted with noise in this frequency range. The low and high frequency responses are expanded individually using the best performing accelerometers in each frequency region.

This paper presents a method for full-field strain estimation by combining experimental measurements with a well correlated Finite Element (FE) model. The measured response is separated in two parts using complementary filters. The wave load acting on the structure will force a quasi-static displacement of the structure below the waterline, whereas the part of the structure that lies above the waterline will perform a rigid body movement. Since the frequencies of the waves are lower than the first natural frequency of the structure, the quasi-static displacement caused by the waves can be separated from the full signal by low-pass filtering. This part of the signal is decomposed and expanded using Ritz-vectors that represent the displacement figure of the structure caused by the waves. The displacement of the structure in the high frequency region is primarily due to the dynamic properties. This part of the signal can be decomposed using experimentally obtained mode shapes, and expanded using the analytical mode shapes [16,17]. Finally the expanded signals from the low and high-pass filtered responses are added together to get the full strain history.

To validate the theory tests were performed on a scaled version of a typical tripod jacket platform. The structure was mounted with 12 accelerometers on the topside and at the top of the main column, and with 14 strain gauges on the tripod. A shaker was used to simulate the wave load. By using the proposed method strain histories were predicted and successfully compared with strains measured in the same points.

2. Theory

Normally the dynamic response of a structure is said to follow the rules of modal superposition meaning that the response can be described as a linear combination of the mode shapes and the modal coordinates. However the waves acting on a structure at frequencies lower than the first natural frequency, will only result in bending in the part of the platform that lies below the waterline, corresponding to an Operational Deflection Shape (ODS). The part of the structure that lies above the waterline will move rigidly. When only small displacements occur it is assumed that 2nd order effects can be neglected. The deformation shape of the structure due to wave load will in the following be denoted as Ritz-vectors.

The theory of using Ritz-vectors to analyze the response of larger civil structures is well known within structural dynamics where they are often used as an alternative to mode shapes. Especially the use of force dependent Ritz-vectors can be suitable for analyzing structures, subjected to horizontal ground acceleration as when a civil structure is subjected to an earthquake [18].

When the structure is excited at its first natural frequency it will move according to its first mode shape. Here bending is assumed all over the longitudinal direction of the structure and not just below the waterline. Fig. 1 illustrates the difference between the Ritz-vector and the 1st bending mode. Although the two shapes look alike, analyses show that there are significant differences when it comes to the strain distribution in the lower part of the structure.

Figs. 2 and 3 show how the signal from an offshore structure can be divided into a quasi-static response and a dynamic response. Fig. 2 shows the Power Spectral Density (PSD) of the measured signal from an accelerometer (integrated into displacements) placed on the topside of an offshore structure in the North Sea. The structure in an unmanned tripod jacket structure placed 250 km of the western coast of Denmark. The structure is placed on approximately 41 m water depth with the highest deck reaching 35 m above the water level. The response at frequencies left of the vertical dashed line will primarily be caused by the waves, whereas the response to the right of the dashed line primarily is cause by the dynamic properties of the structure.

Besides accelerometers, the offshore structure is mounted with three wave radars of the type WaveRadar Rex. By use of microwave radar technology, the distance from a fixed point on the platform to the sea surface is measured at high frequencies and from which the wave height can be extracted. Fig. 3 shows the PSD of the data measured with wave radar at the same time as the accelerations are measured. This confirms the assumption of the quasi-static and dynamic response. The peak at the quasi-static response at $\sim$0.1 Hz, corresponds to the peak at the PSD in Fig. 3, whereas the value of the PSD is almost zero at 0.51 Hz, where the platform has its two first natural frequencies, implying that the structure is “free vibrating” at these frequencies.

2.1. Response estimation for the quasi-static response

In order to predict the response in unknown points of the structure in the low-pass filtered response it is necessary to predict the