Ocean Engineering 140 (2017) 43–49

Contents lists available at ScienceDirect

Ocean Engineering

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

Research on structural damage detection of offshore platforms based on grouping modal strain energy

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A R T I C L E I N F O

Keywords:
Offshore platform
Modal analysis
Structural damage
Modal strain energy

A B S T R A C T

Nowadays, natural load excitation cannot detect all modal problems when testing vibration responses of offshore platforms. To overcome this issue, the present paper proposes a novel method to detect structural damages of offshore platforms based on grouping modal strain energy. This method divides the unit modal strain energy into axial tension-compression and bending. It may not only expand known modals and overcome the incomplete modal parameters under natural load excitation, but also could estimate the damage locations based on low-order modal parameters. The proposed method was verified by numerical simulations. Based on simulations on different damage conditions of a jacket offshore platform, damage locations could be determined accurately through comprehensive analysis of grouping modal strain energy distribution.

1. Introduction

Offshore platforms will be attacked continuously by various natural loads during the service period (Hahn, 1994). It is confirmed (R. G. Bea et al., 1994) that fatigue damages of components are the main cause of major offshore platform accidents in China and foreign countries. Therefore, it is extremely necessary to detect structural damages of offshore platforms (Nevena and Tygesen, 2014). Damage identification based on dynamic behavior changes of structure has attracted increasing attentions of researchers in the world (Spyrakos and Chen, 1990).

For big structures like offshore platforms, conventional manual excitation (CME) is disadvantageous due to high cost, production interruption and difficult online monitoring (Grigoriu and Alibe, 1986). Compared with CME method, damage detection based on response signal under natural load not only requires lower test cost and has little effect on the normal production, but also could reflect real dynamic responses of the structure (Kenji and Katta, 1997). Simple structures could apply direct comparison of modal shape, which estimates damages directly from the drawn vibration mode graph (West, 1982). However, for big structures like offshore platforms, such direct comparisons should consume remarkable time and labor, and environmental loadings often fail to excite all modals of large platform structures which induces incomplete actual modals in practical tests. Therefore, it is necessary to develop a modal parameter recognition algorithm and a method to locate damages under incomplete modals.

Vandiver (1977) put forward the Modal Assurance Criterion (MAC) to characterize correlation between two modals. On this basis, Coppolino and Rubin (1986) proposed the Coordinate Modal Assurance Criterion (COMAC) to accomplish the positioning task. Stubbs and Kim (1995) was the first one who suggested to use modal strain energy as a judgment index of damages. The theory was that stress in local component may redistribute upon damage, which increased the change rate of the local modal strain energy. Pandey etc. proposed a method, using the curvature modal (1991) and the change of flexibility (1994) for damage detection (Pandey and Biswas, 1994). Sophia and Karolos (1997) listed the sensitivity of natural frequency for the local stiffness changes as a pending equations, using the incomplete natural frequencies change data (before and after the damage) and markov parameters to identify the damage location and degree. Zhang and Aktan (1998) proposed the concept of consistent load surface of structure damage identification (ULS). The results showed that the ULS was sensitive to local damage, but for the use of the mode number and the boundary condition was not sensitive. Based on sensitivity and statistical model, Messina et al. (1998) proposed a multiple damage location assurance criterion (MDLAC), which provided more than one place damage location and absolute reliable information. MDLAC method only need a part information of the natural vibration frequency change of the structural before and after the damage, and hence it was suitable to practical application. Based on the flexibility, Bernal (2002) put forward a new damage location vectors (DLV) method. When there was no damage, this method may give the maximum change of flexibility. For as much as possible to

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http://dx.doi.org/10.1016/j.oceaneng.2017.05.021
Received 15 November 2016; Received in revised form 9 April 2017; Accepted 15 May 2017
0029-8018/

extract the structural damage information from the measured data, Yang et al. (2004) proposed two methods: one was based on empirical mode decomposition (EMD), extracted from measured data due to the sudden change of stiffness damage peak signal change, and hence the time and location of damage can be detected; Secondly, based on EMD and Hilbert transform, the damage was checked and the natural vibration frequency and damping ratio of structures were determined before and after damage. Based on fractal dimension analysis, Hadjileontiadis etc. (2005) put forward the cracks detection factor (FDCD) of beam structure. It can be used for damage detection effectively. Stacey et al. (2008) developed a comprehensive framework for the structural integrity management (SIM) of fixed jacket structures, which reflected the Health and Safety Executive Offshore Division's technical policy. Hua-Jun et al. (2010) proposed the cross modal approach based on model modification. This method utilized modes of vibration and frequency simultaneously, but it doesn't need to match them correspondingly. Hemez et al. (2009) put forward the modal reduction method. It only considers degree of freedom (DOF) of main vibration mode directions in the finite element model results, and the secondary DOF was neglected. Salama put forward the modal expansion method. It expanded modals of data through model dynamic iteration, which was equal to increasing measured DOF (Liao Fang et al., 2012). However, this method was dependent on the finite element model, similar to the modal reduction method.

2. Comparison of various modal damage index methods

2.1. MAC

Vandiver JK compared tested eigenvector with finite element analysis results and proposed the Modal Assurance Criterion (MAC) to characterize correlation between two modals. This dimensionless indicator directly reflects the change of the modal shape before and after the injury, but cannot locate the damage. The i^{th}-order formula is shown in Eq. (1).

$$MAC_i = \frac{(\{\phi_i\}^T\{\phi_i^*\})^2}{(\{\phi_i\}^T\{\phi_i\})(\{\phi_i^*\}^T\{\phi_i^*\})} \tag{1}$$

where $\{\phi_i\}$ is the i^{th}-order modal vibration mode of the structure. $\{\phi_i^*\}$ is the i^{th}-order modal vibration mode of the damaged structure.

2.2. COMAC

Based on MAC, Coppolino put forward the Coordinate Modal Assurance Criterion (COMAC). COMAC considers local MAC value on a specific direction and is directly correlated with DOF. However, COMAC is incomputable with respect to offshore platforms due to the unmeasurable rotational freedom and restricted installation of sensor in some positions.

$$COMAC = \frac{[\sum_{i=1}^{N} |\{\phi_i\}\{\phi_i^*\}|]^2}{\sum_{i=1}^{N}(\{\phi_i\})^2\sum_{i=1}^{N}(\{\phi_i^*\})^2} \tag{2}$$

where $\{\phi_i\}$ is the i^{th}-order modal vibration mode of the structure, $\{\phi_i^*\}$ is the i^{th}-order modal vibration mode of the damaged structure, N is the number of modal.

2.3. Modal curvature

Curvature reflects deformation modal of neutral surface of the structure. Such deformation modal is inversely proportional to bending rigidity of the cross section (Ciambella and Vestroni, 2015). Based on the theory that damage will degrade component stiffness, curvature mode shape method assumes that stiffness degradation will increase beam curvature (Pandey et al., 1991a, 1991b). Similar with expression of curvature, a curvature mode shape index expressed by central difference curvature was proposed, which was more sensitive to damages compared to MAC. Modal curvature of the j^{th} structural unit could be expressed by surrounding nodes:

$$C_i^j = \frac{\phi_i^{j-1} - 2\phi_i^j + \phi_i^{j+1}}{h^2} \tag{3}$$

where C_i^j is the modal curvature of j^{th} structure in the i^{th} -order modal shape. ϕ_i^{j-1}、ϕ_i^j、ϕ_i^{j+1} are the i^{th} -order modal shape in the point $j-1$, j, $j+1$, respectively. And h is the average distance from nodes ($j-1$) to the j and from node j to the node ($j+1$).

In practical test, damage location could be estimated according to the mean index value of all modals. Curvature mode shape index is very effective under serious damages (Kim Jeong-Tae and Yeon-Sun, 2003). However, curvature mode shape method requires numerical differentiation of modal shape, more sensor measuring points on the same direction and small spatial distance between measuring points. Otherwise, the central difference estimation will produce great errors (Dawari and Vesmawala, 2013). For these reasons, curvature mode shape method is inapplicable to large spatial structures, and it may be only applicable to narrow and long structures like bridge.

2.4. Flexibility matrix

Stiffness matrix and flexibility matrix are a pair of correlated concept. If normalize the structure mass, the stiffness matrix and flexibility matrix expressed by modal parameters could be gained:

$$\boldsymbol{K} = \boldsymbol{M}\phi_i\omega^2(\phi_i)^T\boldsymbol{M} = \boldsymbol{M}\left(\sum_{j=1}\omega^2\phi_i(\phi_i)^T\right)\boldsymbol{M} \tag{4}$$

$$\boldsymbol{F} = \phi_i\omega^{-2}(\phi_i)^T = \sum_{j=1}\omega^{-2}\phi_i(\phi_i)^T \tag{5}$$

where $\boldsymbol{M}$ is the Mass matrix; ϕ_i is the i^{th}-order modal vibration mode of the structure; $\boldsymbol{K}$ is the stiffness matrix; $\boldsymbol{F}$ is the flexibility matrix and ω is the angular frequency.

As shown in Eqs. (4) and (5), increasing angular frequency induces the increment of element value of the stiffness matrix while the element value of flexibility matrix decreases. This reflects that the flexibility matrix is more sensitive to low frequency.

2.5. Modal strain energy

The theory of modal strain energy (MSE) method is that component damages will cause stress redistribution in local areas, and hence the change rate of local modal strain energy is increased (Carrasco et al., 1997). That is, if one unit is damaged, it will present big change rate of modal strain energy before and after the damage (Shi et al., 2000). However, internal stress redistribution varies between modals of different DOF. Different testing modals may result in different results. Modal strain energy of the j^{th} unit at the i^{th}-order can be expressed as:

$$mse_i^j = (\phi_i^j)^T\boldsymbol{K}^j\phi_i^j \tag{6}$$

where $\boldsymbol{K}^j$ is the stiffness matrix of the j^{th} unit; ϕ_i^j is the i^{th}-order modal vibration mode of the j^{th} unit.

2.6. Numerical analysis comparison of common modal damage indexes

In this paper, ANSYS was used to analyze a simplified platform model (Fig. 1). Length, outer diameter and wall thickness of leg are 25 m, 1.5 m and 0.12 m, respectively, and those of waling are 20 m, 1.2 m and 0.08 m, respectively. Internal and external diagonal bracings are simplified. Since high-order modals are difficult to be acquired in practical measurement, the numerical analysis only involves the first three orders of modals.