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Numerical study on mode curvature for damage detection of a drilling riser using transfer matrix technique

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ABSTRACT

In order to prevent marine pipeline accidents caused by corrosion defect, crack or loose contact, the technique of non-destructive testing or examination (NDT or NDE) becomes great important in the flied of structural health monitoring (SHM) in ocean engineering. The objective of this study is to propose a numerical method to localize and size the structure damage of a drilling riser. One theoretical development is a simple and effective algorithm used for ocean risers' mode extraction and damage detection based on the transfer matrix technique. The merits of the developed method are that damage of risers with different boundary conditions and variable cross-sections can be localized and sized. Additionally, the relationships between damage locations and modes are discussed by comparing mode shape difference, mode curvature and mode curvature difference. Numerical results show that mode curvature values of damaged elements have little influence on those of intact elements. Based on this fact, a damage index method is developed to evaluate damage severities and explore the influence of single and multiple damage severities on damage indexes. More importantly, the outcomes are verified to be accurate enough to indicate the feasibility and reliability of the numerical method by the standard FEM package.

1. Introduction

Due to vicious ocean environment, improper installation (operation), or vortex-induced vibration [1], structural damage such as corrosion, crack or loose contact often occurs in ocean risers [2,3]. Without effective ways to detect the damage, failure or accident usually occurs or causes a huge economic and environmental disaster [4,5]. Therefore, it is essential to develop a feasible SHM method to ensure the safety and reliability of risers. Widely used in civil, automotive and aerospace engineering communities, the SHM method [6] gives an idea to detect structural damage of ocean risers.

Up to date, lots of studies have focused on the damage detection methods for ocean risers [2–14]. Lozev et al. [5] pointed out that NDT method had more obvious advantages than other riser inspections, for instance, the piping pig inspection, which often causes the false positives and negatives of corrosion defects. Riveros et al. [7], who used the time series analysis method and the measured data from experiments and finite element models, developed a statistical-based approach to monitor the flexible risers. Elman and Alvim [8] predicted the potential failure of a flexible riser via laboratory tests using a bank of sensors to get the modal data. Jacques et al. [9] tested a flexible riser's health status using a series of optical fiber sensors and mechanical actuator. Shahverdi et al. [10] indicated the structural damage of free span pipelines by analyzing the data obtained from ANSYS models using the wavelet packet transform technique. Huang et al. [11] investigated two kinds of methods (the vibration-based method and the wave-propagation based damage identification method) via model test, and pointed out that both of the two methods could effectively detect the deepwater risers' damage. Hernández et al. [12] demonstrated the effectiveness of the modal slope difference, modal shape difference and damage index methods in damage detection of deepwater steel catenary risers using the FEM. Je and Park [13] studied four kinds of NDT methods in ocean risers, namely, the coordinate modal assurance criterion, modal strain energy, mode shape curvature square and damage index methods, and concluded the sensors' optimal number for the risers' integrity estimation using the OrcaFlex software. Min et al. [14] studied the performance of natural frequencies for the top tensioned riser using the 2D numerical model, and evaluated the damage locations and severities by the damage index method.

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At present, numerous damage detection methods of risers have been proposed, but most of them are based on available data obtained from finite element software programs and signal measurement tests. Few of them deal with a feasible and reliable numerical method for modal data extraction and the application in damage detection. Though multifarious numerical methods of mode extraction for risers [15–20] have been developed, most of them often rely on the governing differential equations, which usually cause tedious and complex calculations. Besides, the relationships of modal characteristics (natural frequencies and mode shapes), damage location, damage degrees and damage indexes of risers are also paid little attention to. Hence, the main purpose of this study is to develop a numerical method to estimate the damage locations and severities, and to explore the interrelationships of those damage factors for marine risers.

To achieve this goal, two numerical procedures *Freq* and *Mshap* are developed to extract the modal characteristics of the intact and damaged risers, and three kinds of critical techniques are used in this study, namely, the transfer matrix technique, the mode curvature technique and the damage index technique. Papers [21] and [22] pointed out that the transfer matrix technique was efficient to get modal characteristics of beam-like structures. Via a numerical example in this study, it is found that this numerical method also has many advantages, such as the risers with variable cross sections and different boundary conditions can be easily calculated. Up to now, the mode curvature technique has attracted lots of attentions as well due to its effective accuracy for damage location. But, one limitation of this method is also obvious, that is, the singularity of points in mode-shape-based parameters is an obstacle to locating damage [23]. To overcome this deficiency, a comprehensive consideration of mode shape difference, mode curvature and mode curvature difference is attempted to determine the damage location using the both even and odd modes.

This study is organized as follows: the numerical model and mode governing equations of the riser are established based on some reasonable simplifications in Section 2. Numerical solutions are solved in Section 3, where modal results are calculated using the transfer matrix method and verified by the standard FEM package. In the same section, damage locations and severities are evaluated by the mode curvature and damage index techniques. Section 4 is numerical results and discussions. Finally, some conclusions and perspectives are ended with in Section 5.

2. Simplified model and governing equation

Generally, ocean riser, which connects platform with the ball joint near the surface to wellhead with the flex joint near the seabed, is an important part of marine structures. The object of this study is a drilling riser, and the basic compositions of the riser may be shown in Fig. 1.

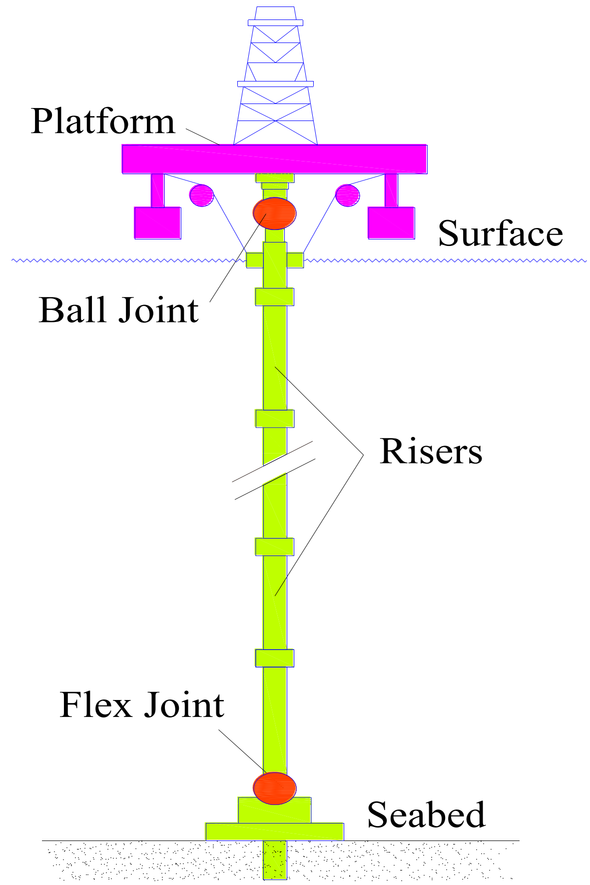

Fig. 1. The main components of drilling riser system.

2.1. Simplified model of drilling riser

Because of the unique beam-like structural feature [24], modal characteristics of the drilling riser can be easily solved using the transfer matrix technique. Some assumptions are made for the riser: 1) the modal analysis is conducted within 2D plane, which indicates that only one transverse vibration is considered while the other transverse vibration along the vertical direction and the longitudinal vibration along the riser axial direction are both neglected; 2) the structure is assumed to be continuous; 3) the material is isotropic and always in the elastic state; and 4) the upper and lower flexible joints are simplified as ideal hinge constraints. Based on those assumptions, the mechanical model (as sketched in Fig. 2(1)) and the modal governing equations of the ocean riser will be established.

2.2. Transfer matrix method

According to the principle of the transfer matrix technique, many structures, such as turbo generator and propeller shafts, can be discretized into a series of elastic and inertial units. The relationship of force and displacement between each unit can be expressed by the transfer matrix. Thus, the structure of the drilling riser can also be divided into a series of non-mass elastic beam units and lumped mass units, as shown in Fig. 2.2–2. 3.

For the i^{th} segments, the physical parameters associated with vibration are lumped mass m_i, bending stiffness EI_i, length of segment l_i, transverse displacement y_i, rotation angle θ_i, bending moment M_i and shear force S_i.

To take the lumped mass unit m_i as a research object, it is easy to be found that the boundary displacements between the upper and lower ends are continuous.

$$y_i^L = y_i^U \tag{1}$$

$$\theta_i^L = \theta_i^U \tag{2}$$

where the superscripts of the L and U represent the lower and upper ends of a unit.

Mainly subjected to bending moment, shear force and inertia force (as sketched in Fig. 3), the equilibrium equations of the lumped mass are expressed as:

$$M_i^L = M_i^U \tag{3}$$

$$S_i^L = S_i^U - m_i y''_i = S_i^U + m_i \omega^2 y_i \tag{4}$$