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Damage detection in top-tensioned risers using modal parameters

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ABSTRACT

A main goal of this study is to propose a damage detection technique to detect and localize damages of a top-tensioned riser. In this paper, the top-tensioned finite element (FE) model is considered as an analytical model of the riser, and a vibration-based damage detection method is proposed. The present method consists of a FE model updating and damage index method. In order to accomplish the goal of this study, first, a sensitivity-based FE model updating method using natural frequencies is introduced. Second, natural frequencies of the axial mode of the top-tensioned riser are estimated by eigenvalue analysis. Finally, the locations and severities of the damages are estimated from the damage index method. Two numerical examples are considered to verify the performance of the proposed method.

1. INTRODUCTION

Top-tensioned risers are very important component of offshore facilities. Because they are exposed to harsh environmental conditions, it is very significant to retain riser's performance and to detect damage before risers are destroyed. For these reasons, an accurate health monitoring method for top-tensioned risers must be developed to detect and localize the damages. This paper deals with the development of a health monitoring methods for top-tensioned riser.

Damage detection methods have been widely used in civil engineering. Many researchers have focused on the changes between pre-damage and post-damage natural frequencies and mode shapes (Vandiver, 1977; Stubbs et al., 1992). Recently, many investigations on the health monitoring of marine risers were carried out. Several damage detection methods for risers were studied by Riverios et al. (2007), Jacques et al. (2010) and Bao et al. (2013).

The main objective of this paper is to propose a new damage detection method for

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top-tensioned risers without pre-damage modal parameters. To achieve the stated goal, a sensitivity-based FE updating method with natural frequencies is applied, and a damage index method is also adopted to detect and locate the damages of top-tensioned risers. Two numerical examples are considered to verify the proposed method.

2. FINITE ELEMENT MODEL OF TOP-TENSIONED RISER

The finite element (FE) structural model (Rustad et al., 2008) is applied to obtain the natural frequencies of the top-tensioned riser. The element stiffness matrix, **k**, consists of two components; the elastic stiffness, $\mathbf{k}_E$, and the geometric stiffness, $\mathbf{k}_G$. The element stiffness matrix for the element *i*, $\mathbf{k}_i$, has following form:

$$\mathbf{k}_i = \mathbf{k}_{Ei} + \mathbf{k}_{Gi} = \frac{1}{l_i}\left(EA_c \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix} + P_i \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \right) \tag{1}$$

where *E* is Young's modulus of elasticity, A_c is the cross-sectional area of the element, and l_i is the length of element *i*. The axial tension P_i in each element is defined as a function of the elongation of the element *i*:

$$P_i = \frac{EA_c}{l_0}\Delta l_i - l_0, \qquad \Delta l_i = l_i - l_0 \tag{2}$$

where l_0 is the initial length of an element in an un-tensioned riser.

The element mass matrix, **m**, consists of three terms; the structural mass of the riser, $\mathbf{m}_S$, the internal fluid, $\mathbf{m}_F$, and the hydrodynamic added mass, $\mathbf{m}_A$.

$$\mathbf{m}_{Si} = \frac{\rho_s A_c l_i}{6}\begin{bmatrix} 2 & 0 & 1 & 0 \\ 0 & 2 & 0 & 1 \\ 1 & 0 & 2 & 0 \\ 0 & 1 & 0 & 2 \end{bmatrix}, \mathbf{m}_{Fi} = \frac{\rho_f A_{\text{int}} l_i}{6}\begin{bmatrix} 2 & 0 & 1 & 0 \\ 0 & 2 & 0 & 1 \\ 1 & 0 & 2 & 0 \\ 0 & 1 & 0 & 2 \end{bmatrix}, \mathbf{m}_{Ai} = \frac{\rho_w C_m A_e l_i}{6}\begin{bmatrix} 2 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{3}$$

where ρ_s is the mass density of the riser, ρ_f is the mass density of the internal fluid, A_{int} is the internal area of the riser, ρ_w is the mass density of water, C_m is hydrodynamic added mass coefficient and A_e is the external area of the riser. The element stiffness matrix for the element *i*, $\mathbf{m}_i$, is written as:

$$\mathbf{m}_i = \mathbf{m}_{Si} + \mathbf{m}_{Fi} + \mathbf{m}_{Ai} \tag{4}$$

3. DAMAGE DETECTION METHOD

The damage index method makes use of the changes in modal parameters such as natural frequencies and mode shapes of the pre-damaged and post-damaged structures to detect and locate damage (Stubbs et al., 1992). In this paper, the damage index method is modified to detect damage of the top-tensioned riser without modal parameters of pre-damaged structures. The sensitivity-based finite element model updating method with natural frequencies is employed to supply information about damages. The damage index for the *i*th element, DI_i, can be expressed as

$$DI_i = \frac{E_{i,\mathrm{int}}}{E_{i,\mathrm{up}}} \tag{5}$$

where $E_{i,\mathrm{int}}$ is the Young's modulus of the *i*th element of the initial FE model and $E_{i,\mathrm{up}}$ is the Young's modulus of the *i*th element of the updated FE model through FE model updating.

To further generalize the DI_i independently of the structure type, the normalized DI_i, NDI_i, is given by

$$NDI_i = \frac{DI_i - \mu_{DI}}{\sigma_{DI}} \tag{6}$$

where μ_{DI} and σ_{DI} represent mean and standard deviation of the damage index, respectively. To classify whether damage exists in a specific element, NDI_i should be compared with a threshold value, η. In this paper, Neyman-Pearson criteria (Gibson and Melsa, 1975) is utilized to assess damage exists.

Five steps are utilized to detect damage of the top-tensioned riser. These steps are described below:

1. Extract natural frequencies, $EXP(\omega_n)$ of the riser using modal parameter identification methods from the experimental data;
2. Make a FE model corresponding real structure using all possible knowledge about the design and construction of the riser;
3. Perform eigenvalue analysis to get natural frequencies of the initial FE model, $FEM(\omega_n)$;
4. Perform sensitivity-based FE model updating to get modified Young's modulus, and
5. Detect and locate damages using the modified damage index method.

4. NUMERICAL EXAMPLES

4.1 Description of the numerical model

A numerical model of a top-tensioned vertical riser shown in Fig. 1 is considered to verify the effectiveness of the proposed method. The model is taken fixed conditions for both directions at its bottom end, and the top node is free in the vertical direction, only affected by the top tension acting as a vertical force. The material properties and geometric information of the riser are listed in Table 1.

Table 1. Properties and geometric information of the riser

Property	Base beam
Riser length	2200 m
Outside/Inside diameter	0.23/ 0.2 m
Top tension	1800 kN
Riser material density	7860 kg/m^3
Sea water density	1025 kg/m^3
Riser internal fluid density	800 kg/m^3
Riser material Young's modulus	203 GPa
Added mass coefficient	1

The FE model consists of 20 elements and 21 nodes, and structural damping is not considered. The FE model is considered as baseline model for numerical examples.

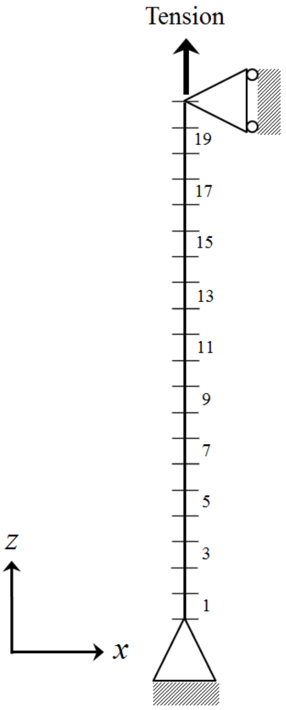

Fig. 1 Fixed-roller vertical riser model with top-tension

4.2 Damage scenarios

For verifying the accuracy and efficiency of the proposed damage detection method, 2 scenarios listed in Table 2 are investigated. In both scenarios, damage is inflicted in the structure by reducing the Young's modulus of the appropriate elements. In Case 1, the damage is limited in one location of the structure, and 30% of Young's modulus in element 1 is reduced to simulate damage. In Case 2, two damage locations are considered.

Table 2. Damage scenarios

Damage scenario	Damage location	Damage severity (%)
Case 1	E1	30
Case 2	E5, E15	30, 30

4.2 Damage detection

The damage detection scheme is applied to the simulated damage cases. Eigenvalue analyses are carried out to obtain the natural frequencies of the post-damaged structures. In case of top-tensioned riser, the target parameters are extracted from the axial modes because the Young's modulus of the riser effects the axial direction. In this paper, first 10 natural frequencies of axial mode are considered as target parameters for FE model updating. The FE model updating procedure is implemented to identify the structural properties of the target model for 2 cases. In each updating process, Young's modulus of all elements are iteratively updated until $\alpha \approx 0$.

The locations of potential damage in the structures are estimated by the damage index method. The normalized damage indexes obtained from Eq. 6 are shown in Fig. 2 and Fig. 3.

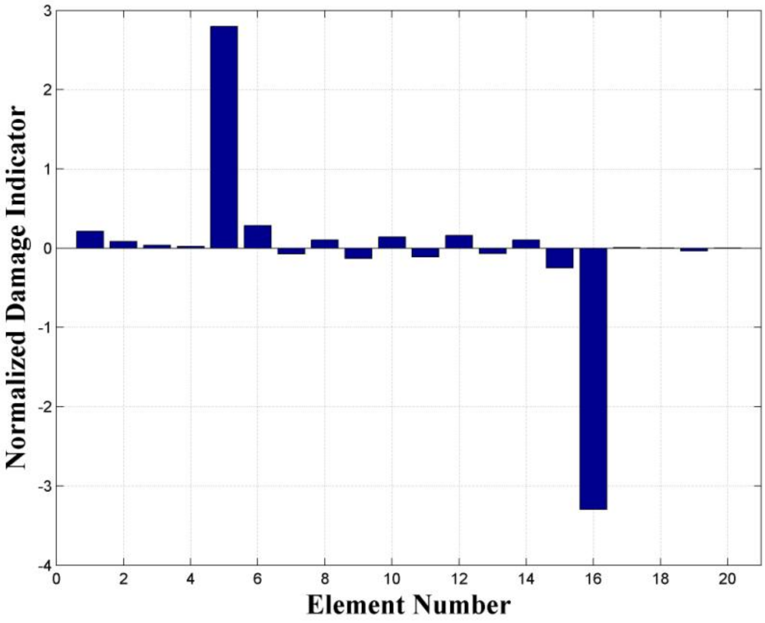

Fig. 2 Damage localization results for damage scenario Case 1

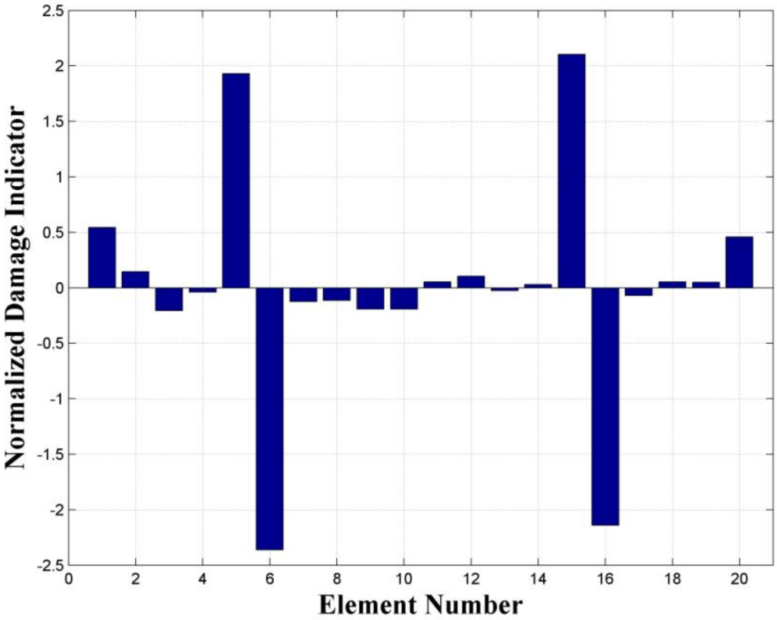

Fig. 3 Damage localization results for damage scenario Case 2

The negative indexes are related to undamaged cases and the positive indexes identify a potentially damaged element, the main task is selecting an adequate threshold level in order to detect the real damaged elements. Note that the values of damage threshold, 3, 2 and 1 correspond to 99.87%, 98% and 84% confidence level for the presence of damage, respectively (Park et al., 2011). For all damage cases, the threshold value is selected 1. Fig. 2 and Fig. 3 show that damaged elements of all cases are perfectly detected.

The damage severities are obtained by Eq. 7.

$$\mathrm{DamageSeverity}\left(\%\right)=\frac{\mathrm{Updated}\left(E\right)}{\mathrm{Initial}\left(E\right)}\times 100 \tag{7}$$

The results of the damage severities for the two damage scenarios are presented in Fig. 4 and Fig. 5. In Fig. 4, the damage severity of Case 1 is estimated at 80.33 %. In Case 2, the damage severities of the element 5 and the element 15 estimated by Eq. 7 are 80.17 % and 78.66 %, respectively. In both cases, errors are generated. These errors might be attributed to errors in FE model updating with natural frequencies.

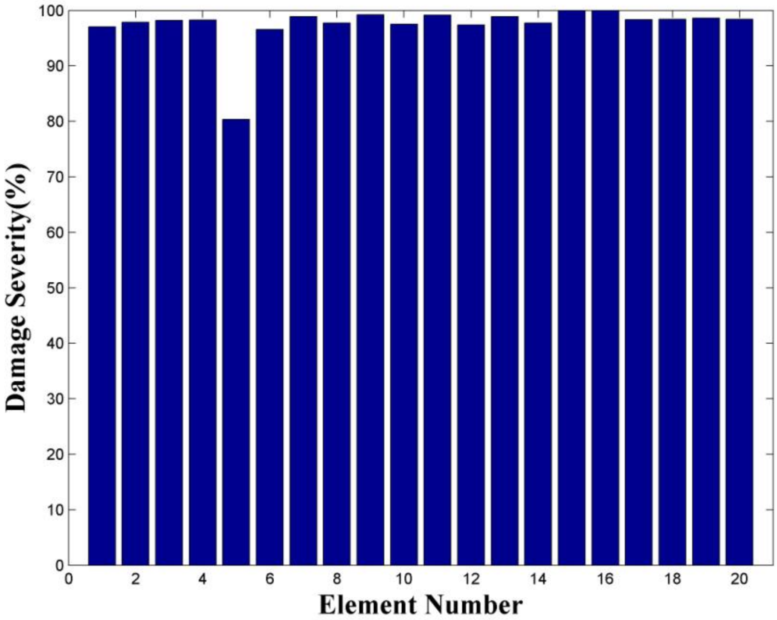

Fig. 4 Damage severity results for damage scenario Case 1

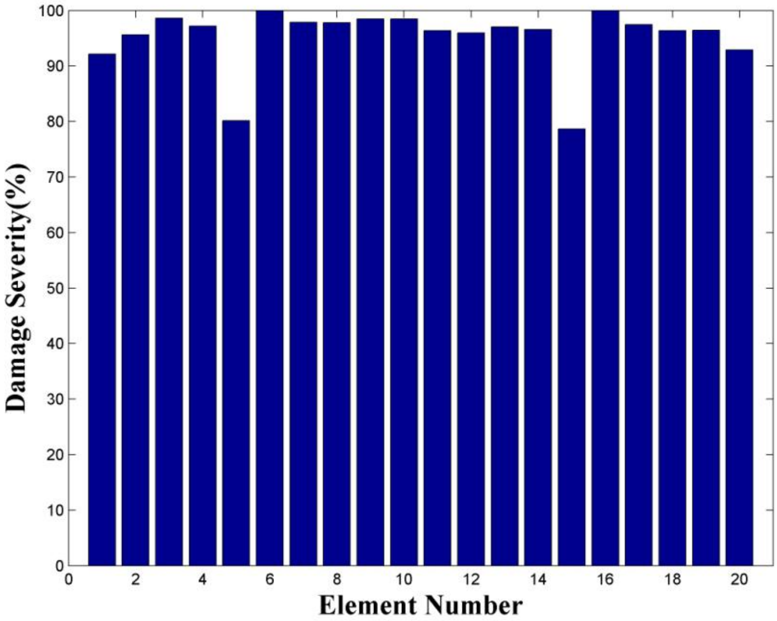

Fig. 5 Damage severity results for damage scenario Case 2

5. CONCLUSIONS

This paper presents damage detection approach for the top-tensioned riser without pre-damaged response data. The proposed method consists of FE model updating method and damage index method. The accuracy of the proposed method was numerically verified by two damage scenarios associated with the marine risers. Based on the numerical studies, the following conclusions are drawn: (1) the natural frequencies of the axial mode are effective parameters for damage detection of the riser; (2) the proposed method can detect and localize single and multiple damage locations of the riser; (3) the damage severity of the riser can be estimated by the proposed method; and (4) improvement of FE model updating performance is needed to improve estimation accuracy of damage severities.

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