Localization of free-spanning damage using mode shape curvature

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Abstract. This study proposes a damage indicator based on mode shape curvature to localize free-spanning damage of submarine pipeline systems. The feasibility of curvatures of low-frequency mode shapes for localizing free-spanning damage of pipeline systems is discussed, and damage indicators based on mode shape curvatures are proposed. The efficacy of the proposed damage indicators is demonstrated by numerical simulations of dynamic responses of a submarine pipeline under ambient conditions with considering the real subsea environment. The proposed approach is simple, which does not require baseline data, and thus is promising in practical applications.

1. Introduction

Many oil and gas resources exist in deep offshore areas. Submarine pipelines play an important role to transport oil, gas and other associated products over long distances to shores. In recent years, submarine pipeline failures have happened occasionally around the world. These accidents not only interrupt the supply of the transported materials, but also may destroy severely the ecological environment due to spills and discharges of the transported materials into water, inflicting huge economic losses and costs to restore ecological conditions.

Submarine pipeline failures can be caused by random or intentional external actions on pipelines, design and technological errors in construction, inadequate strength of pipes, inadequate thickness of pipe walls and protective coatings on pipes, and flaws in the pipes and weld joints [1]. In addition, submarine pipelines are exposed to adverse environmental conditions, such as strong currents and waves, seabed shifting, submarine landslides, ground movement and interaction with chemicals passing through them. Under the adverse operation environment, pipelines are vulnerable to the development of free-spans under pipes. Long free-spanning damage could result in large stress on pipe walls. With a short free-span, vortex-induced vibrations can be imposed on pipes, and fatigue damage can occur [2]. If a natural frequency of the pipeline is close to or equal to the frequency of the vortex-induced vibration, the pipeline will be in resonance, which will endanger the integrity of the pipeline [3].

While design errors and manufacturing flaws as well as external actions can be prevented by careful design, fabrication, construction and administration, free-spanning damage is random and unpredictable and thus is difficult to be prevented. To maintain the integrity of the pipeline system, it

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is very significant to develop effective and reliable approaches to identify and localize free-spanning damage at the earliest stage.

The method used commonly to detect free-spanning damage is periodical visual inspection. However, it is laborious and economically expensive. Peng et al. implemented an energy-based indicator for assessing bedding conditions of pipelines [4]. Zhu et al. applied a statistical finite element model updating technique to assess bedding conditions and damage in pipelines [5].

The objective of this study is to develop a simple, low cost monitoring system to identify and localize free-spanning damage. First, the feasibility of the mode shape curvature for localizing free-spanning damage is discussed. Then, the proposed damage indicators based on mode shape curvatures are validated using numerical simulations.

2. Localization of Free-spanning Damage Using Mode Shape Curvature

To localize free-spanning damage, the mode shape curvature [6] is identified as a feasible damage indicator. Because the free-spanning can be taken as the loss of local stiffness, the local flexibility associated with free-spans would be increased. Under the same external force, the curvature of the deflection corresponding to the free-spans would be much greater than the rest of the pipeline. The prior research suggests that the deflection of the pipeline is dominated by the first few modes [7]. Therefore, for the first few modes, the curvatures of the mode shape components associated with the free-spanning exhibit maxima in amplitudes. And accordingly, the free-spanning can be indicated from the damage indicators based on the curvatures of lower-frequency mode shapes.

Considering a pipeline-soil system with n nodes, the mode shape curvature associated with the jth node and the ith mode can be expressed as

$$C_{j,i} = \frac{\phi_{j,i+1} - 2\phi_{j,i} + \phi_{j,i-1}}{h_j^2}, \quad i = 2, 3, \ldots, n-1$$

where $\phi_{j,i}$ is the jth component of the ith mode shape, and $h_j$ is the length of the jth element (for simplification of expression, assuming that length of each element is equal). The damage indicator associated with mode shape curvatures can be defined as

$$DI_1 = \begin{bmatrix} C_{1,i} & C_{2,i} & \cdots & C_{j,i} & \cdots & C_{n-2,i} \end{bmatrix}$$

or

$$DI_2 = \begin{bmatrix} C_{1,i}^2 & C_{2,i}^2 & \cdots & C_{j,i}^2 & \cdots & C_{n-2,i}^2 \end{bmatrix}$$

By looking for the maxima (in amplitudes) in the damage indicators, the center of the free-spanning can be localized precisely. This approach does not require the baseline data, which makes the approach attractive in actual practices because most pipelines have been laid and used for a while and baseline data may not be ensured.

To facilitate localizing free-spanning damage, the obtained damage indicators are normalized as

$$NDI_1 = \frac{DI_1}{\text{max}(abs(DI_1))}, \quad NDI_2 = \frac{DI_2}{\text{max}(DI_2)}$$

3. Numerical Simulations

To verify the effectiveness of the proposed damage indicators based on mode shape curvature, a 100m-long pipeline is considered here. The geometry and material properties of the pipeline are listed in Table 1. A finite element model of this pipeline is developed using ANSYS. The pipe model is built using 100 immersed pipe elements (PIPE59) with each of 1 m long. The bedding condition is simulated using 101 spring-damper elements (COMBIN14). The stiffness coefficient of the springs is
7.9 x 10^6 N/m and the damping coefficient is 5000N.s/m. The effect of seawater around the pipe is simulated as added lumped masses.

Table 1. Specifications of the pipeline properties

| Pipeline characteristics | Value | Material properties | Value |
|--------------------------|-------|---------------------|-------|
| Outside diameter of cement coating | 0.87 m | Young’s modulus of cement | 2.4 x 10^10 Pa |
| Outside diameter of steel pipe | 0.75 m | Young’s modulus of steel | 2.0 x 10^11 Pa |
| Cement coating thickness | 0.06 m |
| Steel pipe thickness | 0.02 m |

In this study, the two ends of the pipeline are assumed to be fully fixed. Actually, if some DOFs at the two ends are not constrained, some rigid modes will be introduced. In that case, just ignore the rigid modes and consider the bending modes.

3.1. The influence of free-spanning on modal parameters

To investigate how free-spanning damage affects natural frequencies and mode shapes of the pipeline-soil system, several damage cases with free-spans occurring at different locations are considered, as listed in Table 2. Modal analysis is performed on the intact pipeline-soil system and the damage cases, respectively.

Table 2. Simulated free-spanning damage cases

| Description |
|-------------|
| Damage Case 1 | The soil springs and dashpots at Nodes 22-30 are removed |
| Damage Case 2 | The soil springs and dashpots at Nodes 40-50 are removed |
| Damage Case 3 | The soil spring and dashpot at Nodes 22 are removed |
| Damage Case 4 | The soil springs and dashpots at Nodes 22-26 and Nodes 70-74 are removed |
| Damage Case 5 | The soil springs and dashpots at Nodes 22-30 and Nodes 40-50 are removed |

For each case, the first five natural frequencies associated with bending about the x-axis are listed in Table 3. It can be observed that only the first few natural frequencies decrease appreciably when free-spanning damage occurs, except for the small damage case (Damage Case 3). However, we can only tell if free-spanning damage occurs from the reduction of natural frequencies. For Damage Case 3, we even cannot find the difference in natural frequencies from the intact case.

Table 3. Natural frequencies for the intact and damage cases

| Intact | Damage Case 1 | Damage Case 2 | Damage Case 3 | Damage Case 4 | Damage Case 5 |
|--------|---------------|---------------|---------------|---------------|---------------|
| 1      | 3.89          | 3.05          | 2.81          | 3.87          | 3.48          | 2.68          |
| 2      | 3.97          | 3.91          | 3.93          | 3.94          | 3.53          | 3.21          |
| 3      | 4.22          | 4.13          | 4.13          | 4.18          | 4.05          | 3.99          |
| 4      | 4.76          | 4.70          | 4.64          | 4.74          | 4.70          | 4.59          |
| 5      | 5.65          | 5.59          | 5.55          | 5.65          | 5.56          | 5.49          |

The first two mode shapes for all cases are presented in Fig. 1. Once free-spanning damage occurs, the first mode shape does not look like half of a sine wave. Instead, the mode shape components associated with the free-span exhibit maximum values (see the graphs associated with “22-30” and “40-50” in Fig. 1.). In addition, there are one or two modal nodes for the cases with free-spanning
damage, while there is no modal node for the intact pipe-soil system. However, the two observations do not hold true when short single free-spanning damage or multiple free-spanning damages occur (see the graphs associated with “22”, “22-30 and 40-50”, and “22-26 and 70-74”). Similar observations can be found for the second mode shape. Therefore, it is difficult to localize free-spanning using the mode shapes directly.

![Mode shapes for the intact and damaged cases](image)

Note: ‘22-30’ denotes that the soil springs at Nodes 22 to 30 are removed.

(a) the first mode shape for all cases  
(b) the second mode shape for all cases

**Figure 1.** Mode shapes for the intact and damaged cases

3.2. Localizing free-spanning using the damage indicators based on mode shape curvatures

The procedures for localizing free-spanning damage in pipeline-soil systems are as follows: 1) identify the bending mode shapes about the x-axis; 2) compute the mode shape curvatures at each node for each mode using Eq. (1); 3) extract damage indicators based on mode shape curvatures using Eq. (2) or Eq. (3); 4) compute normalized damage indicators using Eq. (4). For single free-spanning damage scenarios, only the first mode shape is needed to extract the damage indicators. For multiple free-spanning damage scenarios, the first two mode shapes are needed.

The damage indicators for Damage Case 1 are presented in Fig. 2. For both DI1 and DI2, the damage indicators in one region are much greater in amplitude than other regions. It suggests that free-spanning damage occurs in the pipeline-soil system. For DI1, the maximum value in amplitude of damage indicators is -1. It corresponds to Node 26, which is the center of the free-spanning damage specified in Damage Case 1. For DI2, the maximum of damage indicator is 1 and also associated with Node 26. Once the free-spanning damage is identified and the center of the free-span is localized, actions regarding reinforcement and maintenance strategies can be taken.

Figure 3 presents the damage indicators for Damage Case 2. By looking for the damage indicator of -1 (from DI1) and 1 (from DI2), the center of the free-spanning damage is localized at Node 45, which is consistent with the damage specified in Damage Case 2. To demonstrate the effectiveness of this approach for small damage scenarios, Damage Case 3 with one soil spring removed is considered. The damage indicators for Damage Case 3 are presented in Fig. 4. Although the damage indicator associated with the center of the simulated free-span is not 1 or -1, the center of free-spanning damage can still be localized accurately from the local maximum in the two damage indicators.
By comparing the two damage indicators, DI1 and DI2, in each damaged case, they complement to each other. From the trend of DI1, the number of damage locations can be easily determined; from DI2, the specific number of damages can be easily localized by finding the maxima of damage indicators.

For comparison, the normalized damage indicators for the intact case are extracted and plotted in Fig. 5. It can be observed that the damage indicators constitute smooth curves and form regular shapes. In addition, the maximum values in amplitude (equal to -1 and 1) of the DI1 and DI2 indicators occur at the supports.
When there is no damage or damage is insignificant, the damage indicators associated with the pipe boundaries may turn out to be local maxima (1 or -1), as shown in Figs. 4 and 5. This could lead to false identification at pipe boundaries. In this situation, some other methods need to be applied to check if the boundaries are really damaged.

To localize multiple free-spanning damages, two mode shapes are used to extract damage indicators. The extracted damage indicators for Damage Case 4 are presented in Fig. 6. From Fig. 6a), the maximum values in amplitude of the damage indicators extracted from the two mode shapes are -1 and -1. They correspond to Nodes 24 and 72. It suggests that multiple free-spanning damages can be localized by looking for the damage indicators with the value of -1 from DI1. From Fig. 6b), by combining the maximum values (1 and 1) of damage indicators extracted from the first and second modes, the centers of the two free-spans are localized at Node 24 and Node 72, which is consistent with the damage specified in Damage Case 4.

Damage indicators for Damage Case 5 are presented in Fig. 7. By looking for the damage indicators with the value of -1 from DI1 and the damage indicators with the value of 1 from DI2, the centers of the two free-spans are successfully localized at Nodes 26 and 45.
Considering that bedding conditions may not be uniform in some cases, a damage case with non-uniform bedding conditions are considered. Assuming that the pipeline is evenly divided into five segments, the stiffness coefficient k of the springs and damping coefficient c in the second and fourth segments are set to 0.8 times the original ones, and the k and c in the third and fifth segments are set to 0.9 times the original ones. The simulated damage case is that the soil springs and dashpots at Nodes 70-74 are removed. The extracted damage indicators are plotted in Fig. 8. The center of the free-span, Node 72, is associated with the damage indicator of -1 in DI1 and is associated with the damage indicator of 1 in DI2. It suggests that the two proposed damage indicators are still effective when the bedding conditions are not uniform, which makes the damage indicators attractive in actual practices.

4. Conclusions
This paper proposes a damage indicator based on mode shape curvature to localize free-spanning damage of submarine pipeline systems. This approach has the following advantages: 1) it does not require the baseline data; 2) it can localize multiple free-spanning damages; 3) it is still effective when the bedding conditions are not uniform; 4) it does not need to measure the input. Numerical simulations are performed on a submarine pipeline system with considering the real subsea environment. The results have demonstrated the efficacy of the proposed approach.

In general, the sensitivity of this approach very much depends on the sensor density. The more number of sensors, the more sensitive of this approach is to damages. In view of a submarine pipeline system, which could extend hundreds of kilometres, completely monitoring such a pipeline needs a large number of sensors. This not only makes the sensing system very expensive, but also results in huge volume of data, requiring significant effort to process data for pipeline condition monitoring. Therefore, in the future, the present authors will develop a mobile wireless sensor network-based monitoring system to overcome the above problems. With this mobile wireless sensor network, any high spatial resolution of identified mode shapes can be achieved, yielding better damage localization results. It is believed that the proposed monitoring system with the proposed damage indicator in this paper will find wide and immediate applications in offshore industry.

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