Research on Damage Assessment Method Using Weighting Modal Information

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Abstract: Many damage detection methods based on the modes and their evolution can be achieved with high accuracy by numerical examples without noise. However, a certain level of noise always exists in practical measurement which has a great effect on the identification. In view of this situation, a robust damage assessment method based on weighting modal information for nondestructive detection in beams is presented in this paper. In the process of damage detecting and locating, displacement mode as the basic parameter is weighted and optimized to ensure its accuracy. Meanwhile, the relation between the damage positions and different order model of vibration is considered to improve the capability of damage identification. Numerical examples of single and multi-damaged simply-supported beams are performed using first five modes which can be measured easily. The results show that the proposed method works well for the damage detection and the assessments are in good agreement with the actual condition even with 5% of random noise being added to the simulations. Finally, experimental examples of pipeline structures in different damaged cases were provided to verify the correctness and feasibility of the proposed method through approach of experimental model, which may provide inspiration for further engineering application.

1. Introduction
The major reasons of engineering structural damage are fatigue and rusty. As an important way of fluid transportation, pipeline structure plays an irreplaceable role in oil, gas and chemical industry, since it is commonly acted upon by internal and external force in the process of its usage, it is a very urgent task to identify the damage qualitatively and quantitatively, as well as predict remaining service life of
the structures. A significant number of researchs devoted to vibration-based methods for damage detection of engineering structures have been proposed during recent years [1-5]. Among the methods for damage detection based on dynamical test, it is a hot topic as well as difficult issue to deal with about how to select an effective index which is not only sensitive to the local damage but also impervious to environmental changes and noise interference. In the paper by Cawley and Adams [6], a method for locate structural damage was proposed based on the change of first two natural frequencies. However, following research indicated that frequencies cannot be adequate since damage results more in local features of the structure. Pandey et al. [7] pointed that model curvature can provide a better index for a complex structure. It can be used for truss and plate, not just for beam. Wahab and Roeck[8] presented a new index which is an average of model curvature of first few modes.

To improve the sensitivity of damage index, Raghavendrachar and Aktan [9] combined the model frequencies and shapes for damage detection. Its effectiveness was verified both by numerical analysis and experiment. Cao and Friswell [10] adopted the mathematical approach of Pandey and Biswas [11] to modify the flexibility curvature index, and numerical studies were carried out to demonstrate the advantages. Unfortunately, the anti-noise capability was not considered.

In this sense, experiment must be carried out to check the proposed method which may lose efficiency on damage localization. This paper presents the weighting mode displacement superposition method, based on structural modal analysis theory, aimed at the usual damaged styles in pipeline structures. The concept of weighting coefficient is introduced in this method, which depends on the relationship between the damage positions and different order model of vibration, and improves the capability of damage identification method based on displacement mode. Numerical simulations with 5% of random noise added and experimental results show that the proposed method works well for the damage detection. It is thus proved that the presented method provides good performance for damage detection.

2. Theory

According to most previous studies [6-9], it is regarded that damages located near the node of vibration mode have little effect on modal parameters. So the mode selection become difficult on account of the uncertainty of the damage positions before detection, which directly influences the detecting reliability. In order to avoid the difficulty of mode selection, the indicator of damage assessment is presented with reference to continuum structure such as simply-supported beam, which can be written as

\[ H = \sum_{j}^{n} W_j \frac{1}{\lambda_j} \phi_j^{T}, \]  

(1)

\[ \delta = \text{diag}(|H^d - H^u|), \]  

(2)

where \( \lambda_j \) is square of the j-th natural frequency, \( \phi_j \) is the j-th mode obtained by normalization according to max, \( W_j \) denotes weighting coefficient of the j-th mode in the indicator function. Superscript \( u \) and \( d \) represent the undamaged and damage condition respectively, \( n \) means the modal account obtained by numerical simulations or modal experiments. In the current implementation, the first five modes will be used in Eq. (1), since high-order mode is somewhat difficult for dynamic test and model
In view of the reasons mentioned above, this paper presents the novel conception of sensitive mode that damage location is near node of vibration mode, and all of others are nonsensitive mode. The weighting coefficient of sensitive mode $W_j = 1.0$, while $W_j = 0.5$ for nonsensitive mode in Eq. (1).

The displacement mode of node $i$ and $i+1$ adjacent to element $i$ will be changed obviously, when the element $i$ is damaged, and amplitude of variation is highly significant compared with other nodes. Damage detection criteria can be written as

$$\delta_i \gg \frac{1}{m-2} \sum_{k=1}^{m} \delta_k, (k \neq i, i+1),$$

$$\delta_{i+1} \gg \frac{1}{m-2} \sum_{k=1}^{m} \delta_k, (k \neq i, i+1),$$

where $m$ means the total nodes.

The damage element (element $i$) can be predicted preliminarily using Eq. (1) without weighting coefficient $W_j$. According to the position of damage, it is safe to figure out the sensitive modes in all the modes. Then, the displacement mode modified is obtained by weighing the sensitive modes with Eq. (1). The new damage element is obtained based on weighed information of mode. If the new damage element coincides with the former, the method works and vice versa. In practical computation, the data from a few lower-order modes are adopted. When the method based on weighting modal information fails, more higher-order modes could be added, because it is easy to predict the position of damage with complete mode information. Procedure of this approach is shown in Fig. 1.
3. The modeling of a simply-supported beam

3.1. The finite element model
To assess the performance of the purposed method, we consider a beam with a circular ring cross section divided into 20 beam finite elements with four degrees-of-freedom per node (see Fig. 2). The beam is assumed to be simply supported at each end node.

The beam has 2.6m in length and a circular ring cross section of external diameter \( D = 0.108 \text{m} \), internal diameter \( d = 0.096 \). According to experimental specimen, the Young modulus \( E \), Poisson’s ratio \( \nu \), and the mass density \( \rho \) are \( E = 2.0 \times 10^{11} \text{N/m}^2 \), \( \nu = 0.2685 \), \( \rho = 7.85 \times 10^3 \text{kg/m}^3 \). To simulate the real structure the following two cases are studied:

Case 1: Single damage. Reduction of 20% to the stiffness is introduced in the 9th element (between nodes 9 and 10 in Fig. 2).

Case 2: Multiple damages (two damaged elements in the paper). Reduction of 20% to the stiffness is introduced in the 9th element (between nodes 9 and 10 in Fig. 2), and 15% in the 16th element (between nodes 16 and 17).

For experimental measurements, it is expected that there would be some deviation due to noise originating from testing environment as well as electronic device. To simulate the experimental measurements, 5% of random noise is added.

3.2. The damaged element
Here, an assumption within the modeling of the pipe is given that the damage only influences the stiffness rather than the mass. In order to represent the reduction to stiffness of the damaged beam, the same volume reduction is made in each damaged element. The type is ring cross cutting (see Fig. 3).
4. Numerical studies

In this section, in order to verify the feasibility of the proposed approach, two numerical example cases are considered with different damage positions and damage sizes. The position and size of the damage for each case are defined in Section 3.

These two examples were performed to demonstrate the robustness of the damage identification method with respect to the damage’s location using the first five modes which can be obtained simply and accurately. The results of two examples are as follows.

![Numerical result for single damaged element: (a) no weighted, (b) weighted](image)

**Figure 4.** Numerical result for single damaged element: (a) no weighted, (b) weighted

![Numerical result for two damaged elements: (a) no weighted, (b) weighted](image)

**Figure 5.** Numerical result for two damaged elements: (a) no weighted, (b) weighted
Fig. 4 and 5 are illustrated the obtained results. The objective of both numerical examples above is to demonstrate that damage detection and the identification of the damage positions can be detected with adequate precision. And the improvement made by the weighting method is fairly obvious. Moreover, it should be noted that 5% of random noise is added to the simulations according to the presence of noise in the measurements.

5. Experimental results of pipeline structures

Modal information of a pipeline structure in accordance with simulations will be acquired in this section. The experiment is schematically illustrated in Fig. 6. The size and parameter are the same to those of the finite element model. A 16-channel data acquisition system, B&K 3560C (with modules 3038 and 7537, Brüel & Kjær S&V, A/S, Nærum, Denmark) intelligent signal acquisition and analysis system, is employed in the experiment, and the modal analysis is performed with PLUSE 10.3 software supplied by Brüel & Kjaer. Moreover, initial frequency response function and coherence functions are checked to ensure the quality of acquired data.

![Figure 6. The experimental model of simply-supported beam](image)

One accelerometer is mounted between nodes 17 and 18 to measure the acceleration signals, while an impact hammer excites the beam at each node in turn, respectively. One necessary step of the beam experiment is to obtain the frequencies and mode shapes. The experimental results using the approach presented in this paper are shown in Fig. 7 and 8.
It should be noted that the sensor placement affects the damage identification and the modal analysis results. The study on sensor placement for damage identification and modal analysis is beyond the scope of the paper, and will be further investigated.

6. Conclusion

This research deals with the nondestructive detection of single and a couple of large area corrosion in a simply-supported beam.

This paper presents the weighting mode displacement superposition method, based on structural modal analysis theory, aimed at the usual damaged styles in pipeline structures. The concept of weighting coefficient is introduced in this method, which depends on the relationship between the damage positions and different orders of model shape, and improves the capability of damage identification method based on displacement mode. Numerical examples of single and multi-damaged simply-supported beams are performed using first five modes which can be measured easily. The results show that the proposed method works well for the damage detection and the assessments are in good agreement with the actual condition even with 5% of random noise being added to the simulations. Finally, experimental examples of pipeline structure in different damaged cases according
to the numerical examples are provided to verify the correctness and feasibility of the proposed method through approach of experimental model.

The method presented in the paper shows high computational efficiency and reliability with a simple theoretical basis, and just needs the first few modes of structure which can be obtained simply in the test. The results can be used as a theoretic and engineering guidance for the damage assessment.

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