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Damage identification in beam-like pipeline based on modal information

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Abstract. Damage detection based on measured vibration data has received intensive studies recently. Frequently, the damage to a structure may be reflected by a change of some system parameters, such as a degradation of the stiffness. In this paper, we apply a method to nondestructively locate and estimate the severity of damage in corrosion pipeline for which a few natural frequencies or mode shapes are available. The method is based on the strain modal sensitivity ratio (SMSR) and the orthogonality conditions sensitivities (OCS) applied to vibration features identified during the monitoring of the pipeline. The advantage of these methods is that it only requires measuring few modal parameters. The SMSR-based and OCS-based damage detection methods are illustrated using computer-simulated and laboratory testing data. The results show that the current method provides a precise indication of both the location and the extent of corrosion pipeline.

Keywords: damage identification; corrosion pipeline; the strain modal sensitivity ratio; the orthogonality conditions sensitivities; mode shape.

1. Introduction

Due to tremendous growth of pipeline accidents, damage detection in pipeline is an important issue from the point of view of safety and functionality. It is essential to carry out periodical inspection in pipelines to detect any pipeline damage, which may require major or minor repair for safety and serviceability of the structures. The cost of repair is obviously lesser than that required for the reconstruction of the whole pipeline system. Nondestructive technique such as visual inspection, radiograph, ultrasonic testing, acoustic emission, etc., may be used to detect damage in the pipelines. However, most of these nondestructive techniques used to evaluate the damage in pipeline require much time and money to be applied. Therefore, the development of damage

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identification methods which are cheaper and faster to perform is very important. The problems can be avoided through the use of vibration-monitoring such as modal analysis. Much of pipeline system can be quickly detected using modal analysis detection method which is new tool applied for pipeline damage detection recently.

Damages may be characterized by changes in the modal parameters, i.e., natural frequencies, modal damping ratios and mode shapes. Many researchers have attempted to detect and localize damage using changes in modal parameter. Such as a method based on the changes in dynamic characteristics to identify damage in structures was proposed (Adams *et al.* 1978). The ratios of frequency changes have attempted to detect and localize damage (Hearn and Testa 1991). The damage location in reinforced concrete structures using dynamic stiffness determination was identified (Maeck and Abdel Wahab 2000). Location of cracks was detected by observing changes in curvature mode shape (Pandey *et al.* 1991). Flexibility curvature in simulated experiments on the reinforced concrete beam was used (Lu *et al.* 2002). A frequency response function curvature method based on Pandey's work was described (Sampaio 1999). Using curvature mode shapes for better localization of damage in bridges was considered (Dutta and Talukdar 2003). A newly derived algorithm to predict locations of damage in structures using changes in modal characteristics was presented (Kim and Stubbs 1995, 2002); These researches all have made active progresses and contributions.

In this paper, two methods based on the strain modal sensitivity ratio (Yang *et al.* 2006) and the orthogonality conditions sensitivities (Araúji dos Santos *et al.* 2000) by which the detection and assessment of damaged pipeline elements can be carried out, are proposed. The method is intended to be applied on real industrial pipeline by using known a few (1-3) modal shapes and frequencies which can be obtained either from experimental measurements or from simulated data. The two methods are proved to be simple and efficient by detecting various damage pipelines.

2. Theory of nondestructive damage detection

The methodology presented here is received the information on the location and the severity of damage in the pipeline directly from measured changes in the modal characteristics of the pipeline system. The modal characteristics of interest here are natural frequencies and mode shapes. Once two sets of modal parameters are measured, for the pipeline and its corresponding damaged state, the damage detection method described here are used to predict the damage location and to estimate the severity of the damage at that location.

2.1 SMSR method

With reference to Fig. 1, suppose we are given undamaged pipeline with *i*th natural frequency, ω_i,

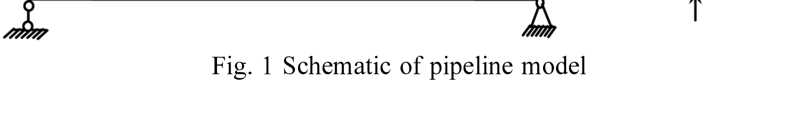


Fig. 1 Schematic of pipeline model

and ith mode shape, ϕ_i, using finite element method or experimental test. Next, assume that at some later time the pipeline is damaged (e.g., as shown in Fig. 1) in one or more locations of the structure. The resulting characteristic equation of the damaged structure yields, respectively, frequencies and mode shapes ω_i^* and ϕ_i^*. Note that the asterisk denotes the damaged state.

This method proposes the ratio in the strain mode shapes between the intact and the damaged case for the detection and location of the damage. Actually, the ratio in the strain mode shapes are found in the region of damage (Yang *et al.* 2006). The strain mode shape of the intact case is given by

$$\varepsilon_i = \frac{\sigma_i}{E} = \frac{M(x_i)D}{2EI} = \frac{D}{2\Delta^2}(y_{i+1} - 2y_i + y_{i-1}) = A\bar{y}_i \tag{1}$$

where $A = D/2\Delta^2$, $\bar{y}_i = (y_{i+1} - 2y_i + y_{i-1})$, D is outer diameter of pipeline, Δ is step, y_i is deflection of ith node using mode shapes determined.

The sensitivity of the ith strain mode and jth member are defined as

$$F_{ij} = \frac{\varepsilon_{ij}}{\varepsilon_{rms(i)}} \tag{2}$$

where $\varepsilon_{rms(i)}$ are the root mean square of ith strain mode for intact pipeline structure.

When there are damage case, the corresponding modal parameter in Eq. (1) and Eq. (2) will be characterized by asterisks. Then for the damaged pipeline, the sensitivity of the ith strain mode and jth member are defined as

$$F_{ij}^* = \frac{\varepsilon_{ij}^*}{\varepsilon_{rms(i)}^*} \tag{3}$$

Eq. (3) is divided by Eq. (2), yield

$$\beta_j = \frac{\sum_{i=1}^{nm} \varepsilon_{ij}^* \varepsilon_{rms(i)}}{\sum_{i=1}^{nm} \varepsilon_{ij} \varepsilon_{rms(i)}^*} \tag{4}$$

in which nm is mode number.

A damage detection criterion (1), (2) can be obtained

$$\text{criterion (1):} \quad \beta_i >> \beta_{i+1}, \beta_{i-1} \tag{5}$$

If $\beta_{i+1} > \beta_{i-1}$, then the element between node i and node $(i+1)$ has damage, if $\beta_{i-1} > \beta_{i+1}$, then the element between node i and node $(i-1)$ has damage.

$$\text{criterion (2):} \quad \beta_i > 1, \ \beta_{i+1} > 1 \tag{6}$$

If $\beta_i > 1$, $\beta_{(i+1)} > 1$ element between node i and $(i+1)$ occurs corrosion damage.

2.2 OCS method

For the pipeline of m elements and n nodes (as shown in Fig. 1), the damage inflicted at ith location may be predicted using the following the orthogonally conditions sensitivities method (Araúji dos Santos *et al.* 2000)

$$\sum_{e=1}^{N} \bar{q}_{ie}^{T} K_e \bar{q}_{je} \delta b_e = \bar{q}_i^T K \bar{q}_j - \delta_{ij} \bar{\lambda}_j \tag{7}$$

where $\bar{q}_{ie}$ and $\bar{q}_{je}$ are the element e displacement vector of the ith and jth mode shape of the damaged pipeline, respectively, N is the number of elements of the discretised pipeline, $\bar{q}_i$ an $\bar{q}_j$ are the ith and jth eigenvector of the damaged pipeline respectively, K_e is the element e stiffness matrix, K is the total stiffness matrix for pipeline system, $\delta b_e \in [0, 1]$ is the damage parameter, δ_{ij} is Kronecker delta function and $\bar{\lambda}_j$ is the jth eigenvalue of the damaged pipeline.

Eq. (7) can be written more compactly as

$$S\delta b = \delta\lambda \tag{8}$$

where

$$S(k, e) = \bar{q}_{ie}^{T} K_e \bar{q}_{je} \tag{9}$$

$$\delta b(e) = \delta b_e \tag{10}$$

$$\delta\lambda(k) = \bar{q}_i^T K \bar{q}_j - \delta_{ij} \bar{\lambda}_j \tag{11}$$

with $k = 1, \ldots, m(m+1)/2$ and $e = 1, \ldots, N$, S is the sensitivity matrix of the damage pipeline, δb is the vector of damage parameter and $\delta\lambda$ is the vector of modal parameters of damaged pipeline. K is the stiffness matrix of intact pipeline.

Considering that OCS method will be applied to pipeline experimental detection, structural parameter identification will be corrected by modal test results. Mass and stiffness matrix correction using an incomplete set of measured models (Berman 1979, Wei 1980). The methods described here introduce some small modifications in such a way that the mass and stiffness matrices can be written in the form $M + \Delta M$ and $K + \Delta K$. The advantage of these method is that it does not need eigenvalue and eigenvector computed and it only modifies theory model K_0, M_0, which is computed by finite element method, using modal matrix and eigenvalue matrix through experimental test to obtain modification parameter M, K.

$$E_0 = \Phi^T M_0 \Phi \tag{12}$$

E_0 is orthogonal verify matrix and symmetry matrix.

$$\Delta M = M_0 \Phi E_0^{-1} (I - E_0) E_0^{-1} \Phi^T M_0 \tag{13}$$

ΔM is value of small variety

$$M = M_0 + \Delta M \tag{14}$$

$$K = K_0 + Y + Y^T \tag{15}$$

where

$$Y = \frac{1}{2}M_0\Phi(\Phi^T K_0\Phi + \Lambda)\Phi^T M_0 - K_0\Phi\Phi^T M_0 \tag{16}$$

On substituting Eq. (9) into Eq. (8) and yields

$$\delta b = [\bar{q}_{ie}^T(K_0 + Y + Y^T)_e \bar{q}_{je}^T]^{-1}\delta\lambda \tag{17}$$

$\delta b_e \in [0, 1]$, is dimensionless damage parameter, e denotes element number. Eq. (17) can be solved to estimate the location and magnitude of pipeline's damage. The appealing features of this method include the following: (1) damage can be located and quantified using few modes; (2) successful experiment of applying this method to pipeline damage detection; (3) multiple damages localization and extent estimation to pipeline.

3. Numerical verification

3.1 Description of pipeline

A simply supported pipeline structure with damage in element 3, 6 shown in Fig. 2 is used to verify the damage identification methods described above. The FEM analysis is carried out to simulate the experimental data by using two-node linear pipeline elements. The pipeline is equally divided into 10 two-dimensional pipeline elements as shown in the Fig. 2. The length of each element is 0.3 m. All elements are assumed to be made of the same material with $E = 205$ GPa and $\rho = 7.8 \times 10^3$ kg/m^3.

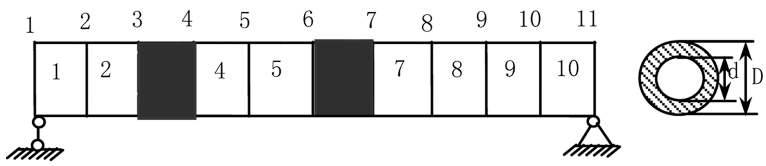


Fig. 2 Schematic of test structure with damage in element 3, 6

Table 1 Simulated damage locations and severities

Damage case	Damage element	Severity $\left(\frac{\Delta E}{E}\right)$ %	Severity $\left(\frac{\Delta A}{A}\right)$ %
1	3	9.44	7.55
2	3	18.5	15
3	6	9.44	7.55
4	6	18.5	15
5	3, 6	9.44	7.55
6	3, 6	18.5	15

Table 2 Natural frequencies of the intact and damaged pipeline

Frequency	Intact (Hz)	Case 1 (Hz)	Case 2 (Hz)	Case 3 (Hz)	Case 4 (Hz)	Case 5 (Hz)	Case 6 (Hz)
1st	38.665	38.4415	38.359	38.3909	38.236	38.3404	38.1185
2nd	154.21	153.134	152.60	153.493	153.43	153.086	152.469
3rd	345.37	343.446	342.92	343.209	342.41	342.769	341.396

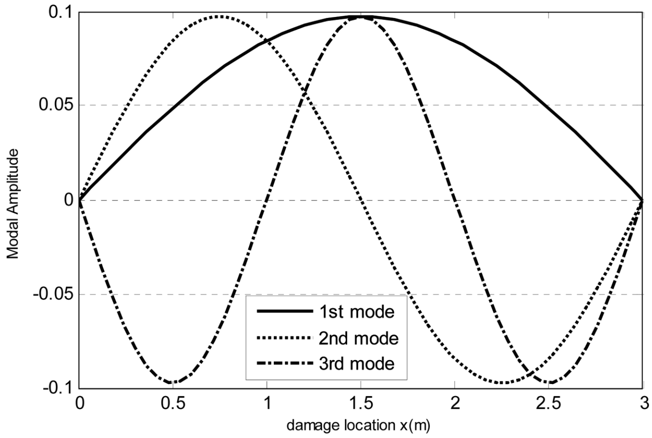


Fig. 3 Mode shape of the intact pipeline

The intact and damaged modal parameters of pipeline model were generated numerically using the finite element method. The structure is subjected to six damage scenarios in which the number of inflicted damage location ranges from one to two. Damage is numerically simulated by reducing the elastic module or area of the appropriate elements. The locations and corresponding magnitudes of the damage simulated for each damage scenario are summarized in Table 1. The natural frequencies of the intact and damaged pipeline are shown in Table 2 and the first three mode shapes are shown in Fig. 3.

3.2 Damage detection by SMSR method

For the first three natural frequencies and mode shape, the damaged index β_i was calculated using Eq. (4). Damage indices of damage cases 1-6 are plotted in Fig. 4. In the Fig. 4(a), it can be observed that the maximum peaks appear at node 3, and the value of node 4 is more than the one of node 2, so using criterion (1) the damaged element 3 between node 3 and node 4 is located successfully for a few mode. In the same way, observing Figs. 4(b), (c), (d), it can be verified that the corresponding damaged element are obtained easily using this method. Observing Figs. 4(e), (f), it is observed that the element 3 and 6 occurs damage.

In these cases this method located the damages correctly. SMSR method may indicate the damaged element for the working pipeline quickly and accurately.

3.3 Damage detection by OCS method

Fig. 5 show the obtained results using OCS method from modal parameter for the six damaged

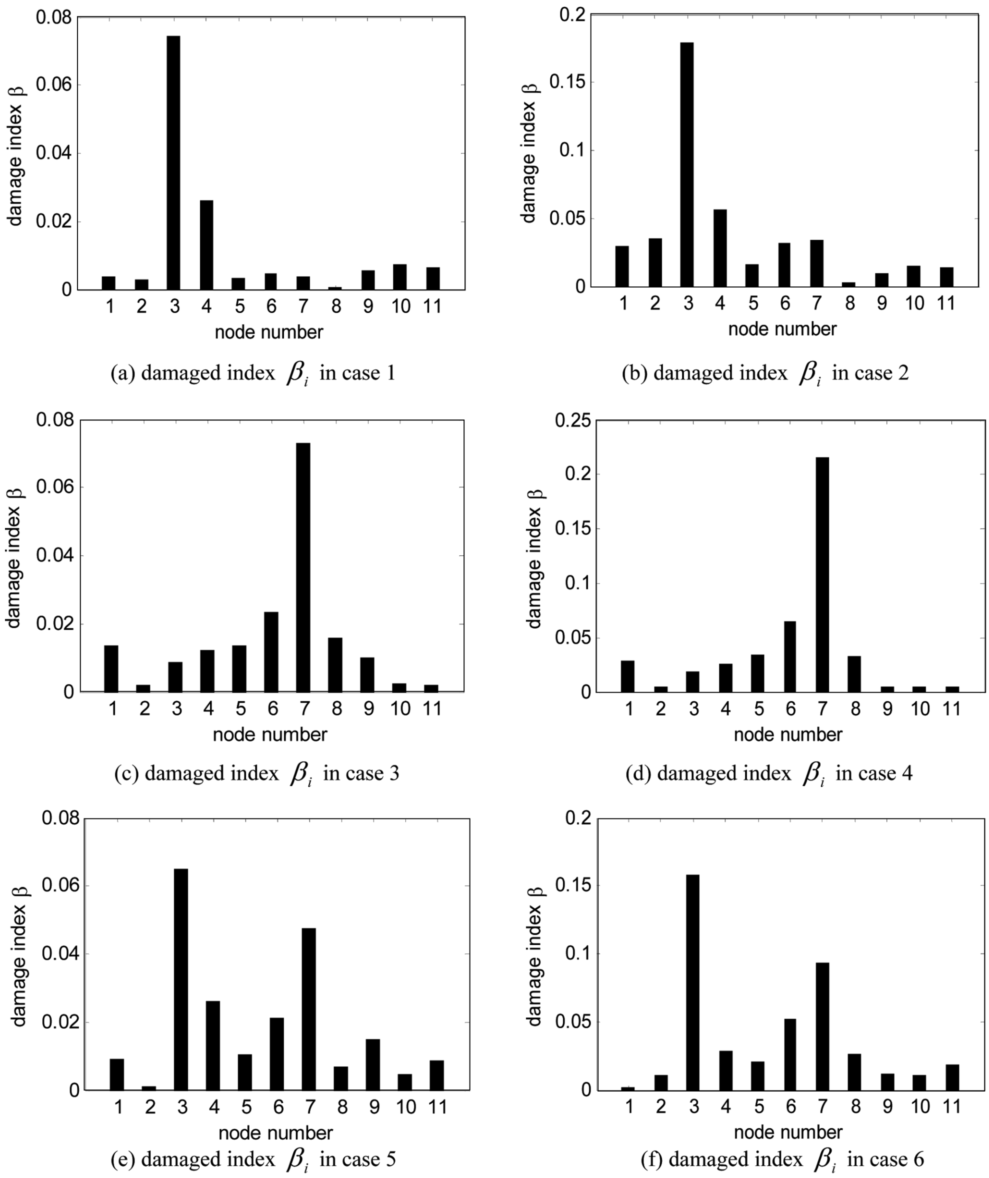
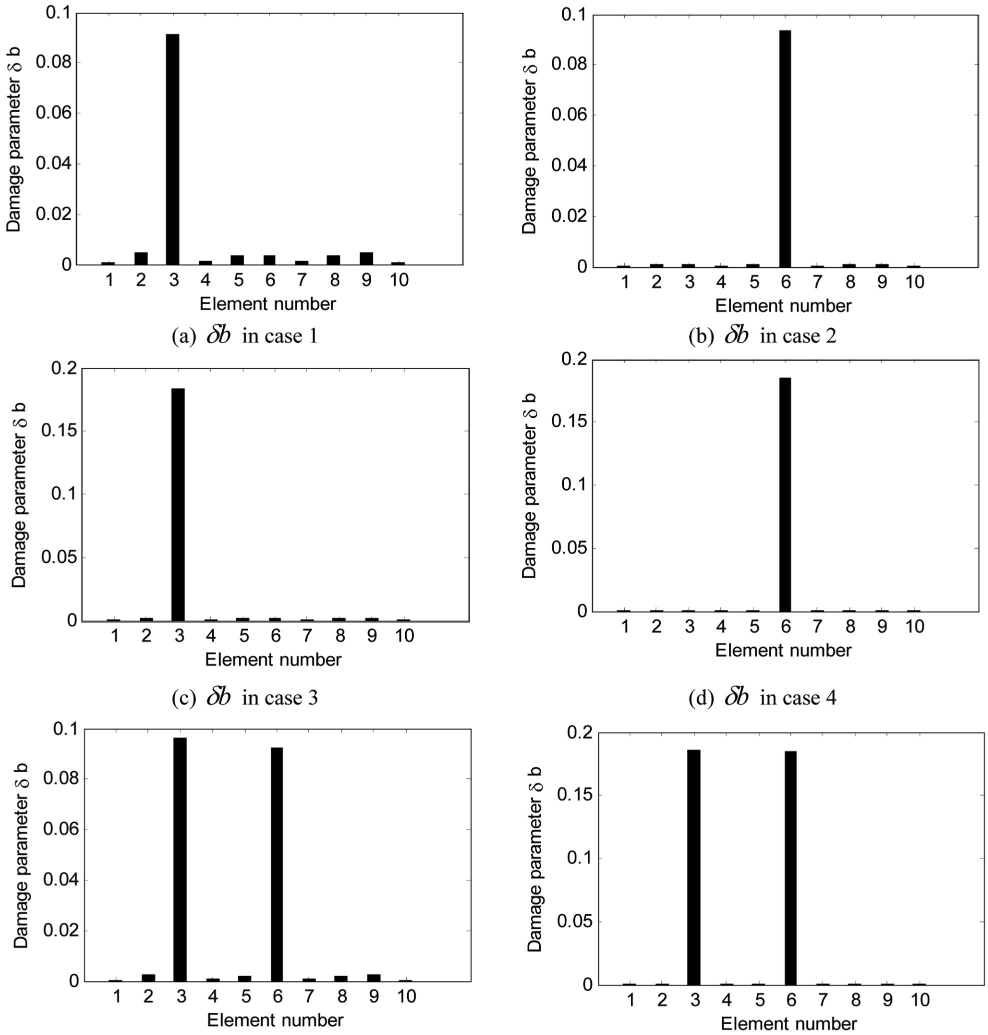


Fig. 4 Damage location by the strain modal sensitivity ratio in six damage cases

cases (see Table 1). From Figs. 5(a), (c) the damaged element 3 can be detected very clearly when using the first three natural frequencies and mode shape. Few undamaged elements may be estimated as damaged ones. Furthermore, for assessing the damage extent in case 1 and case 3, the corresponding results from Figs. 5(a), (c) show that the δb value of predicted element 3 was close to one of the simulated element (see Table 1) using OCS method. For case 2 and case 4, the results of single damage location and severity can also be accurately obtained. The damage quantification for case 5 and 6 which elements 3 and 6 are damaged was done using Eq. (17). Observing Figs. 5(e) (f) it can be verified the simulating situation using only a few natural frequencies and mode shape.



(a) δb in case 1 (b) δb in case 2

(c) δb in case 3 (d) δb in case 4

(e) δb in case 5 (f) δb in case 6

Fig. 5 Damage location by the orthogonality conditions sensitivities in six damage cases

4. Experimental verification

4.1 Experiment system setup

A 32-channel Dynamic Signal Process System (DSPS) (see Fig. 7), an intelligent signal and analysis system, was employed for the measurement of accelerations as well as excitation. Modal test system was designed as shown in Fig. 6. Single dot excitation and single response testing method were adopted here. The experimental set up of the corrosion damage is shown in Fig. 7. Three same properties pipelines were prepared. (see Fig. 8) Each beam specimen was made of which was *No.*1, *No.*2, *No.*3 of pipeline section area $A = 0.0023\ \mathrm{m}^2$ and length $L = 3$ m. The corresponding material properties are Young's modulus are $E = 210$ GPa Poisson's ratio $\nu = 0.3$, and

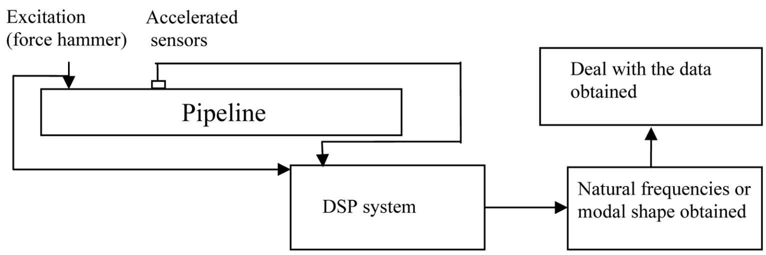


Fig. 6 Modal test system

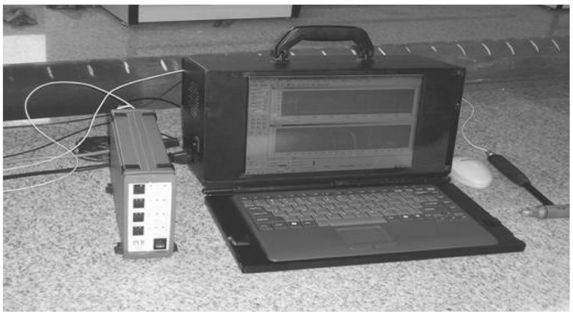


Fig. 7 Testing system

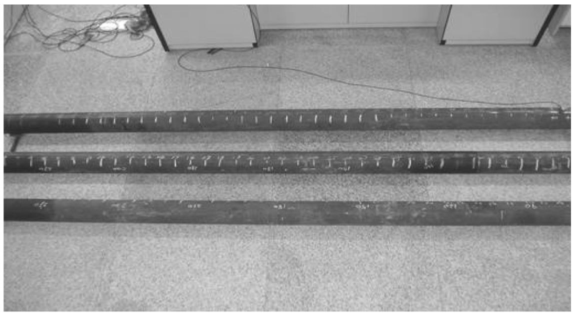


Fig. 8 Testing pipeline

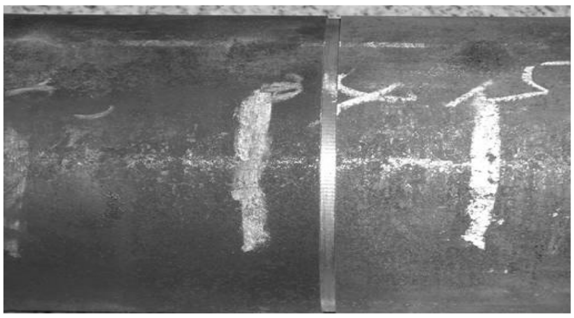


Fig. 9 Damage situation in No.7 element of *No.*2 pipeline

Fig. 10 Damage situation in No.7 element of *No.*2 pipeline

density $\rho = 7.8 \times 10^3$ kg/m^3. Each pipeline was discretized 10 element with 11 node. Among these pipeline, *No.*1 pipeline is undamage one and the others are all damage in No.7 element (see Figs. 9 and 10).

4.2 Damage detection by SMSR method

*No.*1~*No.*3 pipeline modal frequency and modal vector of pipeline through experimental test are listed in Table 3 and in Fig. 11.

Using test data, the results of the first three order strain sensitivity ratio which are computed by Eq. (17) are shown in Fig. 12.

Fig. 12 shows that the value of node 7 strain sensitivity ratio for *No.*2 and *No.*3 corrosion

Table 3 Resonant frequency of model pipeline

Damage case	Resonant frequency (Hz)		
	Mode 1	Mode 2	Mode 3
*No.*1 intact	32.432	71.631	240.930
*No.*2 7th element	29.635	61.321	237.778
*No.*3 7th element	26.253	94.822	231.238

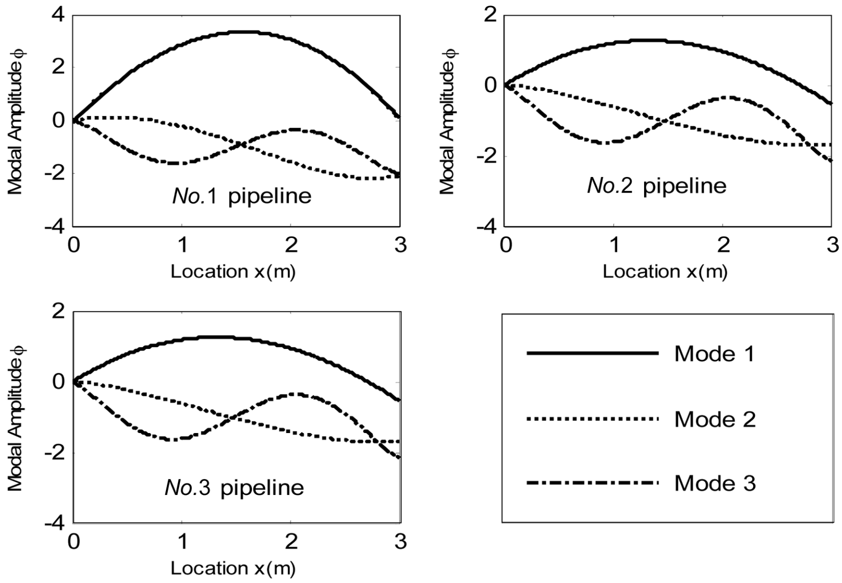


Fig. 11 (a), (b), (c) the first three mode shapes of *No.*1, *No.*2, *No.*3 pipeline

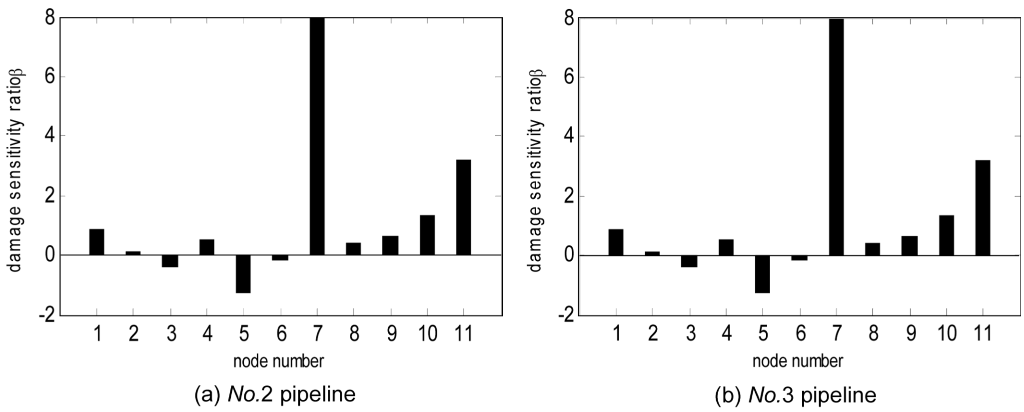
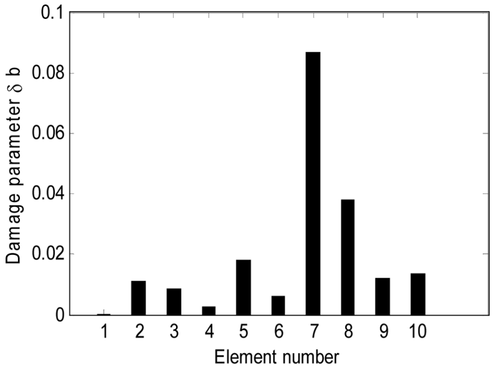
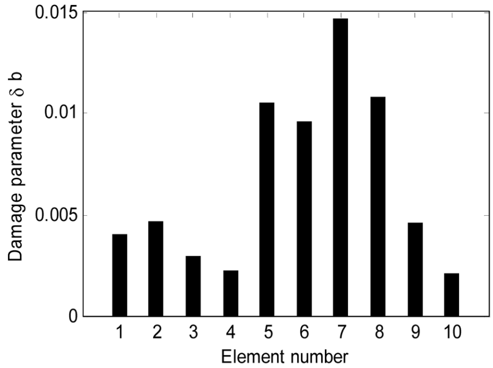


Fig. 12 Damage index : strain sensitivity ratio β

pipelines is more than others, and that $\beta_8 > \beta_6$, which is accord with criterion (1) (Eq. (5)). So No.7 element between node 7 and node 8 has corrosion damage. This situation is accord with practical corrosion pipelines.



(a) Damage parameter δb of *No.*2 pipeline



(b) Damage parameter δb of *No.*2 pipeline

Fig. 13 Damage parameter δb of *No.*2, *No.*3 pipeline

4.3 Damage detection by OCS method

The damaged parameter δb (i.e., Eq. (17)) was computed by using the frequency results listed in Table 3 and the value of the first three modal shapes in Fig. 11. The damaged parameter δb for the *No.*2, *No.*3 pipelines are plotted in Fig. 13. Observing Fig. 13(a) which shows the results for damage in element 7 for *No.*2 pipeline it can be seen that the corresponding damage indices indicates only the damaged element 7 and shows the damage quantification in element 7. The corresponding area reduction for *No.*2 pipeline considered was 8%. The damage index δb indicated an area reduction 8.9% which is near to practical one. Fig. 13(b) shows that the maximum peak appears No.7 element and indicates an area reduction 1.5%, but the value of damaged parameter δb of No.5, 6, 8 element are near to the one of No.7 element, because the damage severity of *No.3* pipeline is smaller than the one of *No.2*. So, when the damage is very small we can detect damage location using the method above first, and then use other accurate methods detect damage severity.

5. Conclusions

This paper presented a methodology to nondestructively locate and estimate the severity damage in pipelines for which both frequencies and mode shapes were available. First, a strain modal sensitivity ratio method (SMSR) was outlined. A damage-localization algorithm that locates damage from changes in modal parameter were formulated. Next, an orthogonality conditions sensitivities (OCS) method was outlined. A damage index algorithm that locates and estimates severity of damage from few modal parameter was formulated. The SMSR method and the OCS method were evaluated for several damage scenarios by locating and quantifying damage in numerically simulated pipeline or experimental pipeline for which only two sets of modal parameters were available. For the verification test, natural frequencies and mode shapes of the pipeline were generated from finite element models and experimental test data. By applying the SMSR approach to the test pipeline, it was observed that damage could be located simply and quickly. The predicted locations are nearly accurately the correct locations in the 3 m pipeline. By applying the OCS approach to the test pipeline, it was observed that damage could be located accurately. The predicted locations were identical to the inflicted locations. It was also observed that the severity of the damage could be estimated accurately.

These methods have three merits: (a). The experimental data can easily obtained; (b). The lower-order modal shape is only required; (c). This method has good advantage at practical engineering applications.

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