COMPARATIVE STUDY OF TWO DAMAGE IDENTIFICATION ALGORITHMS BASED ON VIBRATION MEASUREMENTS

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1. INTRODUCTION

Many research studies have been conducted in the area of non-destructive damage detection (NDD) using changes in modal parameters. Research studies have related changes in natural frequencies, mode shapes and damping to changes in beam properties such as cracks, notches or changes in boundary conditions(1). Damage Index Method(2) is one of the most referenced methods for detecting and localizing damage in beam type structures using changes in mode shapes. In this paper, a new algorithm for this method will be derived in order to use amplitudes of Cross Spectral Density (CSD) instead of using mode shapes. The new algorithm and the existing one will be applied and compared using experimental data extracted from simple steel beam after making one and multiple cracks. Both algorithms are evaluated by detecting damage and predicting its location. The performance of each algorithm is assessed quantifying the accuracy of damage prediction results.

2. EXPERIMENTAL SETUP

In this research, simple steel beam supported by four bolts in both sides has been examined before and after making some cracks, as shown in Fig. 1. The multi-layer piezoelectric actuator is used for local excitation. The main advantage of using piezoelectric actuator is that it produces vibration with different frequencies ranging from 0 to 400 Hz that is effective in measuring mode shapes(3). Seven accelerometers were positioned on the top flange and one accelerometer was used as a reference channel, as shown in Fig. 2. Cubic polynomial was used to approximate CSD amplitude between each two sensors in order to create artificial degrees of freedom. Therefore, the total distance between accelerometers is divided to 120 nodes (Fig.2). Two cases of damage are introduced to the beam. Case 1 of damage is simulated by making one crack, 2 x 40 mm, at node 40 and Case 2 of damage is simulated by making 2 cracks with the same previous dimensions at nodes 40 and 90 (Fig. 2).

3. DAMAGE INDEX METHOD

This method(2) is used to detect and locate damage in structures using mode shapes before and after damage. For a structure that can be represented as a beam, a damage index β^* is developed based on the change in strain energy stored in the structure when it deforms in its particular mode shape. For location j on the beam this change in the i^{th} mode strain energy is related to the change in curvature of the mode at location j. The damage index for this location and this mode, β_{ij}, is defined as

$$\beta_{ij} = \frac{\left(\int_a^b [\psi_i^{*''}(x)]^2 dx + \int_0^L [\psi_i^{*''}(x)]^2 dx\right)\int_0^L [\psi_i^{''}(x)]^2 dx}{\left(\int_a^b [\psi_i^{''}(x)]^2 dx + \int_0^L [\psi_i^{''}(x)]^2 dx\right)\int_0^L [\psi_i^{*''}(x)]^2 dx} \qquad (1)$$

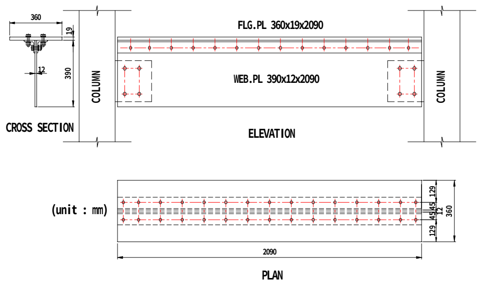

Fig. 1 Beam dimensions

where $\psi''(x)$ $\psi^{*''}(x)$ are the second derivative of i^{th} mode shape corresponding to the undamaged and damaged structure, respectively. L is beam length and a, b are the limits for element j. When more than one mode is used, damage index is defined as the sum of damage indices from each mode as follows

$$\beta_j^* = \sum_{i=1}^{n} \beta_{ij} \qquad (2)$$

where n is the number of modes. Peak value of β^*_j indicates damage at element j.

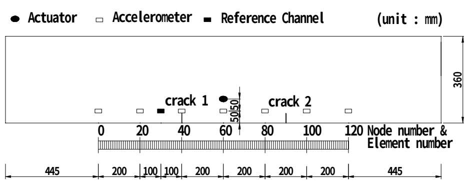

Fig. 2 Actuator and accelerometers positions and element numbers

4. PROPOSED ALGORITHM

Similar to Eq. (1), new algorithm can be formulated using the amplitude of CSD as follows

$$\alpha_{f,j} = \frac{\left(\int_a^b [\phi_f^{*''}(x)]^2 dx + \int_0^L [\phi_f^{*''}(x)]^2 dx\right)\int_0^L [\phi_f^{''}(x)]^2 dx}{\left(\int_a^b [\phi_f^{''}(x)]^2 dx + \int_0^L [\phi_f^{''}(x)]^2 dx\right)\int_0^L [\phi_f^{*''}(x)]^2 dx} \qquad (3)$$

where $\phi_f^{''}(x)$ $\phi_f^{*''}(x)$ are the second derivative of CSD amplitude at frequency f corresponding to the undamaged and damaged structure, respectively. L is beam length and a, b are the limits for element j. Assuming that the collection of the damage indices, $\alpha_{f,j}$, represents a sample population of a normally distributed random variable, a normalized damage indicator is obtained as follows

$$Q_{f,j} = \frac{\alpha_{f,j} - \overline{\alpha_f}}{\sigma_f} \qquad (4)$$

where $\overline{\alpha_f}$ and σ_f represent the mean and standard deviation of the damage indices, respectively. A statistical decision making procedure is employed to determine if the normalized damage index, $Q_{f,j}$, is associated with a damage location. Values of four

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standard deviations from the mean are assumed to be associated with damage locations. In order to reduce the effect of positive false readings, $Q_{f,j}$ values less than four will be removed and values greater than or equal to four will be added over different frequencies on the measurement range. When normalized damage index, $Q_{f,j}$, is calculated using the magnitude of CSD at different frequencies on the measurement range from *F1 to F2,* the new damage index is defined as the sum of absolute values of damage indices at each frequency as follows

$$S_j = \sum_{f=F1}^{F2} \left| Q_{f,j} \right| \qquad (5)$$

$L_{f,j}$ is used as a counter to identify the number of times damage is detected at element number *j*. Adding the value of $L_{f,j}$ over the different frequencies gives the total number of times damage is detected at element *j* on the measurement range as follows

$$O_j = \sum_{f=F1}^{F2} L_{f,j} \qquad (6)$$

Multiplying damage index, S_j, by the total number of times, O_j, defines the accumulated damage indicator, DI_j

$$DI_j = S_j \qquad (7)$$

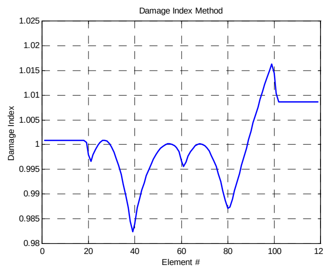

Fig. 3 Damage Index Method applied to exp. data for crack at node 40

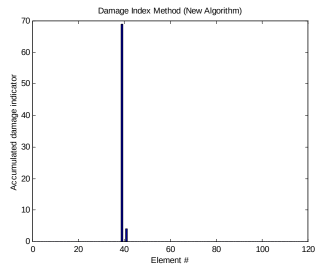

Fig. 4 The new algorithm applied to exp. data for crack at node 40

5. DAMAGE INDEX METHOD APPLIED TO EXP. DATA FOR CRACK AT NODE 40

Fig. 3 shows the obtained results when Damage Index Method is applied to experimental data after making one crack at node 40. Two mode shapes are measured for the intact and damaged beam. These mode shapes are used to detect damage and predict its position using the existing algorithm (Eq. 1). In this figure, two peak values appear at elements 39 and 99, which indicate damage at these elements. The indicated position at element 39 is accurate but the position at element 99 is false positive reading. When the new algorithm is applied, CSD amplitudes, for the intact and damaged beam, in the frequency range from 307 to 375 Hz are used for the new algorithm. Damage is detected and the location of damage is determined very accurately, as shown in Fig. 4. In this figure, damage was indicated obviously at element 39 and small indication of damage at element 41 moreover, no false positive readings appeared when the new algorithm was applied using that frequency range, from 307 to 375 Hz. Fig. 5 shows the number of times crack detected at each element. Damage at element 39 is detected 4 times and damage at element 41 is detected only once.

6. DAMAGE INDEX METHOD APPLIED TO EXPERIMENTAL DATA FOR TWO CRACKS AT NODES 40 AND 90

Two mode shapes were used for the existing algorithm and the obtained results are shown in Fig. 6. In this figure, peak values appear at elements 39, 80 and 99. Therefore, damage at node 40 is indicated accurately and damage at element 90 is indicated between elements 80 and 99. It is noticed that because sensors are positioned at nodes 0, 20, 40, 60, 80, 100 and 120, the accuracy of localizing the damage position was decreased when damage occurred between sensors. Although using cubic polynomial to approximate modal amplitude or CSD amplitude between sensors was not effective in increasing the accuracy of localizing damage between sensors but it is, on the other hand, useful to get the curvature of modal data or CSD data.

Here, Damage Index Method will be applied using the new algorithm and CSD amplitudes in the same frequency range from 307 to 375 Hz. Damage at element 40 was detected and the position is indicated very accurately at element 41. On the other hand, damage at element 90 was detected but the position is indicated at element 99, as shown in Fig. 7. The same remark is observed; when damage occurs between sensors it is detected at the nearest sensor position. Accumulated damage indicator at element 99 is higher than that at node 41. Damage was detected twice at element 99 and only once at element 41 (Fig. 8).

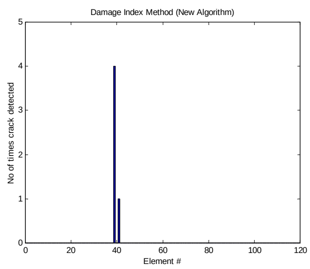

Fig. 5 No of times crack detected in exp. data for crack at node 40

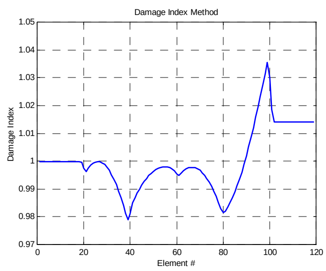

Fig. 6 Damage Index Method applied to exp. data for crack at nodes 40 & 90

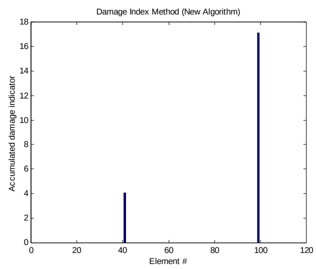

Fig. 7 The new algorithm applied to exp. data for crack at nodes 40 & 90

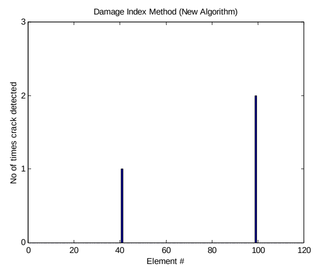

Fig. 8 No of times crack detected in exp. data for crack at nodes 40 & 90

7. CONCLUDING REMARKS

The proposed algorithm for damage identification using CSD amplitudes has shown better results in detecting and localizing cracks than the existing one. The new algorithm showed very accurate results in detecting damage and localizing its position for single and multiple cracks. Since CSD is measured from acceleration or displacement response without the need for measuring the excitation force, therefore the proposed algorithm can be a good tool for continuous health monitoring for structures using ambient vibration data. Interpolation using cubic polynomial function to approximate modal amplitude or CSD amplitude between sensors is not efficient for predicting damage position when the damage exists between sensors. On the other hand, interpolation is useful tool to calculate the second derivative for modal data or CSD data.

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