CRACK DETECTION IN SIMPLY SUPPORTED BEAMS WITHOUT BASELINE MODAL PARAMETERS BY WAVELET PACKET TRANSFORM

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1. INTRODUCTION

Most of vibration based damage identification methods assume that the displacement or the acceleration response time histories at various locations along the structure both before and after damage are available for damage assessment. These responses are used to estimate modal data. The change of modal data between the baseline state and the current state is then used to identify the location of possible damage in the structure. However, the baseline data are usually not available for most of the existing structures and these methods cannot be applied. In this paper, a new approach for damage detection in beam-like structures is presented. The proposed method does not require the modal data of the undamaged structure as a baseline for damage detection. Another advantage of the proposed method is that it can be implemented using a small number of sensors. In the proposed technique, the measured dynamic signals are decomposed into the wavelet packet components (WPT) and the power spectrum density (PSD) index is computed to indicate the structural damage. The method is applied to a tested steel beam. The results show that the proposed method has great potential in crack detection of beam-like structures.

2. PROPOSED ALGORITHM

Wavelet packets[1] consist of a set of linearly combined usual wavelet functions. The wavelet packets inherit the properties such as orthonormality and time-frequency localization from their corresponding wavelet functions. A wavelet packet $\psi^{i}_{j,k}(t)$ is a function with three indices where integers *i*, *j* and *k* are the modulation, scale and translation parameters, respectively,

$$\psi^{i}_{j,k}(t) = 2^{j/2}\psi^{j}(2^{j}t-k)\,,\; i = 1, 2, 3, \ldots \tag{1}$$

The wavelet functions ψ^{j} can be obtained from the following recursive relationships:

$$\psi^{2j}(t) = \sqrt{2}\sum_{k=-\infty}^{\infty} h(k)\psi^{i}(2t-k)\,, \tag{2}$$

$$\psi^{2j+1}(t) = \sqrt{2}\sum_{k=-\infty}^{\infty} g(k)\psi^{i}(2t-k)\,. \tag{3}$$

The first wavelet is so-called a mother wavelet function as follows:

$$\psi^{1}(t) = \psi(t) \tag{4}$$

After *j* level of decomposition, the original signal *f* (*t*) can be expressed as

$$f(t) = \sum_{i=1}^{2^{j}} f^{i}_{j}(t)\,. \tag{5}$$

The wavelet packet component signal $f^{i}_{j}(t)$ can be represented by a linear combination of wavelet packet functions $\psi^{i}_{j,k}(t)$ as follows:

$$f^{i}_{j}(t) = \sum_{k=-\infty}^{\infty} c^{i}_{j,k}(t)\psi^{i}_{j,k}(t)\,, \tag{6}$$

where the wavelet packet coefficients $c^{i}_{j,k}(t)$ can be obtained from

$$c^{i}_{j,k}(t) = \int_{-\infty}^{\infty} f(t)\psi^{i}_{j,k}(t)dt \tag{7}$$

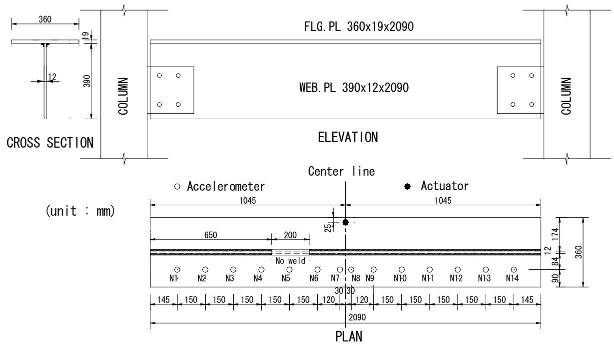

Fig. 1 Beam layout, main dimensions and sensor locations

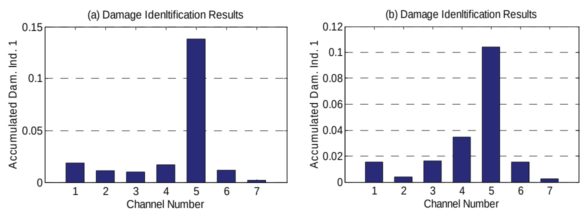

Fig. 2 Damage identification results for damage location at N5 using experimental data obtained from test 1 and test 2

The proposed method for damage detection uses the difference between the PSD magnitudes of two new signal series obtained from the wavelet packet components of a damaged beam. Firstly, the original signal is divided and reconstructed into two signal series as follows. If the original signal is made up of $d_1; d_2; \ldots; d_N$ measuring points, where *N* is the total number of measuring points, the first signal segment (s1) is the first half of the original signal, that is, $d_1; d_2; \ldots; d_{N/2}$; and the second signal segment (s2) is the second half of the original signal, that is, $d_N; d_{N-1}; \ldots; d_{N/2+1}$. After obtaining the two new signal series s1 and s2, the WPT decomposition of s1 and s2 is made, respectively, and the PSD magnitudes of each WPT component of the two new signal series are obtained. The difference between the PSD magnitude of each component in the WPT tree of the two new signal series s1 and s2 will be a better damage indicator than the change of PSD of the original signal. When the original signal is decomposed to the level *j*, 2^{j} WPT components can be obtained. For each WPT component *i*, let $G^{i}_{l}(f)$ denote the PSD magnitude measured at channel number *l* at frequency value *f*. The absolute difference in PSD magnitude between the two signals s1 and s2 can then be defined as[2]

$$D^{i}_{l}(f) = \left|G^{i}_{l}(f) - G^{i^{*}}_{l}(f)\right| \tag{8}$$

where the asterisk denotes the signal series s2. When the change in spectral function magnitude is measured at different frequencies on the measurement range from f_1 to f_m, a matrix [**D**] can be formulated as follows

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$$\mathbf{D} = \begin{bmatrix} D_1(f_1) & D_2(f_1) & \ldots\ldots & D_n(f_1) \\ D_1(f_2) & D_2(f_2) & \ldots\ldots & D_n(f_2) \\ . & . & \ldots\ldots & . \\ . & . & \ldots\ldots & . \\ . & . & \ldots\ldots & . \\ D_1(f_m) & D_2(f_m) & \ldots\ldots & D_n(f_m) \end{bmatrix} \qquad (9)$$

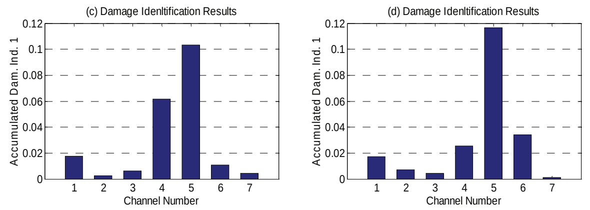

Fig. 2 cont. Damage identification results from test 3 and test 4

where $n = N/2$. A statistical decision making procedure is employed to determine the location of damage. The first step in this procedure is the selection of the maximum change in PSD magnitude at each frequency value (the maximum value in each row of matrix [**D**]) and discarding all other changes measured at other nodes. For example in matrix [**D**], if $D_3(f_1)$ is the maximum value in the first row then this value will be used as $M_3(f_1)$ and other values in this row will be discarded. The same process is applied to the different rows in matrix [**D**] to formulate the matrix of maximum changes of PSD magnitude at different frequencies, [**M**]. The total of maximum changes in PSD magnitude is calculated from the sum of the columns of matrix [**M**]

$$\mathbf{TM} = \left\{ \sum_f M_1(f) \quad \sum_f M_2(f) \quad . \quad . \quad . \quad \sum_f M_n(f) \right\}. \qquad (10)$$

In order to monitor the frequency of damage detection at any node, a new matrix [**C**] is formulated. The matrix consists of 0's at the undamaged locations and 1's at the damaged locations. The total number of times of detecting the damage at different nodes is calculated from the sum of the columns of matrix [**C**] as

$$\mathbf{TC} = \left\{ \sum_f C_1(f) \quad \sum_f C_2(f) \quad . \quad . \quad . \quad \sum_f C_n(f) \right\}. \qquad (11)$$

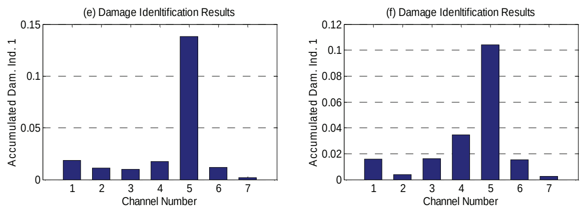

Fig. 2 cont. Damage identification results from test 5 and test 6

In order to reduce the effect of noise or measurement errors, a value of one standard deviation of the elements in vector {**TM**} will be subtracted from the vector {**TM**}. Any resulting negative values will be discarded. The same procedure will be applied to the vector {**TC**}. The damage localization indicator is defined as the scalar product of the resulting vectors

$$\mathbf{DI}1 = \{TM^*\} \cdot \times \{TC^*\}. \qquad (12)$$

Damage indicator is normalized such that the maximum relative amplitude for the indicator is 1.0. Thus a direct comparison between different cases is possible. The accumulated damage indicator is estimated from the sum of the damage indicators over different WPT components divided by (N/2) to normalize the data and then squared to reduce the influence of false positive readings.

3. DAMAGE IDENTIFICATION RESULTS

To make the damage identification practical, the proposed damage identification procedure is verified with real measurement data from dynamic tests on the structures where the noise and measurement errors are present. The damage indices in most of modal-based dynamic identification techniques are sensitive to noise and measurement errors, which is the main difficulty for practical applications. T-section steel beam with span length of 209 cm, as shown in Fig. 1, is used to illustrate the proposed damage assessment algorithm. The beam is constructed from a flange plate and a web plate. The two plates are welded together from both sides of the web except at a distance of 200 mm length starting at 650 mm from the left end of the beam, as shown in Fig. 1. The un-welded area represents the introduced damage to the beam. As can be seen in Fig. 1, channel 5 is the closest sensor to the damage location. 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 1 to 400 Hz that is effective in exciting several mode shapes. The actuator location is shown in Fig. 1. The actuator reaches its peak frequency within 15 seconds. The sampling frequency for all signals is 1600 Hz. Two accelerometers were mounted on the top flange to measure the acceleration response in the vertical direction at the first pair of measuring locations N1 and N14. Then the two accelerometers were moved to the second pair of measuring locations N2 and N13 and so on. The test was repeated seven times for each pair of measuring locations. The first set of data was constructed from the acceleration data recorded at all locations in test 1. Similarly, another six sets of data were constructed from the following tests. For the tested beam, the wavelet function DB5 is used to decompose the acceleration signals. The decomposition level is chosen to be 5 where a total of 32 component energies are generated. After decomposing the signals, PSD magnitude of each signal component, measured in the frequency range of 1-400 Hz (the same excitation range), were used to estimate the damage localization indicators. The histograms of the six sets of data are shown in Fig. 2. The damage location can be seen very clearly in these histograms. The accuracy of locating the damage varies slightly with repeating the experiment. However, for all sets of data, the maximum value of the damage indicators is always indicated at the correct damage location. All results have demonstrated that the location of damage can be identified from the real acceleration measurements.

4. CONCLUSIONS

Wavelet transformation has emerged recently as a powerful mathematical tool for capturing change of structural characteristic induced by damage. The basic premise of utilizing wavelet transformation is that damage in a structure will cause structural response perturbations at damage sites. Such local perturbations, although they may not be apparent from the measured total response data, are often discernible from component wavelets. Based on the analysis results of the tested beam, it is demonstrated that the proposed damage identification method is a good candidate index that is sensitive to structural local damage. All the results show that the proposed method has great potential in the field of crack detection of beam-like structures and it does not need the dynamic data of an intact beam as a baseline for crack detection. Although the proposed damage identification methodology has shown great potential in the laboratory tested beam, an important limitation of current method is that the monitored structural element must be symmetrical.

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