STRUCTURAL DAMAGE IDENTIFICATION FROM MEASURED DYNAMIC RESPONSE

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1. INTRODUCTION

The occurrence of damage in a structure produces changes in its global dynamic characteristics such as its natural frequencies, mode shapes, modal damping, modal participation factors, impulse response and frequency response functions. In this paper, a newly derived algorithm to detect damage, predict its location and assess damage extent in structures using changes in power spectral density (PSD) is presented. The proposed method is based on only the measured data without the need for any modal identification. The method is described theoretically and applied to the experimental data from a steel bridge model. Several damage scenarios were introduced to the members of the test structures. The method detected the damage, determined the exact location and monitored the increase in damage.

2. EXPERIMENTAL SETUP

In this research, a steel bridge model is examined after inducing damage with different levels to some members. The model consists of two girders and six cross beams. Each cross beam is connected to the girders with four bolts, 2 bolts in each side. The model dimensions and layout are shown in Fig. 1. The multi-layer piezoelectric actuator is used for local excitation(1). The main advantage of using piezoelectric actuator is that it produces vibration with different frequencies ranging from 0.1 to 400 Hz that is effective in exciting different mode shapes. The actuator force amplitude is 0.2 kN. One accelerometer is mounted at the bottom of each cross beam to measure the acceleration response in the vertical direction at the mid span of each cross beam. The PSD is calculated from node point accelerations using MATLAB standard and the MATLAB Signal Processing Toolbox. Six cases of damage are introduced to the specimen as follows:

Case 1: Removing one bolt completely from the left side of cross beam no. 2.
Case 2: Case 1 + releasing one bolt at the left side of cross beam no 2.
Case 3: Case 2 + removing one bolt at the right side of cross beam no 2.
Case 4: Case 3 + releasing one bolt at the right side of cross beam no 2.
Case 5: Removing one bolt from the left side of cross beam no. 3.
Case 6: Removing one bolt and releasing the second one from the left side of cross beam no. 2. The same damage is introduced to cross beam no. 5.

3. PROPOSED ALGORITHM

Let $G_i(f)$ denote the PSD magnitude measured at channel number i at frequency value f. The absolute difference in PSD magnitude before and after damage can then be defined as

$$D_i(f) = \left| G_i(f) - G_i^*(f) \right| \tag{1}$$

where $G_i(f)$ and $G_i^*(f)$ represent PSD magnitude for the undamaged and damaged structures respectively. When the change in PSD is measured at different frequencies on the measurement range from f_1 to f_m, a matrix $[D]$ can be formulated as follows

$$D = \begin{bmatrix} D_1(f_1) & D_1(f_2) & \ldots\ldots & D_1(f_m) \\ D_2(f_1) & D_2(f_2) & \ldots\ldots & D_2(f_m) \\ . & . & \ldots\ldots & . \\ . & . & \ldots\ldots & . \\ . & . & \ldots\ldots & . \\ D_n(f_1) & D_n(f_2) & \ldots\ldots & D_n(f_m) \end{bmatrix} \tag{2}$$

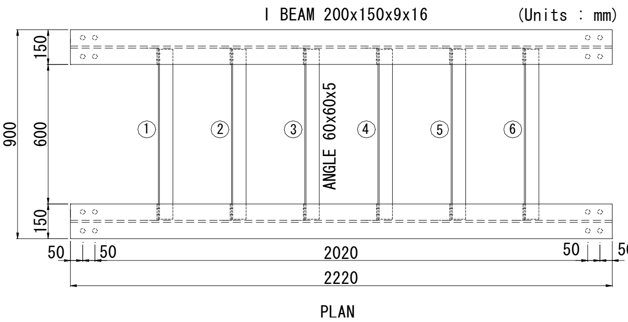

Fig. 1 Basic dimensions of the bridge model and beam numbers

where n represents the number of measuring points. In matrix $[D]$, every column represents the changes in PSD at different measuring channels but at the same frequency value. The summation of PSD changes over different frequencies can be used as the indicator of damage occurrence and the increase in damage. In other words, the first damage indicator is calculated from the sum of rows of matrix $[D]$. However it was found to be a weak indicator of damage localization. A statistical decision making procedure is employed to determine the location of damage. The first step in this procedure is the picking of the maximum change in PSD at each frequency value (the maximum value in each column of matrix $[D]$) and removing all other changes in PSD measured at other nodes. For example in matrix $[D]$, if $D_3(f_1)$ is the maximum value in the first column then this value will be used as $M_3(f_1)$ and other values in this column will be removed. The same process is applied to the different columns in matrix $[D]$ to formulate the matrix of maximum changes of PSD at different frequencies, $[M]$. 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. For example in the matrix $[C]$, we put a value of 1 corresponding to the location of $M_3(f_1)$ and 0's at other elements of that column. The total of maximum changes in PSD is calculated from the sum of the rows of matrix $[M]$ and the total number of occurrences of damage is calculated from the sum of the rows of matrix $[C]$ as

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$$SM=\begin{Bmatrix}\sum_f M_1(f)\\ \sum_f M_2(f)\\ .\\ .\\ .\\ \sum_f M_n(f)\end{Bmatrix}\quad\text{and}\quad SC=\begin{Bmatrix}\sum_f C_1(f)\\ \sum_f C_2(f)\\ .\\ .\\ .\\ \sum_f C_n(f)\end{Bmatrix}\qquad(3)$$

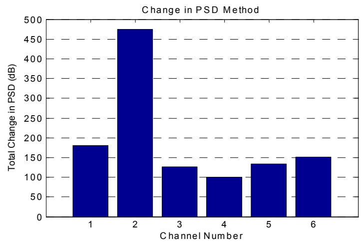

Fig. 2 Total change in PSD for Case 1

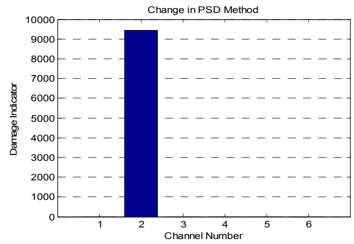

Fig. 3 Damage indicator results for Case 1

In order to reduce the effect of noise or measurement errors, a value of one standard deviation of the elements in vector $\{SM\}$ will be subtracted from the vector $\{SM\}$. Any resulting negative values will be removed. The same procedure will be applied to the vector $\{SC\}$ as follows

$$SMD=\begin{Bmatrix}\sum_f M_1(f)-\sigma\\ \sum_f M_2(f)-\sigma\\ .\\ .\\ .\\ \sum_f M_n(f)-\sigma\end{Bmatrix}\quad\text{and}\quad SCD=\begin{Bmatrix}\sum_f C_1(f)-\lambda\\ \sum_f C_2(f)-\lambda\\ .\\ .\\ .\\ \sum_f C_n(f)-\lambda\end{Bmatrix}\qquad(4)$$

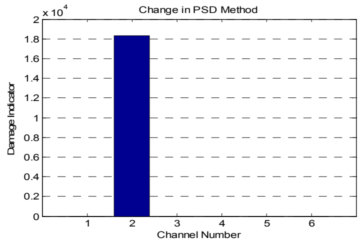

Fig. 4 Damage indicator results for Case 2

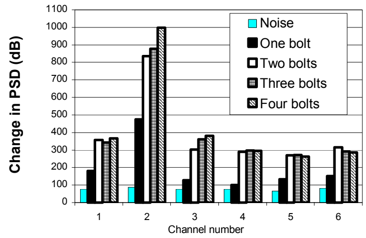

Fig. 5 Total change in PSD for Cases 1–4

The damage indicator is defined as the scalar product of $\{SMD\}$ and $\{SCD\}$ as

$$Damage\_Indicator=\begin{Bmatrix}SMD(1)\times SCD(1)\\ SMD(2)\times SCD(2)\\ .\\ .\\ .\\ SMD(n)\times SCD(n)\end{Bmatrix}\qquad(5)$$

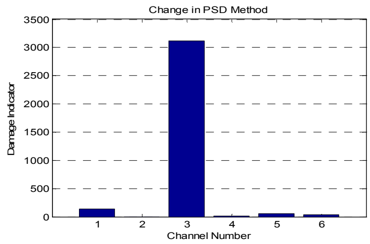

Fig. 6 Damage indicator results for Case 5

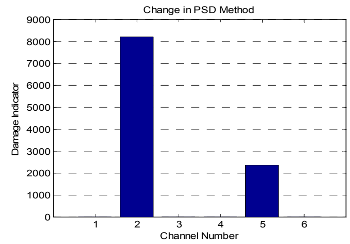

Fig. 7 Damage indicator results for Case 6

Damage indicator will be used to determine the damage location. On the other hand, the total change in PSD will be used to detect the occurrence of damage and assess the damage extent.

4. DAMAGE IDENTIFICATION ALGORITHM APPLIED TO DIFFERENT DAMAGE CASES

The accuracy of the damage identification methods based on frequency response function (FRF) or cross spectral density (CSD) is dependent on the frequency range in which FRF or CSD(2) is measured. The accuracy of the damage identification methods based on mode shapes is dependent on which mode shapes are used. In order to overcome this problem, it was decided to use PSD magnitudes in the frequency range of 50–700 Hz in the proposed algorithm. This range of measurement covers most of the total measurement range of PSD data (from 0 to 800 Hz). In Fig. 2, the total change in PSD increased at all channels after removing the first bolt. Damage indicator has determined the damage location at channel 2 accurately, as shown in Fig. 3. After increasing the damage level in beam no 2, the same previous remarks were also observed. As clearly indicated in Fig. 3 and 4, the damage at beam no 2 was located accurately using the damage indicator without any false positive readings. The total changes in PSD for the first four cases of damage and for the intact structure are plotted in Fig. 5. The following remarks can be drawn from this figure: 1- The total change in PSD due to noise is less than 100 dB at all channels with close values at the different channels. 2- After removing the first bolt (Case 1), the total change in PSD increased slightly at the undamaged locations (damage at one location changes the overall response of the structure) and increased remarkably at the damaged location (channel 2). 3- After releasing one more bolt (Case 2), the total change in PSD continued to increase slightly at the undamaged locations and remarkably at the damaged location. 4- After introducing damage to the third and fourth bolts (Cases 3 and 4), the total change in PSD increased slightly at the damaged location since the beam has already lost most of its stiffness after removing the second bolt. Therefore, it can be concluded that the total change in PSD monitored the increase in damage successfully. Damage position is changed in Case 5 to examine the effects of changing the damage position. The results of this case are shown in Fig. 6. The damage is indicated accurately at channel no 3 using the damage indicator. Case 6 is introduced to investigate the feasibility of the algorithm to detect multiple-damage. Damages at the two positions are detected and localized accurately with no false positive readings using the damage indicator, as shown in Fig. 7.

5. CONCLUSIONS

Changes in the PSD magnitude due to the presence of structural damage have been investigated. The experimental results obtained from a steel bridge model demonstrate the usefulness of the changes in PSD magnitude as a diagnostic parameter in detecting the damage, locating its position and monitoring the increase in damage. PSD is calculated from the acceleration response at every channel without measuring the excitation force. Therefore, ambient vibration can be used as an excitation force for continuous health monitoring of structures. The proposed method encompasses the first three steps of the process of damage detection – existence, localization and monitoring the damage increase being based on only the measured data without the need for any modal identification.

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