



APPLICATION OF A VIBRATION-BASED DAMAGE DETECTION ALGORITHM ON A BENCHMARK STRUCTURE

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Abstract

In recent years there has been great interest in the development of a structural health monitoring (SHM) methodology using vibration measurements. SHM using vibration monitoring is based on the idea of establishing differences in the modal properties of a structure using dynamic response data before and after damage. This paper presents a vibration-based damage identification technique that detects damage, identifies its location and monitors the growth in damage. The paper addresses the benchmark problem on SHM that was recently developed by the ASCE Task Group on SHM. The benchmark study was created to facilitate the comparison of several methods employed for the health monitoring of structures. The structure selected for the benchmark problem is a four-storey, 2-bay by 2-bay, steel braced frame. The damage was introduced by removing brace elements or disconnecting the beam-column bolted connections. The present paper focuses on different cases of this benchmark problem assuming unknown input. The proposed method is shown to be very effective for damage identification, and is relatively insensitive to noise in the sensors. Different issues regarding the performance, limitations, and difficulties of this methodology are discussed.

INTRODUCTION

During the past decade, a significant amount of research has been conducted in the area of damage detection using the dynamic response of a structure. Modal vibration data such as structural natural frequencies and mode shapes can characterize the state of the structure^{1, 2}. This capability is attributable to the fact that damage in the form of changes in the structural physical properties (i.e., stiffness, mass, and boundary conditions) consequently alters such vibration properties of the structure as modal frequencies, mode shapes, and modal damping values³. Changes in the vibration properties can then serve as indicators of damage detection⁴. In 1999, the International Association for Structural Control (IASC) and the Dynamics committee of the American Society of Civil Engineers (ASCE) Engineering Mechanics Division formed the SHM Task Group to study the efficacy of various SHM methods. In order to provide a platform for comparing the performance of various existing SHM methodologies and for assessing their capabilities and limitations a benchmark problem was set-up by the IASC-ASCE Task Group. More details are available on the Task Group web site⁵. This paper presents results for some cases of this benchmark

problem assuming unknown input. A damage identification technique using Power Spectral Density (PSD) data is employed. A brief overview of the methodology is given in the next section. The method can be used to detect damage, locate its position, and monitor the increase in damage using only the measured data without the need for any modal identification or numerical models. Many techniques have been proposed and used to identify the damage using the ASCE benchmark building model. Most of these techniques were used to locate the damage at a certain floor in the building model. However, few techniques were used to locate the damage more precisely and determine where the damage is located in the damaged floor. In this paper, the presented method will be used to determine the closest sensor to the damage location.

DAMAGE IDENTIFICATION ALGORITHM

Many techniques have been proposed in the area of non-destructive damage detection using changes in modal parameters. However, in many structures only few modes are available which may decrease the accuracy of detecting and localizing damage using these techniques. In order to overcome the problem of the limited number of identified modal parameters, PSD information estimated from the various accelerometer readings at all frequencies in the measurement range and not just the modal frequencies will be compared before and after damage using the proposed method. PSD data can then be analyzed using statistical procedures to determine the damage location, as will be explained in detail in this section. PSD is determined from the acceleration time histories without the need to measure the excitation forces. Let $G_i(f)$ denotes 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

$$D_i(f) = \left| G_i(f) - G_i^*(f) \right| \quad (1)$$

where $G_i(f)$ and $G_i^*(f)$ represent PSD magnitude for the undamaged and damaged structures, respectively. The excitation forces used for the undamaged and damaged structure must have the same amplitude, location, and waveform in order to ensure that the changes in PSD data are mainly due to damage and not due to the change in excitation force characteristics. When the change in PSD is measured at different frequencies on the measurement range from f_1 to f_m , a matrix $[\mathbf{D}]$ can be formulated as follows

$$\mathbf{D} = \begin{bmatrix} D_1(f_1) & D_2(f_1) & \dots & D_n(f_1) \\ D_1(f_2) & D_2(f_2) & \dots & D_n(f_2) \\ \cdot & \cdot & \dots & \cdot \\ \cdot & \cdot & \dots & \cdot \\ \cdot & \cdot & \dots & \cdot \\ D_1(f_m) & D_2(f_m) & \dots & D_n(f_m) \end{bmatrix} \quad (2)$$

where n represents the number of measuring points. In matrix $[\mathbf{D}]$, every row 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 columns of matrix $[\mathbf{D}]$ as

$$\mathbf{TotalChange} = \left\{ \sum_f D_1(f) \quad \sum_f D_2(f) \quad \dots \quad \sum_f D_n(f) \right\}. \quad (3)$$

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 selection of the maximum change in PSD at each frequency value (the maximum value in each row of matrix $[\mathbf{D}]$) and removing all other changes in PSD measured at other nodes. For example in matrix $[\mathbf{D}]$, 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 all other values in this row will be discarded. The same process is applied to the different rows in matrix $[\mathbf{D}]$ to formulate the matrix of maximum changes of PSD at different frequencies, $[\mathbf{M}]$

$$\mathbf{M} = \begin{bmatrix} 0 & 0 & M_3(f_1) & 0 & \dots & 0 \\ 0 & M_2(f_2) & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & M_4(f_3) & \dots & 0 \\ \cdot & \cdot & \cdot & \cdot & \dots & \cdot \\ \cdot & \cdot & \cdot & \cdot & \dots & \cdot \\ 0 & 0 & M_3(f_m) & 0 & \dots & 0 \end{bmatrix}. \quad (4)$$

In order to monitor the frequency of damage detection at any node, a new matrix $[\mathbf{C}]$ is formulated. The matrix consists of 0's at the undamaged locations and 1's at the damaged locations. For example in the matrix $[\mathbf{C}]$, a value of 1 is used corresponding to the locations of $M_3(f_1)$, $M_2(f_2)$ and so on, as shown in the following expression

$$\mathbf{C} = \begin{bmatrix} 0 & 0 & 1 & 0 & \dots & 0 \\ 0 & 1 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & 1 & \dots & 0 \\ \cdot & \cdot & \cdot & \cdot & \dots & \cdot \\ \cdot & \cdot & \cdot & \cdot & \dots & \cdot \\ 0 & 0 & 1 & 0 & \dots & 0 \end{bmatrix}. \quad (5)$$

The total of maximum changes in PSD can be calculated from the sum of columns of matrix $[\mathbf{M}]$ as

$$\mathbf{SM} = \left\{ \sum_f M_1(f) \quad \sum_f M_2(f) \quad \dots \quad \sum_f M_n(f) \right\}. \quad (6)$$

The total number of instances of detecting the damage at different nodes is calculated from the sum of columns of matrix $[\mathbf{C}]$ as

$$\mathbf{SC} = \left\{ \sum_f C_1(f) \quad \sum_f C_2(f) \quad \dots \quad \sum_f C_n(f) \right\}. \quad (7)$$

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

$$\begin{aligned} \mathbf{SMD1} &= \left\{ \sum_f M_1(f) - \sigma \quad \sum_f M_2(f) - \sigma \quad \dots \quad \sum_f M_n(f) - \sigma \right\} \\ \mathbf{SMD2} &= \left\{ \sum_f M_1(f) - 2\sigma \quad \sum_f M_2(f) - 2\sigma \quad \dots \quad \sum_f M_n(f) - 2\sigma \right\} \end{aligned} \quad (8)$$

where $\sigma = \sqrt{\frac{\sum_{i=1}^n (SM(i) - \overline{SM})^2}{n-1}}$, $\overline{SM} = \frac{\sum_{i=1}^n SM(i)}{n}$,

$$\begin{aligned} \mathbf{SCD1} &= \left\{ \sum_f C_1(f) - \lambda \quad \sum_f C_2(f) - \lambda \quad \dots \quad \sum_f C_n(f) - \lambda \right\} \\ \mathbf{SCD2} &= \left\{ \sum_f C_1(f) - 2\lambda \quad \sum_f C_2(f) - 2\lambda \quad \dots \quad \sum_f C_n(f) - 2\lambda \right\} \end{aligned} \quad (9)$$

$$\text{where } \lambda = \sqrt{\frac{\sum_{i=1}^n (SC(i) - \overline{SC})^2}{(n-1)}}, \quad \overline{SC} = \frac{\sum_{i=1}^n SC(i)}{n}.$$

The damage localization indicator is defined as the scalar product of $\{\mathbf{SMD}\}$ and $\{\mathbf{SCD}\}$ as shown in the following expressions:

$$\mathbf{D_I_1} = \{SMD1(1) \times SCD1(1) \quad SMD1(2) \times SCD1(2) \quad \dots \quad SMD1(n) \times SCD1(n)\} \quad (10)$$

$$\mathbf{D_I_2} = \{SMD2(1) \times SCD2(1) \quad SMD2(2) \times SCD2(2) \quad \dots \quad SMD2(n) \times SCD2(n)\} \quad (11)$$

Damage localization indicators 1 and 2 will be used to determine the damage location. On the other hand, the total change in PSD (Equation (3)) will be used to detect the occurrence of damage and monitor the growth in damage.

THE BENCHMARK STRUCTURE

The structure selected for the benchmark problem is a four-storey, 2-bay by 2-bay, steel braced frame depicted in Fig. 1. The structure has a 2.5m \times 2.5m base, is 3.6m tall, and is located at the Earthquake Engineering Research Laboratory of the University of British Columbia⁵. The elements that conform the structure are hot rolled grade 300W steel (nominal yield stress 300 MPa) and are of unusual dimensions, designed for a 1/3-scale model. In addition to the main members, horizontal bracing at each floor level is included to ensure effective diaphragm action in the absence of a concrete floor. The mass of the structure is made up of the self-weight of the members plus added masses. Eleven accelerometers are used to measure the acceleration time histories, as shown in Fig. 1. A variety of damage cases were considered in which damage was simulated by removing bracing or loosening bolts in the test structure. A brief description of each damage case is provided in Table (1).

DAMAGE IDENTIFICATION RESULTS

Damage case C

PSD is calculated at each measuring channel from the acceleration time history data using MATLAB Standard and MATLAB Signal Processing Toolbox. Hanning window of size 512 is applied to the time signals to minimize leakage. In this technique, the signal (acceleration data) is divided into overlapping sections (50% overlap) of the specified window length (512) and windows each section using the Hanning window function. In case of using a Hanning window size of 512, the PSD can be measured at 257 frequency lines in the frequency range of 1-125 Hz (frequency step = 125*2/512). In damage case C, damage location exists at the first floor near to channels 1, 8 and 2 respectively, as can be shown in Fig. 1 and Table (1). Fig. 2 shows the PSD at channel 3 (undamaged location) for the undamaged structure and damage case C. As clearly indicated in this figure, small changes can be observed at this channel as the occurrence of damage at any location is expected to change the dynamic response at most of the measuring channel. It can be observed that the largest change in PSD exists in the frequency range of 80-100 Hz. However, this frequency range that shows the largest disturbances in PSD data for specific damage case usually changes for different damage cases. In addition, for the same damage case this frequency range may change according to the sensor location. It was found very difficult to determine the best frequency range in which PSD has to be measured. Therefore, it was decided to use PSD data in the total

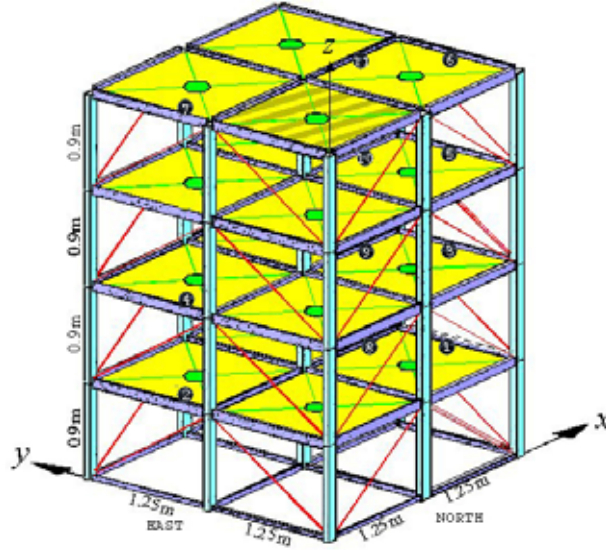


Figure 1. ASCE benchmark building model.

Table 1: Damage cases

Case	Description	Nearest channels
B	Undamaged with added masses to floors 1 and 2	
C	Damage on one brace of floor 1 (removed brace at North face, West bay, indicated by a thick line in Fig. 1)	1, 8, 2 (First Floor)
D	Damage on one brace of floor 1 and one brace of floor 3 (removed brace at West face, North bay, indicated by a thick line in Fig. 1)	1, 8, 2 (First Floor); 3, 9, 4 (Second Floor); 5, 10 (Third Floor)
E	Damage on one brace of floor 1, one brace of floor 3, and joint loosened (bolts on North face to the outside of the West bay)	1, 8, 2 (First Floor); 3, 9, 4 (Second Floor); 5, 10 (Third Floor)

measured frequency range, i.e. PSD will be measured at 257 frequency lines in the frequency range of 1-125 Hz. The total change in PSD at each measuring channel is estimated using equation (3) and the results are shown in Fig. 3(a). In this figure, the damage location cannot be identified, however, the total change in PSD can be used to detect the occurrence of damage or monitor the damage growth. The basic idea here is that the total change in PSD that results from noise, environmental changes or operational loads is assumed to be less than the total change in PSD that results from damage. Moreover, it is assumed that small damage will produce smaller changes in PSD than the more severe damage. At each frequency line the maximum change in PSD is estimated at certain channel (s) and it is assumed that damage is detected once at this channel. The total number of times of detecting damage at each channel is estimated using equation (7) and the results are shown in Fig. 3(b). It is clearly indicated that damage could be detected more frequently at channel 1, which is the nearest channel to the damage location (Fig. 1). Damage localization results using damage indicators 1 and 2 are shown in Figs. 3(c) and (d), respectively. Damage location could be detected accurately at channel 1 using both indicators. Some small false positive readings appeared at channels 3, 4 and 5 in case of using damage indicator 1. On the other hand, damage indicator 2 has shown better results in identifying the damage location.

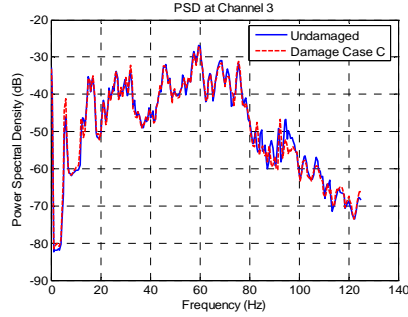


Figure 2. PSD at channel 3 for the undamaged and damaged structure.

Damage case D

In damage case D, damage is introduced to one brace of floor 1 and one brace of floor 3. The braces of floor 3 connect the roofs of floor 2 and 3. Therefore, removing one brace from floor 3 will also have some effect on the roof of floor 2. As indicated in Table (1), damage at floor 1 can be detected at channels 1, 8, 2, damage at floor 2 can be detected at channels 3, 9, 4 and damage at floor 3 can be detected at channels 5, 10. The order of channel numbers is written according to the closer channels to the damage location. Damage indicators 1 and 2 identified damage locations at channel 3 (floor 2) and channel 5 (floor 3), as shown in Fig. 4 (a) and (b) respectively. However, both indicators failed to detect the damage on floor 1. The removed brace from floor 3 exists closer to the sensors locations (channel 3 and 5) than the removed brace from floor 1. Therefore, the damage at the floor 3 was detected more clearly and frequently at channels 3 and 5 and hence, decreasing the chance to detect damage at floor 1. In other words, the existence of big damage at one location can reduce the efficiency of the proposed method to detect a small damage at another location. In addition, when a damage location exists very close to the sensor location it may also reduce the efficiency to detect a similar damage that exists further from the sensor location.

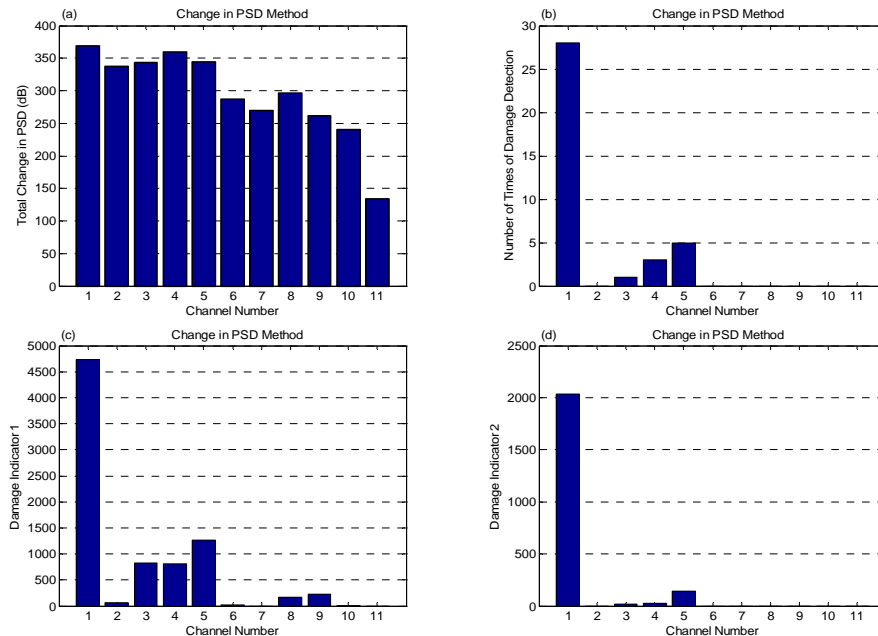


Figure 3. Damage identification results for damage case C: (a) Total change in PSD. (b) Number of times of damage detection. (c) Damage localization using damage indicator 1. (d) Damage localization using damage indicator 2.

Damage case E

Damage case E is similar to damage case D with increasing the amount of damage on floor 1 by loosening the bolts of one joint on that floor. Damage locations are identified very accurately using damage indicator 1, as shown in Fig. 5(a). Damage on floor 1 is detected at channel 1, damage on floor 2 is detected at channels 3 and 9, and damage on floor 3 is detected at channel 5. Damage indicator 2 determined damage locations on floors 2 and 3 but failed to detect the damage on floor 1. It should be noted that damage indicator 2 gave better results in case of single damage (case C) than damage indicator 1. On the other hand, damage indicator 1 performed better for the case of double-damage. This is because the filtering of the data in damage indicator 2 is more severe (2 standard deviations are subtracted), which sometimes remove the readings at some damage locations. On the other hand, the strong filtering is efficient to reduce the number of false positive readings that result from noise or measurement errors.

Monitoring the growth in damage

Since serious damage to a structure usually is the results of growth of less serious damage, it is important to have the ability to monitor the growth in damage. The proposed method cannot be used to estimate damage severity or the extent of damage.

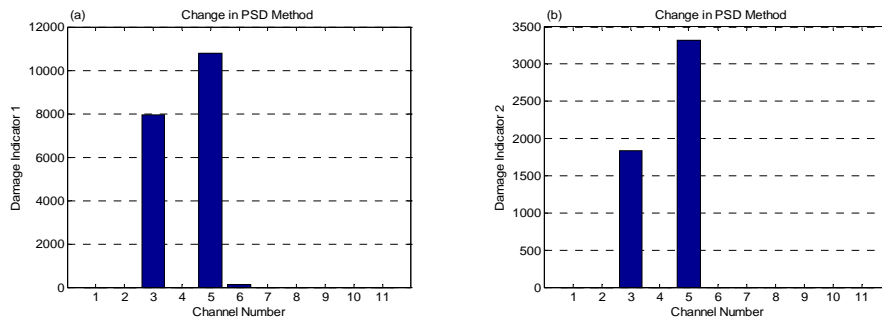


Figure 4. Damage identification results for damage case D: (a) Damage localization using damage indicator 1, (b) Damage localization using damage indicator 2.

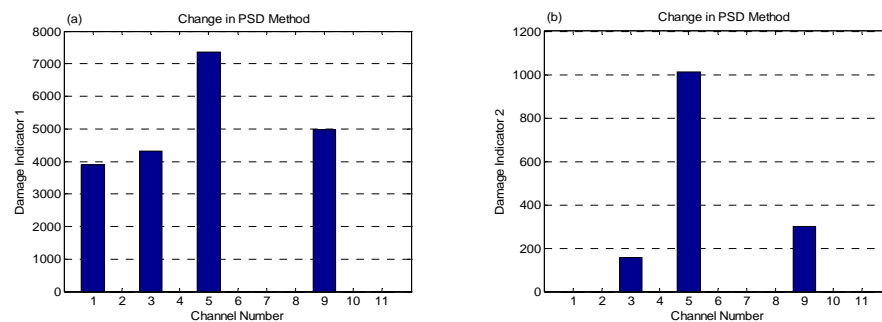


Figure 5. Damage identification results for damage case E. (a) Damage localization using damage indicator 1. (b) Damage localization using damage indicator 2.

However, it can be used to some extent to monitor the growth in damage. As the amount of damage increased from damage case C to damage case E, the total change in PSD increased at different measuring channels, as indicated in Fig. 6. Unfortunately, the damage severity cannot be identified quantitatively. However, for different levels of damage compared with Fig. 6, the amplitude levels are higher for the cases of more severe damage, which can represent the damage severity to some extent. The increase in damage is provided to the structure by introducing

damage to new locations but is not provided at one specific location. Therefore, the increase in the total change in PSD is indicated at different channels.

CONCLUSIONS

A damage detection experimental study using ASCE benchmark building model was presented. The proposed approach is a global NDE method which uses vibration measurements and, therefore, is limited to identifying structural damages that produce measurable changes in the structural dynamic characteristics. The excitation forces used for the undamaged and damaged structure must have the same amplitude, location, and

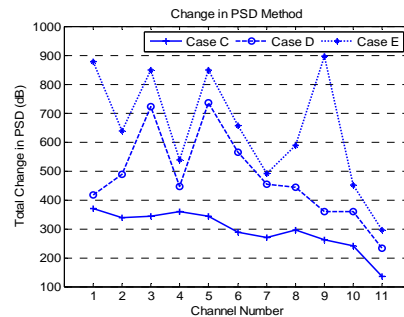


Figure 6. Monitoring damage growth.

waveform in order to ensure that the changes in PSD data are mainly due to damage and not due to the change in excitation force characteristics. The excitation force does not need to be measured and no structural model is needed. The proposed method detected the damage and determined its location accurately for most of the damage cases that were introduced to the test structures. Single and double damage were introduced to the test structures; however, the application of the proposed method to the case of multiple-damage needs to be studied. It was also observed that the method gives better results in case of single damage than the case of double damage. The method can be used to detect the damage, identify its location and monitor the increase in damage but cannot be used to estimate the severity of damage. The proposed algorithm uses the measured PSD in a certain frequency range without the need for any modal data or numerical models. The PSD can be used in the total measured frequency range without the need to determine the best frequency range that gives the most accurate results.

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