Health Monitoring Technique for Steel Bridges

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1. Introduction

Vibration-based damage detection theories and techniques are formulated based on the assumption that damage or deterioration would primarily affect the stiffness and therefore affect the modal characteristics of the dynamic response of the structure. Based on changes in Power Spectral Density (PSD), a damage identification technique is introduced in this paper for detecting damage, predicting its location and monitoring the increase in damage. This method assumes 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 PSD. The change of PSD between the baseline state and the current state is then used to identify the location of possible damage in the structure. The method is applied to the experimental data obtained from a railway steel bridge that is no longer in service. Several damage amounts were introduced to the main girder of the test structure. Results show the method can be used to detect the damage, determine the exact location and monitor the increase in damage. One advantage of the introduced method is that it does not require any numerical model for the structure being monitored and hence can potentially be used for practical application. The use of piezoelectric actuators as a local excitation source for large structures such as bridges is investigated. The advantages of using piezoelectric actuators than conventional excitation methods such as dynamic shakers, hammers or ambient vibrations are also discussed.

2. Damage detection 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[1)]

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

where $G_i(f)$ and $G_i^*(f)$ represent PSD magnitude for the undamaged and damaged structures respectively. The excitation forces used for the undamaged and damaged structure must have the same amplitude and waveform in order to ensure that the changes in PSD data are mainly due to damage. 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

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

where n represents the number of measuring points. In matrix [**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 [**D**] as

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

However, the total change in PSD 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 row 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 row then this value will be used as $M_3(f_1)$ and other values in this row will be removed. The same process is applied to the different rows in matrix [**D**] to formulate the matrix of maximum changes of PSD at different frequencies, [**M**]

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

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 locations of $M_3(f_1)$, $M_2(f_2)$ and so on, as shown in the following expression

$$\mathbf{C} = \begin{bmatrix} 0 & 0 & 1 & 0 & \ldots. & 0 \\ 0 & 1 & 0 & 0 & \ldots. & 0 \\ 0 & 0 & 0 & 1 & \ldots. & 0 \\ . & . & . & . & \ldots. & . \\ . & . & . & . & \ldots. & . \\ 0 & 0 & 1 & 0 & \ldots. & 0 \end{bmatrix}. \tag{5}$$

The total of maximum changes in PSD is calculated from the sum of the columns of matrix [**M**]

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

The total number of times of detecting the damage at different nodes is calculated from the sum of the columns of matrix [**C**] as

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

The first damage localization indicator is defined as the scalar product of {**TM**} and {**TC**} as shown in the following expression

$$\mathbf{DI0} = \{TM(1) * TC(1), TM(2) * TC(2), ... TM(n) * TC(n)\}. \qquad (8)$$

In order to reduce the effect of noise or measurement errors, a value of two times 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**} as follows

$$\mathbf{SM} = \left\{ \sum_f M_1(f) - 2\sigma, \sum_f M_2(f) - 2\sigma, ... \sum_f M_n(f) \right\} \qquad (9)$$

where $\sigma = \sqrt{\sum_{i=1}^{n} (TM(i) - \overline{TM})^2} \Big/ (n-1)$, $\overline{TM} = \sum_{i=1}^{n} TM(i) \Big/ n$,

$$\mathbf{SC} = \left\{ \sum_f C_1(f) - 2\lambda, \sum_f C_2(f) - 2\lambda, ... \sum_f C_n(f) - 2\lambda \right\} \qquad (10)$$

where $\lambda = \sqrt{\sum_{i=1}^{n} (TC(i) - \overline{TC})^2} \Big/ (n-1)$, $\overline{TC} = \sum_{i=1}^{n} TC(i) \Big/ n$.

The second damage localization indicator is defined as the scalar product of {**SM**} and {**SC**} as shown in the following expression

$$\mathbf{DI2} = \{SM(1) * SC(1), SM(2) * SC(2), ... SM(n) * SC(n)\}. \qquad (11)$$

Damage indicators 0 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 assess the increase in damage.

3. Railway steel bridge: description and experimental setup

The experimental work in this research was performed on a railway steel bridge that is no longer in service. The bridge is removed from its service location several years ago. A man, who is interested in collecting old trains, bought the bridge and kept it in his own land. The bridge is supported now on two wooden blocks. The owner of the bridge has granted us a permission to introduce some damage to the bridge such as releasing some bolts and tightening them again. However, introducing torch cuts to the bridge was not permitted. The bridge consists of two steel plate girders and two steel stringers support the train rails. Loads from the stringers are transferred to the plate girders by floor beams located at various intervals. The bridge dimensions and layout are shown in Fig. 1. The multi-layer piezoelectric actuator is used for local excitation. The actuator force amplitude is 200 N. Although this force amplitude is very small compared to shaker forces or ambient vibrations, it was enough to excite the web of the main girder until the position of the farthest accelerometer. Two actuators are used for exciting the web of the main girder in the horizontal direction. The actuators are located at the upper part on the web of the main girder (Fig. 1). The excitation forces used for the undamaged and damaged structure are random, equal in amplitude and have the same vibration waveform but the excitation force does not need to be measured. The main advantages of using piezoelectric actuators than using conventional excitation methods such as dynamic shakers, or ambient vibration can be summarized as follows:

- Actuator size is very small and can be handled easily. Moreover, it can be fixed to any structural element and remotely operated for continuous health monitoring of the structure.
- The traffic over the bridge needs not to be interrupted as the case of using dynamic shakers.
- 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[2)].
- Large number of vibration data can be saved in a short time as the sampling rate in case of using actuator can reach 2 kHz.
- The same excitation force (equal magnitude and the same waveform) can be produced for exciting the undamaged and damaged structure, which is needed for applying damage identification technique studied in this paper.
- Undesired vibrations induced from wind, traffic or any other source can be avoided since the vibration data induced from the actuators can be generated at any desired time.

Eight accelerometers were used to measure the acceleration response in the horizontal direction. One accelerometer is mounted at the geometrical center of gravity of each panel of the main girder, as shown in Fig. 1. Typical acceleration responses measured at the nearest channel (channel 6) and the farthest channel from the actuator location (Channel 8) are shown in Figs. 2a, b respectively. All of the connections of different elements of the bridge are riveted and no damage could be introduced to these connections. Only two angles (look like stiffeners) are bolted to the web of main girder. Therefore, it was decided to remove the bolts one by one from the right angle to introduce damage to the main girder (Fig. 1).

4. Damage identification results

4.1 Before introducing any damage

As mentioned in chapter 2, the total change in PSD determined from Equation 3 will be used to detect the occurrence of damage and monitor the increase in damage. It is therefore important to define a threshold of the total change in PSD that classifies the changes in PSD due to noise, measurement errors, environmental or operational loads from the changes attributed with damage. Because of this need, the experiment was performed a number of times on the undamaged structure prior to the introduction of any damage. PSD data for two different sets of data obtained from the undamaged structure is shown in Fig. 3a. Small changes in PSD can be observed in this figure, obviously due to noise and measurement errors. The total change in PSD was determined using PSD data in the frequency range of 1-800 Hz. The total change in PSD ranged from about 75 to 125 dB as shown in Fig. 3b. When the total change of PSD was determined using other sets of data that were obtained from the undamaged structure, similar and very close values of the total change in PSD were obtained. The threshold of the total change in PSD we used in this experiment is based only on changes due to noise or measurement errors. However, in order to determine more practical threshold, more data are needed to get the changes in PSD that result from changes in temperature over different seasons or from operational loads.

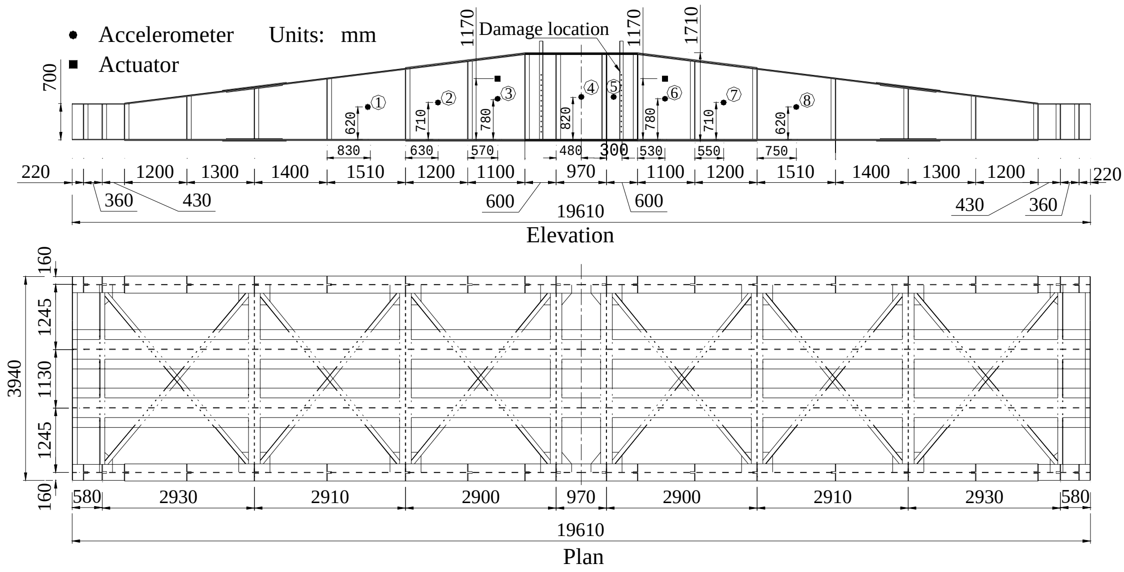

Fig. 1 Bridge layout and main dimensions

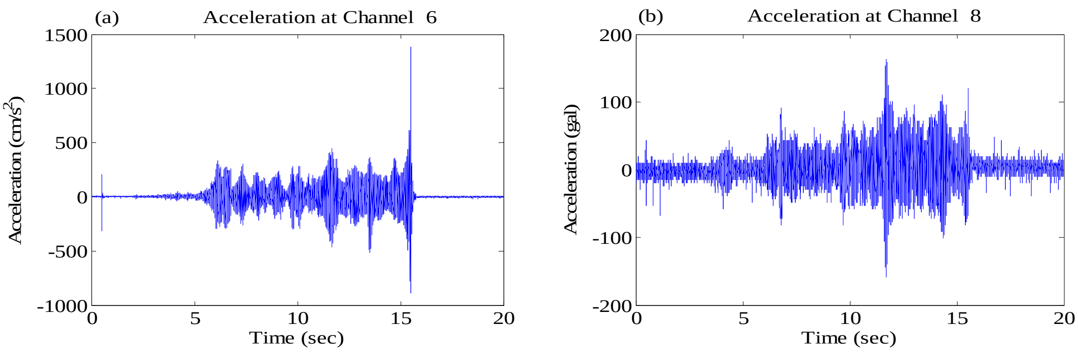

Fig. 2 Typical acceleration responses at different locations

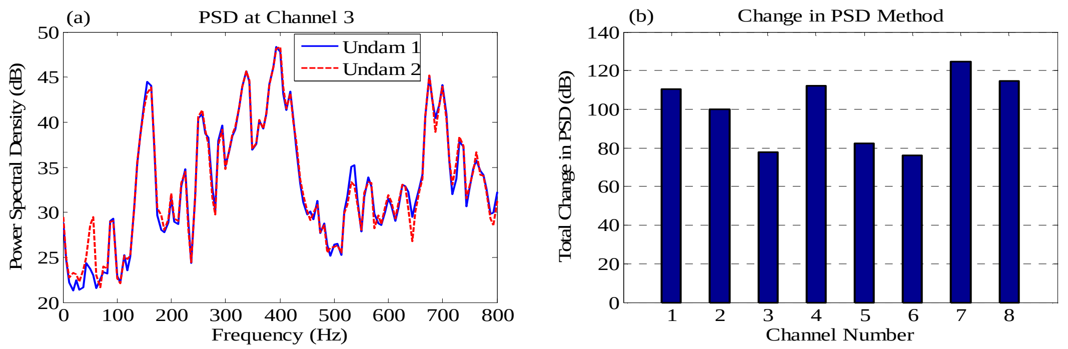

Fig. 3 PSD for two tests performed on the undamaged structure and the associated total change

4.2 One bolt released near to channel 5

The first level of damage is introduced to the bridge by removing the first bolt from the top of the right stiffener (near to channel 5), as shown in Fig. 1. No significant changes in PSD are observed at undamaged locations after removing one bolt since the amplitude, waveform and location of the excitation force are all the same before and after introducing the damage. The total change in PSD measured at different channels after removing the first bolt is shown in Fig. 4a. The total change in PSD increased at all channels especially at the damage location (channel 5). Although the maximum value of the total change in PSD exists at channel 5, this is not clear indication of damage location. Damage indicators 0 and 2 will be used to identify the damage location more accurately as will be explained later in this section.

At each frequency line, the maximum change in PSD is measured at one channel and it is then assumed that damage is detected once at this channel. The same process is repeated using different frequency lines in the measurement range and the total number of detecting the damage at each channel can be determined (Equation 7). The total number of times of detecting damage at different channel using Equation 7 is shown in Fig. 4b. Damage is detected 41 times (out of 128 frequency lines) at the correct location of damage - channel 5. Multiplying the total number of detecting damage to the total of maximum changes in PSD at each measuring channel magnifies the value of damage localization indicator at the correct damage locations and decreases its value at the undamaged locations (Equation 8). The results of damage localization using damage indicator 0 are shown in Fig. 4c. Damage location at channel 5 is identified more accurately in this figure than using the total change in PSD (Fig. 4a); however readings at undamaged locations such as at channels 4 and 8 may degrade the accuracy of the results. When

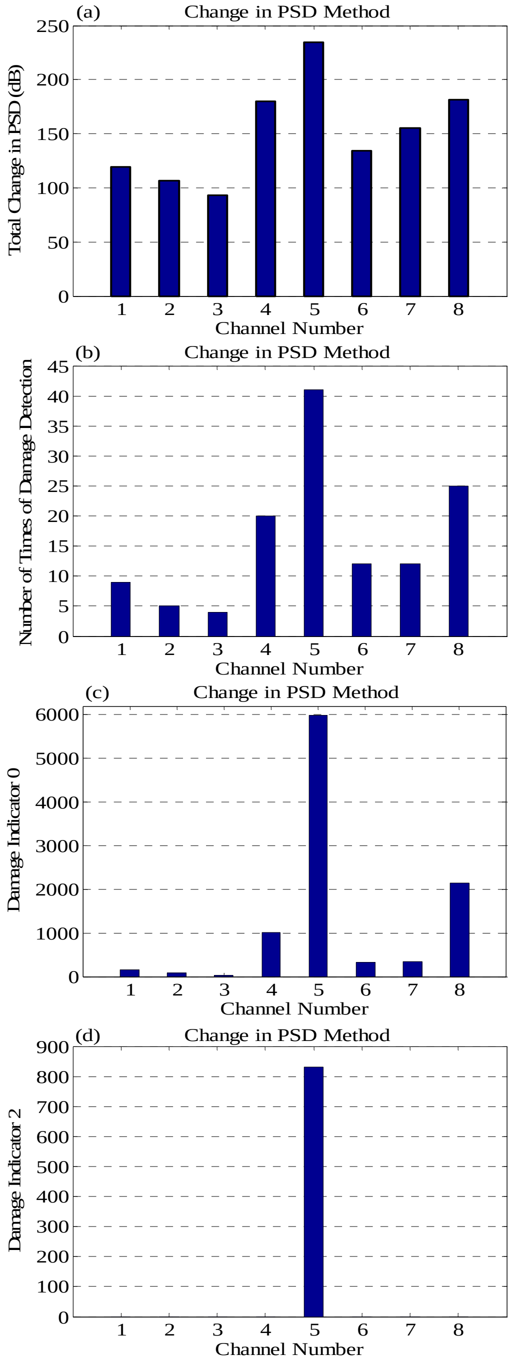

Fig. 4 Damage identifications results after removing one bolt

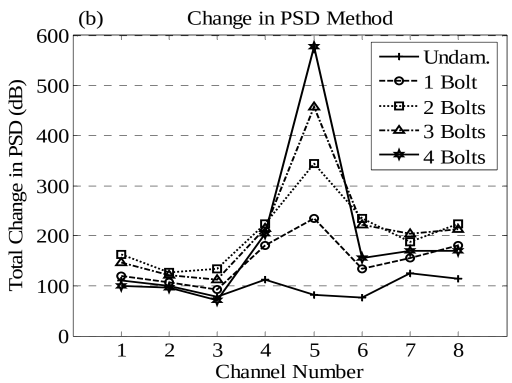

Fig. 5 Monitoring the increase in damage at channel 5

damage indicator 2 is used to locate the damage, results that are more accurate were obtained and damage location was detected at channel 5 without any false positive readings as shown in Fig. 4d.

4.3 Monitoring the increase in damage at channel 5

The resulting values of the total change in PSD for four levels of actual damage – removing one bolt through four bolts, are shown in Fig. 5. In this figure, the values of total change of PSD at different channels are connected with straight line instead of using histogram to show the changes more clearly. In Fig. 5, the value of the total change in PSD at channel 5 (damage location) increases as the damage level increases. It is noteworthy that the value of the total change in PSD increased significantly after removing the third and fourth bolts compared to the value at any other location and the effect of noise or measurement errors became negligible. As the damage level increases, the total change in PSD values at the undamaged locations sometimes increase, decrease or does not change. On the other hand, the value at the damaged location always increases as the damage level increases. Unfortunately, the damage severity cannot be identified quantificationally. However, for the same damage locations but different levels of damage compared with the amplitude levels are higher for the cases of more severe damage, which can represent the damage severity to some extent.

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 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. The main advantages of the proposed methods are:

- PSD is calculated from the acceleration response at every channel without measuring the excitation force. However, the excitation forces used for the undamaged and damaged structure have to be random, equal in amplitude and have the same waveform.
- 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 or numerical models.
- Vibration based damage identification methods sometimes produce false positive readings due to measurement errors, noise and environmental changes. The proposed method has shown better results in identifying the changes in PSD associated with damage from the changes attributed to noise or measurement errors.

In this study, piezoelectric actuators were used as a local excitation source for large structures such as steel bridges. The main advantages of using piezoelectric actuators for local excitation than using conventional excitation methods such as dynamic shakers, hammers, or ambient vibration have been explained.

References

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