A New Algorithm for Damage Detection in Simple Span Bridge Piers, Based on Power Spectral Density Function and Cosh Spectral Distance

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SUMMARY:
The vibration based methods for structural health monitoring can be divided into modal and signal methods. Although modal methods have been widely used for damage detection and health monitoring, signal methods due to higher efficiency have been higher considered. In this study, a new algorithm to detect seismic damages in the bridge's piers was proposed. According to the algorithm, before and after seismic damage, the bridge is excited by a cosine force, and the piers' responses are recorded. The dynamic properties of the response signals are extracted by Power Spectral Density function. Furthermore, the Cosh Spectral Distance is used to detect damage in the bridge's piers. The results demonstrate which the proposed algorithm can identify the damage correctly. To evaluate the algorithm, an analytical model of a bridge with simple spans was used. The algorithm is an output-only method and measuring the excitation force is not needed. Moreover, there is no need to create a numerical model of the bridge.

Keywords: damage detection, bridge piers, Power Spectral Density function, Cosh Spectral Distance

1. GENERAL INSTRUCTIONS

Old methods for detecting structural damage consist of observational and non-destructive Evaluation (NDE) methods. For example, in observational methods can point out to the methods that an expert checks the appearance of cracks in structures. The methods can explore local damages. However, the weakness of this method is that in the large dimension structures, all parts of them may not be available. In addition, it needs to check all the structures locally, which would be very time consuming [Ahmadi et al., 2012a]. Usually, bridges are built over natural barriers such as valleys and rivers or man-made barriers such as roads and railroads. Because these obstacles, bridge inspection is associated with dangerous or difficulties. Although small bridges can be inspected with a ladder, boat or other simple equipments, but large bridges or high-altitude bridges are not easily available. In other words, in civil engineering, non destructive methods and observational inspection are very common, but they are time-consuming and laborious [Balageas et al., 2006]. Considering the difficulties and shortcomings of the NDE methods, researchers have proposed another method [Sampaio, 1999, Ahmadi et al., 2012a]. This method is based on the structural response data in case the appropriate algorithms would be used, the structural health can be considered locally and totally.

Generally, health monitoring and damage detection methods consist of two main processes that are called feature extraction and pattern recognition. Various methods for feature extraction and pattern recognition have been proposed by researchers.

Measuring methods of structural response for health monitoring and damage detection are divided into static-based methods and dynamic (or vibration)-based methods [Yan et al., 2007]. Static-based methods are based on Strain or displacement measurements of structures under determined static loads. Furthermore, to determine changes in deflection, stiffness and load-carrying capacity of the structures, finite-element model updating is used. These methods have been widely used for the health monitoring of bridges. Static-based methods require a large amount of measured data. In addition, finite-element models of structures are needed. Moreover, static load tests must be done, which are disrupted the structure services [Qiao, 2009].

During the last two decades, many joints research regarding vibration based methods have been done, leading to the development of various algorithms and techniques [Doebling et al., 1996, Sohn et al., 2003]. These methods can be divided into modal and signals methods. The modal methods use measured changes in modal parameters to detect damages. The methods have been applied well to determine the dynamical properties of structural systems [Mikami et al., 2011]. Changes in the modal shapes are a well-known technique in the modal methods. Although modal methods can generally be used for health monitoring and damage detection but signal methods in comparison with modal methods are more efficient and are used in various fields such as mechanical engineering, aerospace engineering and civil engineering [Qiao, 2009].

In signal-based methods, changes in the structural characteristics are directly obtained from the measured time histories. According to various signal processing techniques, signal-based methods are classified into three categories: time domain methods, frequency domain methods and time–frequency domain methods. In the time domain methods, using linear and nonlinear functions, features are extracted from the structural time history responses. Auto-Regressive model and Auto-Regressive Moving Average model are examples of time domain functions [De Lautour et al., 2009]. In the frequency domain methods, Fourier analysis is used to transfer the measured time histories from time domain to frequency domain. Fourier transform, Frequency Response Functions and Power Spectral Density are some of examples of the category. In the time-frequency domain methods, to extract features and identify systems, time-frequency representations can be used. A large number of time-frequency representations have been suggested by researchers. Short-Time Fourier Transform, Wavelet Transform, Wigner-Ville Distribution and Reduced Interference Distribution are some of the examples of the time-frequency representations [Hlawatsch et al., 1992, Neild et al., 2003].

2. POWER SPECTRAL DENSITY

Power Spectral Density or power density spectrum represents the distribution of power relative to the frequency. The energy of the signals calculated as follows: [Mertin, 1999, Boashash, 2003]

$$E_X = \int_{-\infty}^{\infty} |x(t)|^2 dt \tag{2.1}$$

where, $x(t)$ and E_x are signal and the energy of the signal, respectively. $|x(t)|^2$ represents the distribution of the energy of the signal relative to the time. According to Parseval's theorem, the previous equation can be written as follows: [Mertin, 1999, Boashash, 2003]

$$E_X = \frac{1}{2\pi} \int_{-\infty}^{\infty} |X(\omega)|^2 d\omega \tag{2.2}$$

where, $X(\omega)$ is the Fourier transform of $x(t)$. $|X(\omega)|^2$ indicates the distribution of the energy of the signal relative to the frequency. Therefore, $|X(\omega)|^2$ is called the power density spectrum and is displayed as follows: [Mertin, 1999, Boashash, 2003]

$$S_{XX}^{E}(\omega) = |X(\omega)|^2 \tag{2.3}$$

power density spectrum can also be expressed as a Fourier transform of Autocorrelation function as below: [Mertin, 1999]

$$r_{xx}^{E}(\tau)=\int x^{*}(t)x(t+\tau)dt=x^{*}(-\tau)\times x(\tau) \tag{2.4}$$

$$S_{xx}^{E}(\omega)=\int_{-\infty}^{\infty} r_{xx}^{E}(\tau)e^{-j\omega\tau}d\tau \tag{2.5}$$

Autocorrelation function represents the similarity between the signal $x(t)$ and its time-shifted variant $x_{\tau}(t)=x(t+\tau)$ which can be defined as follows: [Mertin, 1999]

$$\begin{aligned} d(x,x_{\tau})^{2} &= \|x-x_{\tau}\|^{2}=\langle x,x\rangle-\langle x,x_{\tau}\rangle-\langle x_{\tau},x\rangle+\langle x_{\tau},x_{\tau}\rangle \\ &= 2\|x\|^{2}-2\Re\{\langle x,x_{\tau}\rangle\}=2\|x\|^{2}-2\Re\{r_{xx}^{E}(\tau)\} \end{aligned} \tag{2.6}$$

in which, d indicates the distance between the signals. In addition, $\|x\|$ and $\langle x_{\tau},x\rangle$ are the norm of the signal $x(t)$ and inner product of two signals, respectively. It is worth mentioning when the correlation between the signals increases, the distance between them decreases and vice versa.

3. COSH SPECTRAL DISTANCE

One of the well-known methods for pattern recognition and damage detection is matching method. Generally matching method is used for determining similarity between two Curves, shapes and, etc. with the same type. The matching method is widely used in speech identification and fingerprint recognition. With the match between the new patterns with stored patterns in the database, the matching method detects damages. Three known algorithms in the matching methods are a) Correlation algorithm, b) Least Square Distance algorithm and c) Cosh spectral distance algorithm. In the study, Cosh Spectral Distance (CSD) has been used for the research. CSD represents a sign about the global difference between two patterns. The algorithm is defined as follows: [Qiao, 2009]

$$CSD_{ij}=\frac{1}{2n}\sum_{k=1}^{n}\left(\frac{S_{i}(k)}{S_{j}(k)}-\log\left(\frac{S_{i}(k)}{S_{j}(k)}\right)+\frac{S_{j}(k)}{S_{i}(k)}-\log\left(\frac{S_{j}(k)}{S_{i}(k)}\right)-2\right) \tag{3.1}$$

where, n is the number of sampling points in the pattern, $S_i(k)$ and $S_j(k)$ are the vector values of the patterns *i* and *j* at point *k*, respectively. CSD_{ij} is Cosh Spectral Distance between the patterns. The lower value of CSD algorithm reflects the similarity between the patterns is more.

4. PROPOSED METHODOLOGY FOR DAMAGE DETECTION

When a bridge is damaged, it cannot longer behave like it was designed from the beginning. On the other word after the damage occurs, usually structural stiffness is decreased and damping is increased. The bridge’s pier due to damage probably will experience some changes in the dynamic characteristics and modal parameters. Depending on the severity of the damage, changes in the dynamic characteristics of the bridges are different [Ahmadi et al., 2012b]. In a single degree of freedom system, with stiffness k and mass m, natural frequency is defined as $\omega=\sqrt{k/m}$ which stiffness reduces, also natural frequency decreases. Dynamic characteristics of a system can be extracted with spectral density function.

The main hypothesis of this study is based on the fact that the damage at the pier of bridge will disturb the dynamic responses near its location. The differences between the dynamic responses of a bridge, before and after damage, often cannot be determined from the registered signals but if the signals are processed by Power Spectral Density function, probably the differences will be revealed.

According to the algorithm, an accelerometer sensor is installed in the middle of each pier of the bridge. Then, an excitation force is applied to the bridge and its responses at the piers are registered. After damage occurrences, again the excitation force is applied and the bridge responses are registered. However, there is no need to record the excitation force (input loading). In addition, this algorithm, unlike many other methods, needs not to create an analytical model of the bridge. In this study, since there was no possibility of creating damage in the real bridge, the analytical model of the real bridge has been used. For this purpose, the bridge model has been excited by a low amplitude exciting force which is a cosine function of angular frequency equal to π (Figure 1).

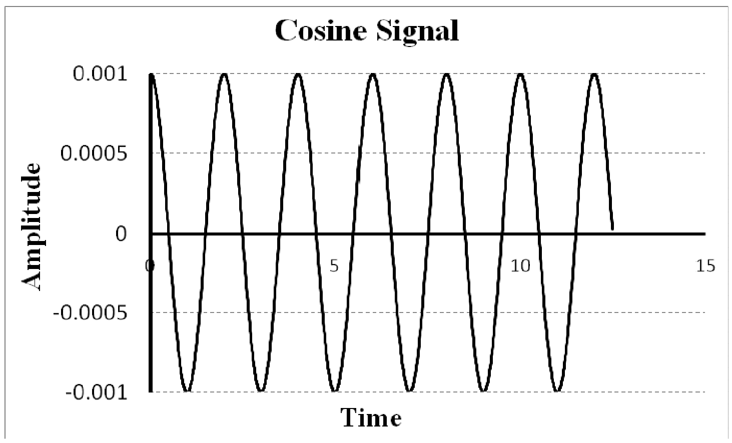

Figure 1. Cosine Exciting Force

To calculate the bridge model responses under exciting force, the model has been analyzed based on the linear time history method, and its responses have been measured on the middle of the piers.

Using Power Spectral Density function, the bridge model responses have been processed and dynamic characteristics have been extracted. Then using the CSD, damage has been detected and its location has been identified.

5. CONFIRMATION OF PROPOSED METHODOLOGY

To evaluate the proposed methodology, the analytical model of W180 bridge was selected as the structural sample. In the following subsections, firstly the bridge model is introduced. Then, according to the proposed methodology, bridge responses under exciting force are registered and their features are extracted by Power Spectral Density function. Moreover, for pattern recognition and damage detection, CSD method was used.

5.1. Analytical Model of W180 Bridge

Analytical model of W180 bridge has 4 spans and is made of concrete. This model is made by researchers at the University of California, Berkeley and University of Central Florida and published in 2008 by Pacific Earthquake Engineering Research Center (PEER) [Aviram et al., 2008]. A view from the bridge model and dimensions of the model are shown in Figure 2 and Figure 3, respectively.

The stress-strain relation for concrete is defined by Mander model. Furthermore, piers and deck are modeled by frame element. The bridge model has 36 nodes and 45 frame elements. The model was analyzed with regard to the gravity loads.

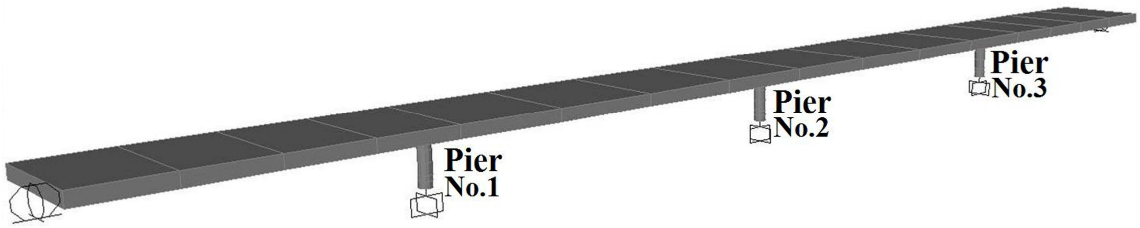

Figure 2. A general view of W180 bridge

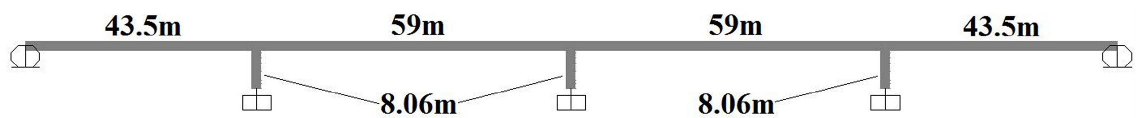

Figure 3. Dimension of the Analytical Model of W180 Bridge

To validate the applicability of the proposed methodology, an assumed damage is considered. The damage is located in the bottom of pier No. 3. To apply it, the stiffness in the bottom of the pier No. 3 was reduced by about 30%.

5.2. System Identification

As already mentioned, in this study a new algorithm is suggested to damage detection in the piers of bridges. Based on the algorithm, an excitation cosine force before and after happening the damage, were applied to the analytical model and its responses at the piers are registered. The responses were processed by Power Spectral Density function. The diagrams of Power Spectral Density related to the response signals of the pier No. 2 are shown in figures 4 and 5.

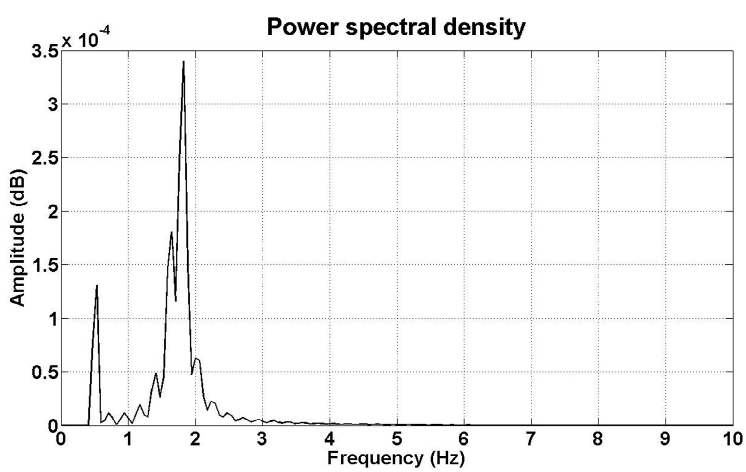

Figure 4. The Power Spectral Density for Recorded Responses of the Undamaged Model

5.3. Damage Detection

Now using the calculated diagrams, the performance of the method can be evaluated. The calculation result is shown in figure 6. As shown in figure 6, under the effect of the exciting force, the probability of the existence of damage in pier No. 3 is equal to 100% while in piers No. 1 and 2 are less than 37%. Therefore, based on the results, damage is occurred in pier No. 3.

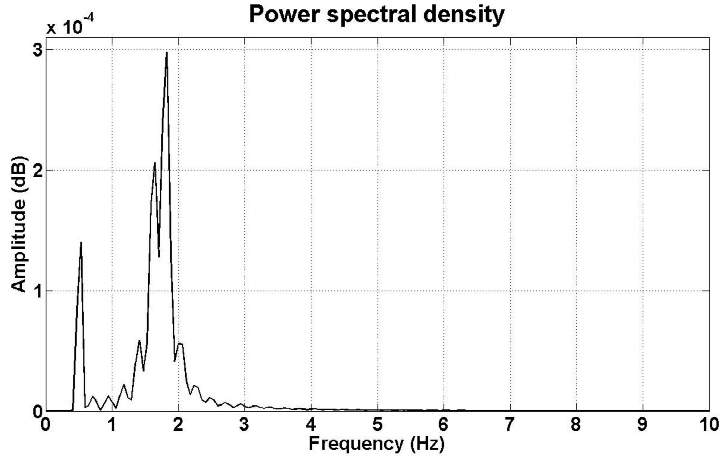

Figure 5. The Power Spectral Density for Recorded Responses of the Damaged Model

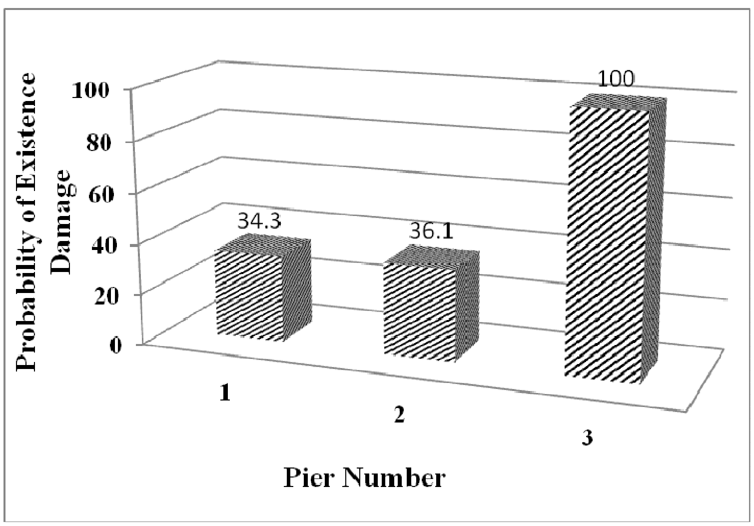

Figure 6. Damage diagnosis diagram based on the recorded responses in the middle of the piers using the proposed methodology.

Accordingly, it is clear that the proposed algorithm has presented very good performance in damage detection and generally, in identification of damage location.

6. CONCLUSION

In this study, a new algorithm based on power spectral density function and CSD method, was proposed to detect damage in bridge piers. To evaluate the proposed algorithm, the analytical model of W180 bridge, was selected as the structural sample. As already mentioned, the proposed approach does not need the numerical model for system identification and damage detection. Moreover, the algorithm could detect damage in the concrete pier of W180 bridge precisely. In addition, the algorithm needs not to measure the input force. In fact, this algorithm can extract the dynamic properties of the bridge and detect any possible damage only based on the measured response of bridge structures. Therefore, considering the simplicity of the proposed algorithm, it can be used in health monitoring of bridges.

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