STRUCTURAL HEALTH MONITORING ON SPANS USING THE RESONANCE REGIONS OF THE POWER SPECTRUM DENSITY (RR-PSD)

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Received: 27 July 2019; Accepted for publication: 13 January 2020

Abstract. This article proposes a new method which can be used to evaluate the damage detection in spans. This method can monitor the stiffness degradation of spans over time. The monitoring process will be conducted at different measuring points on spans, on different spans at the same or different measuring periods. The obtained results show that the change of acreage in the resonance regions of the power spectrum density has brought many positive preliminary outcomes in evaluating the quality of projects during their operational period. The study also shows that the change of acreage in the resonance regions allows us to identify the dangerous points on different spans of a bridge.

Keywords: damage detection, monitoring, resonance regions, dangerous spans, bridge.

Classification numbers: 5.4.2, 5.4.3.

1. INTRODUCTION

In recent years, civil infrastructure, including bridges, have always had an important role in social activities. Damage in bridges not only created traffic stagnation, large economic impacts, but also loss of human lives. Therefore, damage identification and condition assessment of bridges are one of the main tasks of infrastructure management communities to ensure safety in operation.

The first procedure, many of the earlier damage detection techniques consist of experimental approaches such as visual tests, tap tests, acoustic or ultrasonic, stress wave, magnetic field, radiography, eddy-current and thermal field methods. These non-destructive damage detection methods are known as “local” damage detection methods or visual inspections. The disadvantage of these methods is to require knowledge of the damage’s approximate location. On the other hand, application of such methods requires prior knowledge of the possible damage sites and hence these methods can only be applied to accessible portions of the structure [1]. Besides, these methods are generally costly, time-consuming and ineffective.
for large and complex structural systems. Especially, visual inspections also depend highly on the decisions and opinions of the inspectors and can lead to large variations and subjectivity in the results. Furthermore, you can only assess the outward appearance of a structure, so even major internal damage could be missed for years [2]. However, because of specific assessment to damage, local methods are still in popular use today, even for different infrastructures.

The second procedure is the evaluation of load rating, known as load-carrying capacity inspection (triennial inspection). It will determine the relationship between the live or overweight loads and structural responses of the bridge. These responses are usually: strain, deflection, impact factor, fundamental frequency (only determining the first fundamental frequency). Excepting fundamental frequency determined from damping vibration, other responses are only determined in the steady-state response of the bridge. Due to measuring strain and deflection of the bridge with known loads, this procedure is confident to management communities. However, this procedure is costly and closure of a bridge, which causes traffic stagnation, so the inspection is specified to carry out triennially to perennially. This type of inspection has limited ability in detecting all possible damages in the bridges, and they may very well miss damage that grows during the two-year time interval. If only used two of these procedures mandated by the National Bridge Inspection Program, responses’ information of the bridge could be missed. Typically, in August of 2007, The I-35W Mississippi River Bridge suddenly collapsed, killing 13 people and injuring 144 more, although the bridge was inspected annually ever since 1993 [3]. The bridge was 40 years old and had been subjected to increased traffic and environmental loads over its lifetime, causing deterioration and ultimately the failure of some under-designed components. In the recent 20 years, cable-stayed bridges with large lengths have appeared around the world [4-7]. They often connected a mainland with an island to the continent, hence under a strong influence of the environment (wind, temperature, seismic, humidity, corrosion status, ocean waves, etc.), so the possibility of catastrophe is very great. Stemming from the fact, regular measuring (Data Acquisition & Transmission System) is performed. The data will be used to evaluate the bridge condition. These measurement systems are called Structural Health Monitoring (SHM) systems. Field tests were conducted using different sources of dynamic excitation, including ambient (wind and ocean waves), traffic excitation, and impact excitation; the bridges’ response under the different dynamic excitation types were recorded using accelerometers that were attached to the bridge deck. On the other hand, the data mining in the real status always attract the attention of many scientists in the world, so the data mining in this field is a group of vibration-based damage detection (VBDD). The basic idea of VBDD methods is that modal properties (natural frequencies, mode shapes and damping) are a function of the physical properties of the structure (mass, stiffness, mechanical properties of materials and boundary conditions). Therefore, changes in the physical properties of the structure will cause changes in the modal properties.

Therefore, the present study suggests investigating the degradation in overall stiffness \((EJ)\) of the whole span’s bridge. The parameters selected as characteristic based on power spectrum density, which is built from the acceleration signal of random vibration on span’s bridge’s actual circulation. This new parameter can help monitor the degradation stiffness state of span through the time. It also evaluates different levels of defects as well as different measuring points of the same span or of each different span in the same measuring time or at a different time. Besides, the study also proposed the change of acreage in the resonance regions of the power spectrum density concept that characterizes the process of monitoring and evaluating the degradation in overall stiffness. These parameters are based on the change in the shape of change of acreage in the resonance regions of the power spectrum density during the operation process of the whole
span’s bridge. To evaluate the change of moment of the power spectrum density in different positions on the same span, or different spans on the same bridge.

2. THEORY BACKGROUND

In this paper, the first five spectral moments are critically analyzed in the context of damage identification in a non model-based approach to investigate their effectiveness and identify the most sensitive damage-parameter or combination of parameters. These include zero-order moment (mean power), first-order moment (mean-frequency), second-order moment (variance), third-order moment (skewness), and fourth-order moment (kurtosis). Subsequently, identification is to be made of those spectral moments (or a combination of moments) which are the most sensitive and promising parameters for use in future structural damage identification studies based on model-based approaches and a Bayesian statistical framework.

In general, for a given continuous zero-mean stationary Gaussian random process, the $d^{th}$ order non-central moments in the frequency domain and time domain, respectively, are given by the following equations:

\[ \mu_d^f = \int_{-\infty}^{\infty} f^d S_{ww}(f) df \]  

\[ \mu_d^t = \int_{-\infty}^{\infty} t^d W^2(t) dt \]  

Similarly, the central moments can be determined by subtracting the corresponding mean values at each frequency and time, as follows:

\[ \mu_d^f = \frac{1}{\mu_d^f} \int_{-\infty}^{\infty} (f - \mu_f^d)^d S_{ww}(f) df \]  

\[ \mu_d^t = \frac{1}{\mu_d^t} \int_{-\infty}^{\infty} (t - \mu_t^d)^d W(t)^2 dt \]  

where $\mu_{df}$ and $\mu_{dt}$ are $d^{th}$ order spectral moments in the frequency- and time-domain, respectively. $S_{ww}(f)$ is the response power spectral density (or the vibrational energy distribution of random process $W(t)$ in the frequency domain); $W(t)$ is the time series of interest; $f$ is the signal frequency in Hertz. For a discrete-time signal, the non-central and central spectral moments in the frequency domain can be defined, respectively, as follows:

\[ \mu_d^f = \frac{2}{N} \sum_{l=0}^{N-1} S(l) \left( \frac{l}{N\Delta t} \right)^d \]  

\[ \mu_d^t = \frac{2}{N \mu_d^t} \sum_{l=0}^{N-1} S(l) \left( \frac{l}{N\Delta t} - \mu_t^d \right)^d \]  

where $2/N$ is the length of the one-sided power spectrum, and $N = T/\Delta t$; where $\Delta t$ is the sampling interval; $T$ is signal observation time.

Furthermore, it is important to note that different moments have different statistical interpretation and significance that may provide useful information regarding structural damage
conditions. The level of significance should be viewed in the context of the degree of sensitivity and close relationships to structural physical features. Therefore, understanding the significance of each moment and its level of sensitivity to changes in the dynamic properties of structures is necessary before the implementation of these parameters for structural damage identification. In the following section, definitions of the spectral moments in the context of ordinary statistical terminology and their practical implications for structural damage identification are presented.

3. RESULTS AND DISCUSSION

Through a survey span of Saigon Bridge with prestressed concrete material in 6 different measurement times (over 5 years), the span’s PSD can be shown as Fig. 1. We can see that the PSD formed the three resonance regions with significant amplitude as: the first resonance region approximately from 0 Hz to 8 Hz, the second region from 8 Hz to 14 Hz, and the third region between 14 Hz and 24 Hz. From the similar survey as the prestressed concrete materials, manuscript surveyed another span with structural steel material on the Saigon Bridge Fig. 2. It shows that there are mainly two resonance regions with significant amplitude as the first resonance region around from 0 Hz to 8 Hz and the second between 8 Hz from 18 Hz.

![Figure 1. The PSD of prestressed concrete material span on Saigon Bridge through first times.](image1)

![Figure 2. The PSD of structural steel material span on Saigon Bridge through first times.](image2)

3.1. Characteristics change with the number of resonance regions of the actual PSD

During the PSD graphs, there are always coexisted with each other of many resonance regions at the same measurement time. The actual vibration graph of a set data was received with each different measurement time. After the Fourier analysis, it can seem that some PSDs are only the resonance region; some PSDs are two resonance regions and the others are three
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resonance regions. From (Fig. 1) and (Fig. 2), it can see that the total percentage of the PSD with the different structure materials including prestressed concrete and structural steel on Saigon Bridge is many changes in the different measurement times. However, after over 5 years of health monitoring, the data of PSD that has more resonance regions (two or three regions) witnessed a significant downward trend while the total of PSD that has only one resonance region experienced a dramatic upward trend. So, by the operating time of bridge, it can clearly show that the PSD’s probability to contain the resonant region in high-frequency value will decline and replace by the PSDs that have only one resonance region although the traffic load remains unchanged.

![Figure 3](image-url)  
*Figure 3.* The percentage of total PSD with the same resonance region on prestressed concrete structure material.
We can see that the probability of appearance with the PSD that has more resonance regions significantly decreased over the given period. In terms of theory, together with the same as source traffic load and throughout operating time, the bridge’s span will weaken their bearing capacity, therefore, the amplitude of high-level harmonics will decrease accordingly. The theory shows that vibration power by the source traffic load will move from high resonance regions to low regions. Comparison between steel structure material and prestressed concrete material of the Saigon Bridge (Figs. 3-4), the highest resonance region of the prestressed concrete material structure has the percentage of appearance to change faster the steel structure material in the same period. This mean is entirely consistent with structure material properties because of the destruction time of the steel material bigger than concrete. We can see that new findings from this study are an evaluation method their bearing capacity and monitoring status of the bridge’s span during the operation time.

4.3. Characteristics change of acreage in the resonance regions

To represent the change in shape of the resonance regions, special about the acreage value of the resonance regions in the PSD were surveyed in a set data signal of the bridge’s span. To understand the process of the acreage changes in each region, frequency ranges with a width of 2 Hz limited the acreage value of resonance region in PSD. In term of mechanics, the acreage value of resonance region would represent the total vibration energy of harmonics in the frequency range. From Fig. 5 to Fig. 6, the graphs show the acreage change of the resonance regions on the PSD with the frequency ranges that are equally divided with 2 Hz of some Saigon Bridge’s span.

The survey of the PSD share through acreage value of the resonance regions, results have been obtained:

- All spans with prestressed concrete structure material on Saigon Bridge have the same characteristics when acreage at the high-frequency ranges over 12 Hz decreased over the given period. At the low-frequency ranges under 12 Hz, the acreage changed no rules to compare with the other acreage. It can seem that there was an unclear energy transition from high-frequency regions to low-frequency regions and amplitude harmonics were a significant fluctuation.
Figure 5. The acreage changes of PSD on the Saigon Bridge’s span A, B, C, D (prestressed concrete structure material).

- With steel structure material of span E, the region acreage at high-frequency ranges has decreased continuously over time like concrete spans. However, the acreage at the other regions (low-frequency region) witnessed a slight upward trend.

- At the high-frequency region (third region), acreage value of the resonance regions experienced a downward trend over the given period. With two measurement times (first time on 12/2011 and second time on 2/2012) with all spans of Saigon Bridge as shown in Fig. 7, the third region had the significant energy proportion to around 40 % and 30 % respectively and reached the highest point to surround at 17 Hz. In the middle of the measurement times (third time on 5/2012 and fourth on 8/2012), acreage value of the third resonance region saw a dramatic decline trend to under 5 %. These mean show that there was the energy transmission of the third resonance region to come to the second resonance region or the first resonance region. However, acreage value in the second region was no increased co-variable over a short time. From the fifth time on 7/2015 to sixth time on 10/2016, acreage value of the second resonance region witnessed a significant decrease while acreage value of the first resonance region saw a steep increase. Special note, in the sixth measurement time, the acreage of the third resonance region in PSD had amplitude spectrum to become very small or non-existent. The main cause may be explained by the most vibration energy to transmit from high-frequency region to low-frequency region and final their energy are concentrated in the first resonance region. So, when the bearing capacity of the bridge’s span decreased, the acreage value will determine sensitivity with operating status on bridge to base on the highest frequency region and the lowest frequency region in the PSD graph.
This study has monitored the change in structure using the resonance regions of the power spectrum density (RR-PSD) in collected data. The characteristic used in this research is the change in shape of the RR-PSD, and results show that the proposed parameter has a much higher sensitivity compared to natural frequency. Through this research, the following results have been obtained:

- The lowest vibrational frequency measured in the beam throughout monitoring often shows very little to no change; however, the shape of their RR-PSDs always demonstrates large shifts during the interval of monitoring. If the behaviors of the beams are similar in terms of the material’s mechanic properties, the stiffness and the degree of decline over time, then the RR-PSD should be equivalent; yet, real-life surveys of the Saigon Bridge always return differences in the RR-PSD at different locations in the same beam, or in different beams, in the same monitoring interval.

- To evaluate changes in the shape of the power spectrum density, the change in area of each RR-PSD was used to determine the difference between measurement locations within the
same beam or in different beams. This change can be used to evaluate differences between different measurement locations, which sensitivity is particularly of interest since it's higher than other parameters when it comes to evaluating the decline of stiffness of structures during operation.

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