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ENHANCING STRUCTURAL HEALTH MONITORING OF BRIDGE BEAMS THROUGH SPECTRAL MOMENT ANALYSIS

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Abstract. Investigating the occurrence of defects in structures is currently a major issue of significant interest. In this paper, we present experimental research findings on the relationship between the moments of the power spectrum and the presence of damage in bridge beam structures. The study is based on analysing the random oscillation signal of the structure under the effect of random displacement loads. The results demonstrate that the value of the spectral moment is a sensitive feature to abnormal changes inside the structure. As a result, the output obtained from our study suggests using the spectral moment parameter as a new characteristic quantity for monitoring changes in bridge structures. Compared to traditional quantities like deflection, natural frequency, and mode shape, the value of the spectral moment can be more accurately determined. In the future, the spectral moment value can be extended to evaluate different types of structures under complex load conditions.

Keywords: structural defects, bridge beams, power spectrum, spectral moment, monitoring, characteristic quantity, deflection, natural frequency, mode shape, complex load conditions.

1. INTRODUCTION

Bridges are important structures in daily life, economic activity, livelihood, and national defense and security. However, these structures often experience incidents that cause economic and human losses. Therefore, maintaining, repairing, and preserving these structures is always an important task for every country, especially Vietnam. Maintaining and repairing bridges are regularly carried out and are allocated a budget in each country's annual budget. Currently, there are two methods prescribed by the state to assess the condition of bridges.

- The first method is visual inspection [1] [2], which is the most common and traditional manual method used today. This method is carried out by simple measures such as visual observation or with specialized equipment. It is mainly used when bridge management personnel inspect the bridge daily, weekly, quarterly, or at predetermined intervals depending on the importance level of the bridge [3]. During bridge inspections, personnel can detect abnormalities and warn people and vehicles traveling on the bridge [4].

- The second method is called quality assurance. Bridge quality assurance includes activities that check and determine the quality or evaluate the quality suitability of the construction compared to design requirements, standards, and technical standards through reviewing the actual state of the construction through visual inspection combined with analysis and evaluation of test data [5][6][7]. Regular surveys assess the mechanical behavior of the bridge. This method is responsible for evaluating the practical working ability of the bridge. The bridge assurance process has been legalized by state documents, allowing for quantitative assessment of the working ability of the bridge.

Besides the two main methods mentioned above, there are currently some accompanying measures that exist alongside these main methods. These measures allow the detection of surface damages on the bridge, or factors that may damage the bridge such as erosion, obstructions that hinder the flow and create collision risks. However, these measures cannot detect internal damages such as internal cracks, changes in material mechanical properties [8] [9] [10]. Therefore, inspection methods will affect the required load frequency according to regulations and measure parameters such as vibration, deformation, natural frequency of the cycles, inclination, sagging of the arches, columns [11][12] [13]. However, these measures are very expensive. Nowadays, with the development of science and technology, an intermediate measure is applied to determine the bridge's cycle behavior during operation. This measure usually collects oscillation data of the bridge in different working conditions such as vehicle circulation, wind impact, and actual flow. Fixed measurement systems are called Health Monitoring Systems (HMS), mainly used for vital bridges [14][15][16]. The measurement data source of the HMS attracts many scientists to use them in diagnosing the status of the bridge. A new diagnosis method based on the oscillation behavior of the bridge has been proposed, including a range of parameters such as natural frequency, damping coefficient, and natural form proposed in previous studies. Among them, natural frequency is the parameter with the highest proportion of usage. However, experimental studies have shown that the natural frequency is not sensitive to changes in structure. Therefore, many studies aim to determine structural damage using natural form. However, these studies require relatively complex and expensive equipment. [16] used the value of the natural frequency or [12] used natural form. However, the results of these studies are not really optimistic because in reality, to determine high-order natural frequencies and forms, it is necessary to have equipment with higher sampling frequency and more measuring points. The bridge inspection conducted by the studies [10][11] showed that the change in natural frequency is not sensitive enough to determine local damage on the bridge, and the problem is that the equipment is not accurate enough to measure small changes. In addition, the natural frequency is a global quantity, so it is not sensitive to local changes in the system.

This study proposes using a diagnostic method based on the vibration behavior with data not obtained by HMS but rather through direct periodic measurements. The first challenge in this study is selecting sensitive parameters capable of evaluating the quality status of the bridge over time. The study shows that using the vibration signal caused by actual traffic loads to construct a Power Spectral Density (PSD) brings many advantages. Through the PSD, the study proposes a moment spectrum model to establish the relationship between structural changes and the existing damage within the structure. The second challenge in this study is applying it to different types of structures under varying loading conditions. Therefore, the results from this study may have wide-ranging applications in the future.

2. THEORETICAL BASIS

2.1. Theory of bridge span under load

Bridges are often modeled by various types of load-bearing models, with the most widely used being the single-span beam model as shown in Figure 1. In this model, *f(x,t)* represents the displacement force function acting on the bridge. Depending on the complexity of the problem being solved, the function *f(x,t)* can be a constant function (corresponding to a concentrated or fixed load model), a fixed function for forced displacement, a random function, or a moving function:

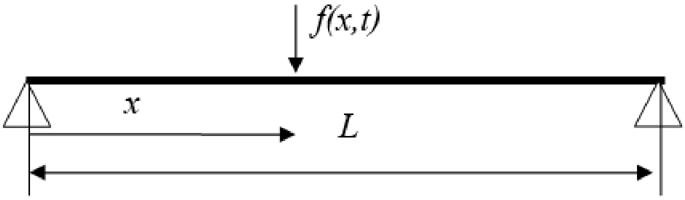

Figure 1. Bridge span model using in the study.

The distribution of loads in reality is represented by a random probability density function *q(z,t)* that varies in velocity. In this context, the load-bearing model of a bridge is a complex stress-bearing model, and the state of stress on the bridge can be in a planar bending, torsion, or simultaneous bending-torsion state. Therefore, studying the complex stress state is reduced to a combination of the three states mentioned above. The general partial differential equation for the degree of oscillation in the simultaneous bending-torsion state is expressed as Eq. (1).

$$\begin{cases} EJ_z \dfrac{\partial^4 y}{\partial x^4} = -\dfrac{A.\gamma}{g}.\dfrac{\partial^2 y}{\partial t^2} - \dfrac{A.\gamma_c}{g}.\dfrac{\partial^2 \varphi}{\partial t^2} \\ C.\dfrac{\partial^2 \varphi}{\partial x^2} - C_1.\dfrac{\partial^4 y}{\partial x^4} = \dfrac{A.\gamma_c}{g}.\dfrac{\partial^2 \left(y + c.\varphi\right)}{\partial t^2} + \dfrac{J_p \gamma}{g}.\dfrac{\partial^2 \varphi}{\partial t^2} \end{cases} \tag{1}$$

when in a planar bending state and subjected to a constant load P, the oscillation function takes the form of Eq. (2):

$$y = \frac{2gPl^3}{A\gamma\pi^2}\sum_{i=1}^{i=\infty}\frac{\sin\frac{i\pi x}{l}}{i^2\left(i^2\pi^2a^2 - v^2l^2\right)}\sin\frac{i\pi x}{l} - \frac{2gPl^4 v}{A\gamma\pi^3 a}\sum_{i=1}^{i=\infty}\frac{\sin\frac{i\pi x}{l}}{i^3\left(i^2\pi^2a^2 - v^2l^2\right)}\sin\frac{i^2\pi^2 at}{l^2} \tag{2}$$

where: ρ is the mass density per unit volume; A is the cross-sectional area, and $a = \sqrt{\frac{EJ}{A\rho}}$. If the load P is a harmonic function, the vibration function can be expressed by Eq. (3).

$$y = \frac{Pl^3}{EJ\pi^4}\sum_{i=1}^{i=\infty}\sin\frac{i\pi x}{l}\left\{\frac{\sin\left(\frac{i\pi v}{l}+\omega\right)t}{i^4-\left(\beta+i\beta\right)^2}+\frac{\sin\left(\frac{i\pi v}{l}-\omega\right)t}{i^4-\left(\beta-i\beta\right)^2}-\right\}$$
$$-\frac{Pl^3}{EJ\pi^4}\sum_{i=1}^{i=\infty}\sin\frac{i\pi x}{l}\left\{\frac{\alpha}{i}\left(\frac{\sin\frac{i^2\pi^2 at}{l^2}}{-i^2\alpha^2+\left(i^2-\beta\right)^2}+\frac{\sin\frac{i^2\pi^2 at}{l^2}}{-i^2\alpha^2+\left(i^2+\beta\right)^2}\right)\right\} \tag{3}$$

Due to the elasticity of the bridge, it will always oscillate under the action of dynamic loads. The natural frequencies of the planar bending, pure torsion, and simultaneous bending-torsion stress states are determined by Eqs. (4-6), respectively. The natural frequency of the planar bending state is expressed by Eq. (4), the natural frequency of the torsion state is expressed by Eq. (5), and the natural frequency of the simultaneous bending-torsion state is expressed by Eq. (6). In these equations, EI_z is the bending stiffness, A is the cross-sectional area, and ρ is the mass density.

$$\omega_{B-i} = \left(i\pi\right)^2\sqrt{\frac{EJ_x}{\rho.A.l^4}} \tag{4}$$

$$\omega_{T-i} = \left(i\pi\right)\sqrt{\frac{GJ_z}{J_0}} \tag{5}$$

$$\omega_{(B-T)i}^2 = \frac{\left(\omega_{Ti}^2+\omega_{Bi}^2\right)\pm\sqrt{\left(\omega_{Ti}^2-\omega_{Bi}^2\right)^2+4\lambda\omega_{Ti}^2\omega_{Bi}^2}}{2\left(1-\lambda\right)} \tag{6}$$

in which: $\omega_{Ui}^2 = \frac{EI_z i^4\pi^4}{l^4\rho F}$; $\omega_{Xi}^2 = \frac{GJ_z i^2\pi^2 l^2 + EJ_z i^4\pi^4}{l^4\rho\left(I+Fc^2\right)}$; $\lambda = \frac{Fc^2}{I+Fc^2}$

2.2. The random theory of the power spectrum

Typically, in practice, complex loads are often divided into combinations of simple loads. This can be accepted that the bridges always operate in the elastic linear range, where the behavior of the bridge is determined by the sum of the component behaviors. The Fourier theorem allows for the analysis of any algebraic function *f(t)* into an approximate sum of harmonic component functions.

$$F(t) = A_0 + \sum_{n=1}^{\infty}\left(A_n\cos n\omega t + B_n\sin n\omega t\right) \tag{7}$$

in which: $A_0 = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} F(t).dt$; $A_n = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} F(t).\cos n\omega t.dt$; $B_n = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} F(t).\sin n\omega t.dt$

2.3. The transfer function of a random signal

The random loading time plays a crucial role in the behavior of the bridge. Therefore, the behavior of the bridge is also random. For a set of n discrete random oscillation signals $x_n(t)$, the characteristic quantities of the signal are determined by the autocorrelation function of the signal $x(t)$ as shown in Eq. (8)

$$R_x(\tau) = \lim_{T\to\infty}\frac{1}{T}\int_{\alpha}^{\alpha+T} x(t)x(t+\tau)\,dt \tag{8}$$

The spectral density function of $R_x(\tau)$ is called the power spectral density (PSD) of $x(t)$, denoted by $S_x(\omega)$

$$S_x(\omega) = \int_{-\infty}^{\infty} R_x(\tau)e^{\omega t}dt \tag{9}$$

Through the power spectral density (PSD), the research model proposed in the draft uses the moment model to form characteristic parameters in evaluating the structural changes of the bridge. The moment spectrum is expressed as Eq. (10)

$$m_0 = \int_0^A S_x(\omega)dA \tag{10}$$

3. EXPERIMENTAL MODEL AND DATA PROCESSING PROCESS

3.1. Experimental model

The aim of this study is to monitor the mechanical behavior changes of a real bridge structure through the vibration measurement process of its bridge components. To evaluate the overall vibration responses of the bridge, various components such as the spans, piers, and abutments will be investigated. However, in the scope of this article, the authors only focus on the vibration response of the bridge span as measured by the sensors. The signal acquisition positions of the Saigon Bridge are shown in Figure 2. The responses will be obtained at various measurement locations under different traffic conditions to capture the best signal form with clear amplitude compared to the initial noise level of the equipment.

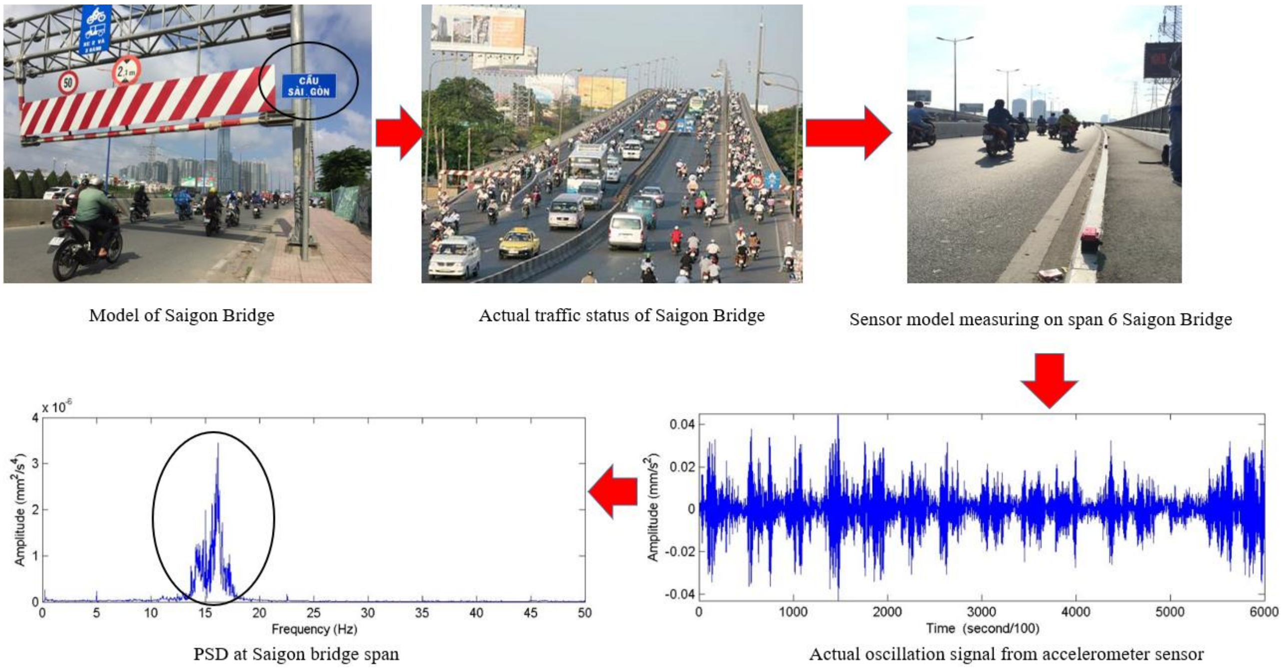

Figure 2. Experimental model at Saigon Bridge.

The research model will be conducted in a state of random vibration measurement with the following requirements:

- The load state of the bridge span is always in a state of random vibration due to uncontrolled and non-segregated traffic flow on the bridge. Additionally, the characteristics of the Saigon Bridge exhibit significant variations in traffic flow between day and night, and between normal and peak hours, resulting in differences in the structural response state during working hours.

- The environmental conditions at the Saigon Bridge are quite complex due to significant temperature fluctuations between day and night. The hot and humid climate causes the mechanical properties of the load-bearing structures on the bridge to change considerably. Therefore, in addition to the random load conditions, this research also includes random environmental conditions for the bridge span.

- The measurement time for this study is conducted at different times of the day. Each measurement will be taken for 30 minutes with a sampling frequency of 100 samples/s. This measurement time model allows the study to explore many different load states of the span under various traffic conditions.

3.2. Data processing process

The data processing procedure depicted in Figure 3 consists of the following steps:

- *Step 1*: Signals are directly collected from the accelerometer sensor located on the bridge deck. These signals are then filtered to remove noise and unreliable data. This helps to ensure that the collected data contains accurate information about the structural response of the bridge at the measurement location.

- *Step 2*: After removing noise and unreliable signals, the data is analyzed to obtain a power spectral density (PSD) model through the Fourier transform. The PSD model converts the signal from the time domain to the frequency domain, where at different measurement times, the study generates pairs of numbers consisting of the value of the frequency harmonics and the amplitude of these values. Additionally, the PSD model forms frequency response regions. In these regions, the study can demonstrate similarities and differences in the PSDs of the bridge deck to propose SM parameters as an evaluation model for the structural changes over time while the bridge is in operation.

- *Step 3*: The SM model is formed to evaluate the working state changes of the bridge at different measurement times. The study collects signals at different time periods to evaluate structural changes through changes in the SM value. Additionally, the study assesses these changes through different traffic flow conditions, such as normal and peak hour traffic.

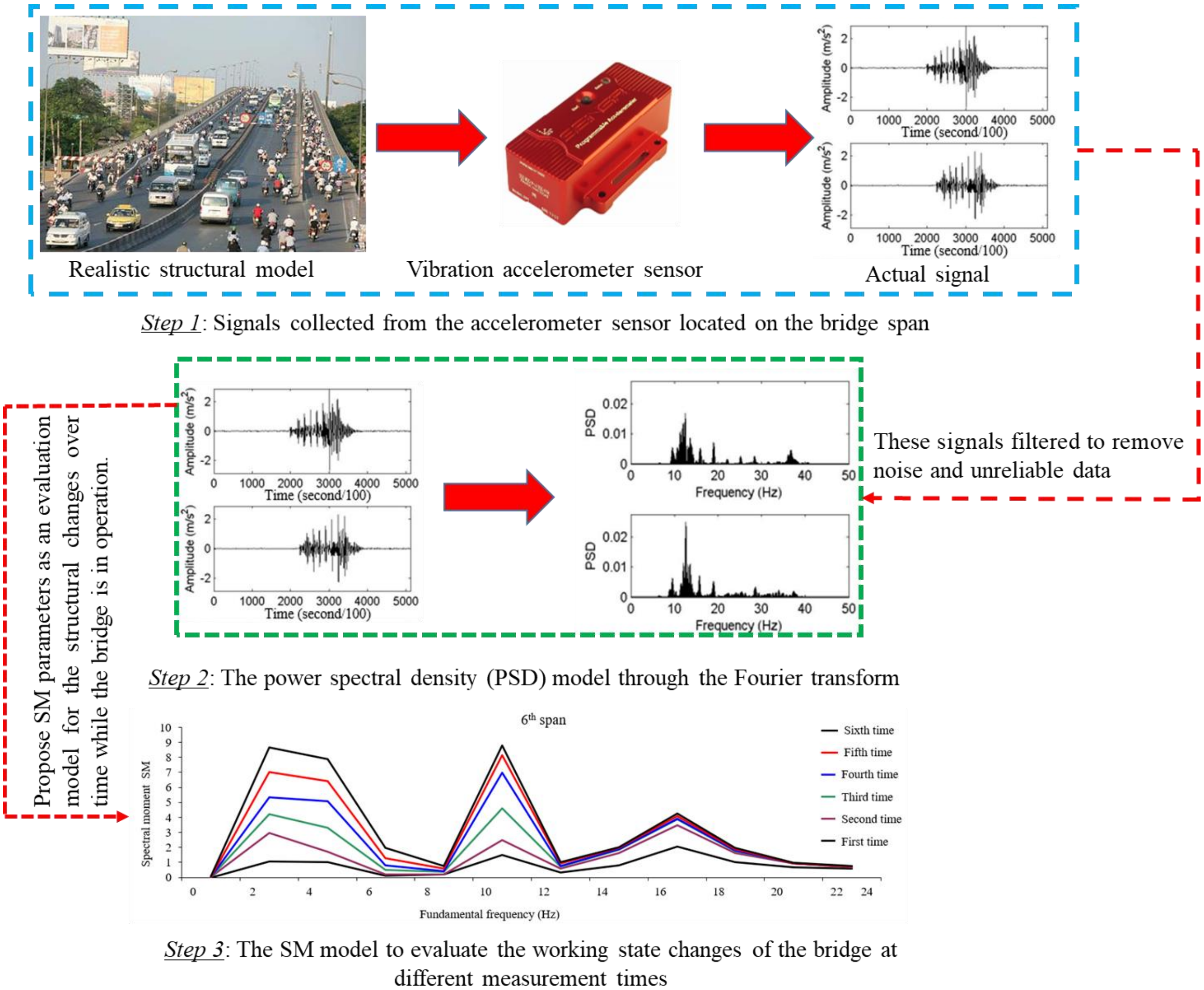

Figure 3. Data processing process.

4. RESULTS AND DISCUSSION

4.1. The power spectrum of the actual vibrating signal

During the actual traffic circulation on the bridge, the mechanical behavior of the bridge is always in a random state because at the same time, the bridge has many means of transportation with different loads and speeds or very few loads passing through the bridge. Continuous vibration signal measurements from actual loads on the Saigon Bridge were carried out, and the graphs representing the measured signals are shown in Figure 2. This shows that the power spectral density (PSD) of the random vibration signal of the bridge will generate a set of randomly varying amplitude values over the entire time domain and frequency range shown on the spectrum.

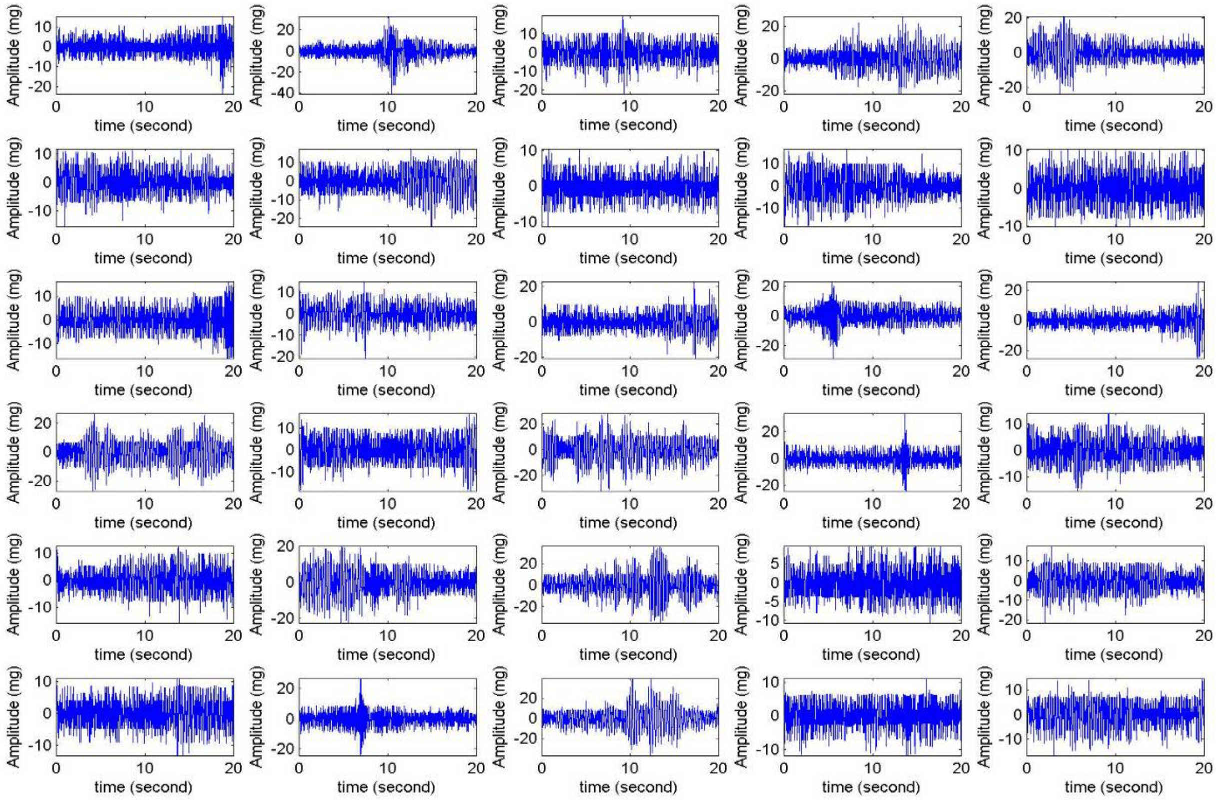

Figure 2. Acceleration signal oscillation of a Saigon bridge span.

From each set of actual oscillation signal measurement data at the bridge, a PSD spectrum can be constructed based on the theory of Fourier analysis, as shown in Figure 3.

As shown in Figure 3, we can see that the variation of traffic loads on the bridge during the data collection period resulted in a relatively diverse range of actual PSD spectra of the Saigon Bridge with different states of load bearing. Investigating the characteristics of PSD spectra variation of the Saigon Bridge over a long period, this study identifies the following characteristics of PSD spectra variation due to actual operation:

- There are 6 PSDs which account for about 20% of the surveyed spectra that only appear in a frequency range from 3 to 6 Hz, so the study could only determine one fundamental frequency at the location of the harmonic with the greatest amplitude. This indicates that the shape of PSD reflects a state resembling to the free vibration of the bridge deck. However, the frequency values in the PSD exhibit minor deviations that could be attributed to the influence of noise and inaccuracies during the measurement and data processing.

- There are 10 PSDs (making up 37% of the surveyed spectra) where the frequency harmonics are mainly concentrated into two resonance regions: region 1 from 3 to 6 Hz and region 2 from 10 to 12 Hz. This indicates that, in addition to the fundamental frequency mentioned above (which accounts for about 20% of the surveyed spectra), the bridge also vibrates with another frequency within the second resonance region.

- Furthermore, there are 14 PSDs (which account for 43% of the surveyed spectra) with spectral shapes and harmonics ranging from 2 to 24 Hz. The survey results indicate that, in addition to containing dominant harmonics in the resonance regions of 3-6 Hz and 10-12 Hz as analyzed above, there are also many harmonics with varying amplitudes within the range of 14 to 20 Hz.

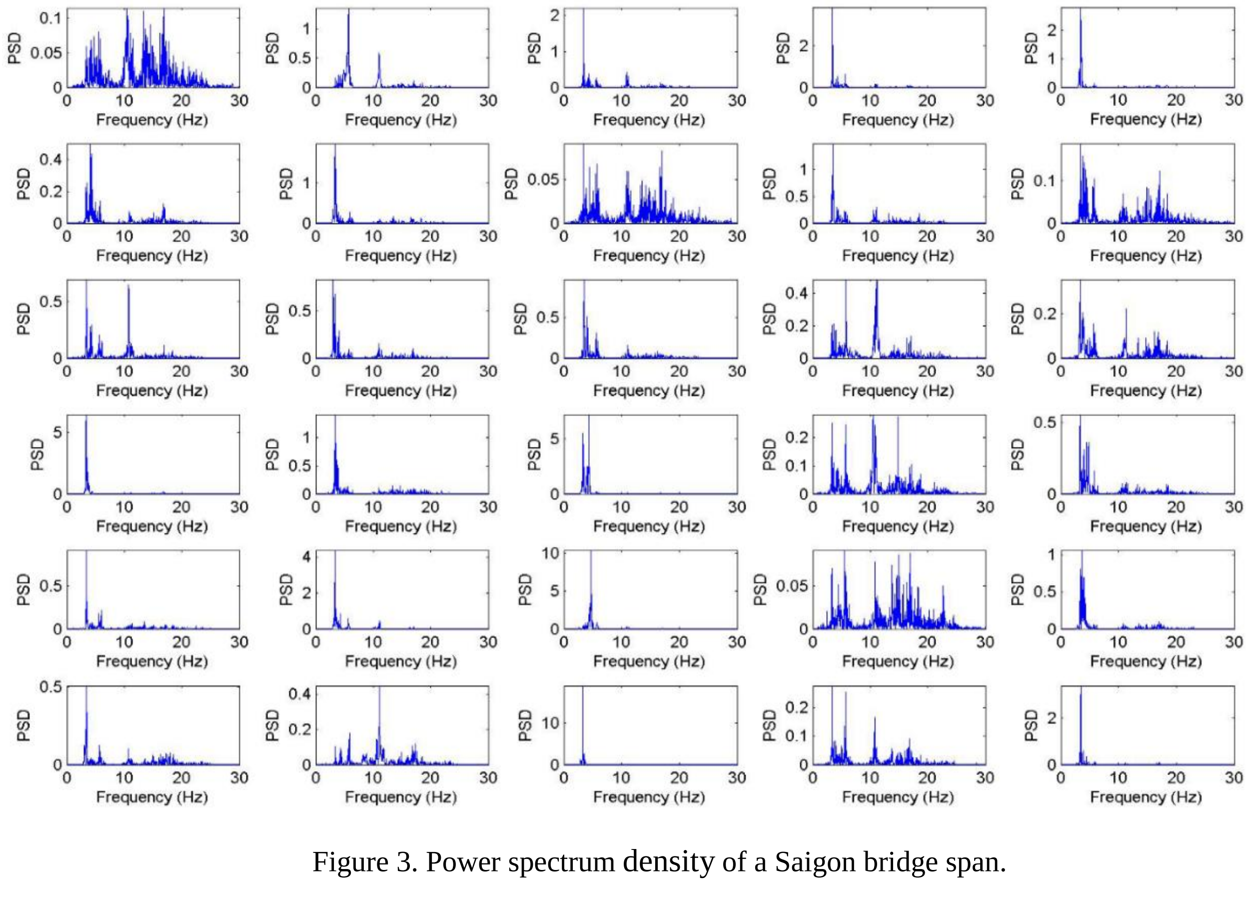

Figure 3. Power spectrum density of a Saigon bridge span.

The conclusion drawn from the actual survey process shows that the resonance frequency region with the lowest value always appears, even though the value of this frequency region may be lower than that of other regions. This implies that the value of the lowest resonance frequency region is more c than its adjacent regions. A complete survey of the power spectral densities (PSDs) of the Saigon Bridge in a single measurement campaign showed that the resonance regions typically cluster around the fundamental frequency, and differences may occur mainly due to noise in the data acquisition process, errors in the measurement process, and data processing. Therefore, the changes and distribution of the PSD shape also reflect the structural behavior of the bridge during operation. Thus, it is necessary to propose a parameter that can assess the bridge's vibration changes in different measurement campaigns.

4.2. Spectral moment change characteristics of PSD

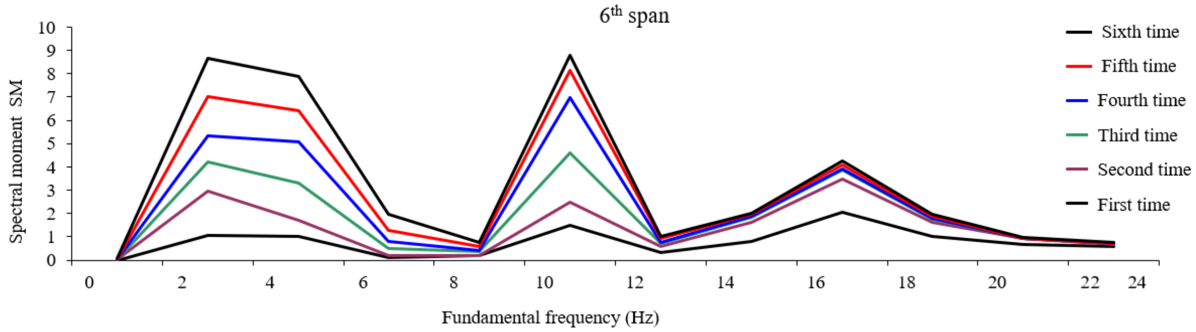

Figure 4. Changing SM values over time in a 6-bridge span in Saigon.

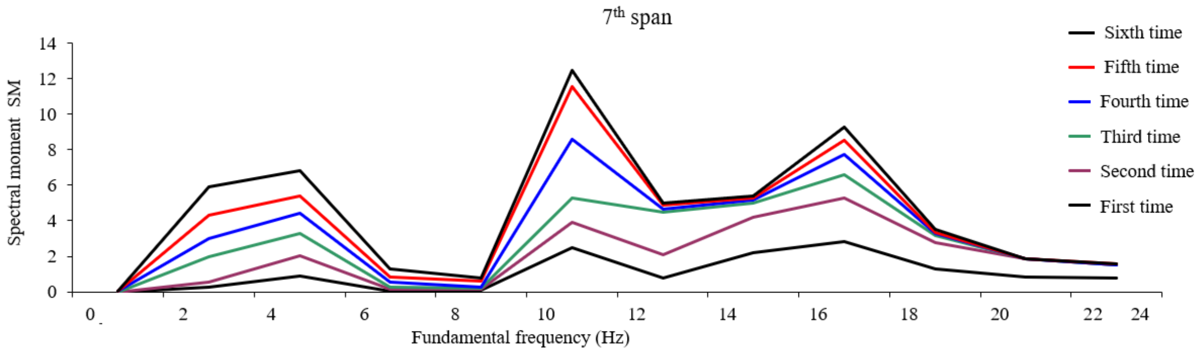

Figure 5. Changing SM values over time in a 7-bridge span in Saigon.

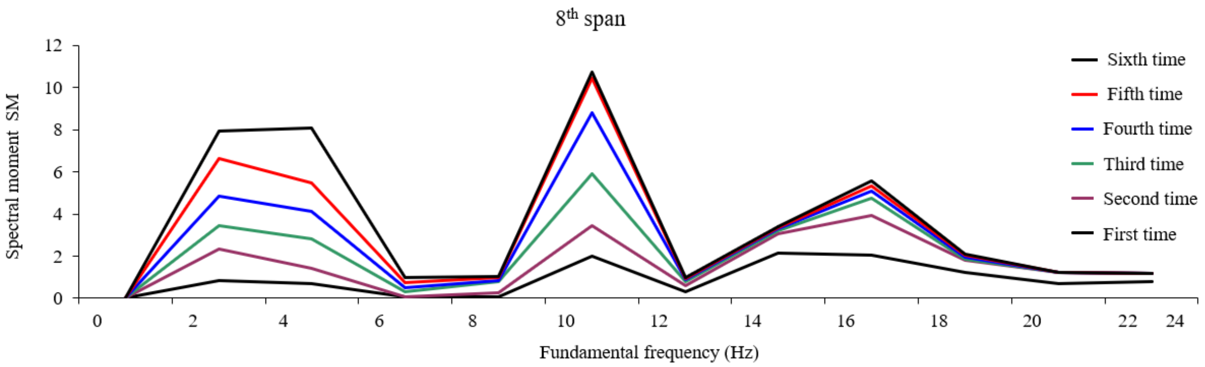

Figure 6. Changing SM values over time in a 8-bridge span in Saigon.

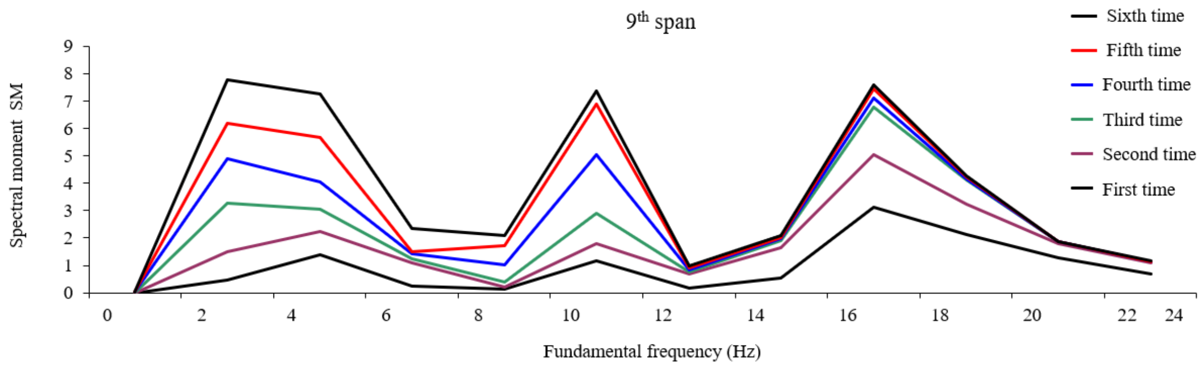

Figure 7. Changing SM values over time in a 9-bridge span in Saigon bridge.

The spectral moment (SM) is calculated with respect to the vertical axis of the PSD to represent the shape change in terms of the magnitude of the oscillation spectrum. Mechanically, the SM represents the fast or slow transfer of oscillation energy of the harmonics in the frequency range being surveyed. To understand the process of changing the SM values in each resonance range, the study proposes to evaluate the change in SM values along the boundary limits of the frequency ranges with a continuous width of 2 Hz. Figures 4 to 7 show the SM graphs of some Saigon bridge rhythms.

In the current methods of assessing the condition of bridges in Vietnam, techniques such as visual observation or load capacity testing are widely used due to their ability to evaluate the condition of structures. However, these two methods have many limitations, making it difficult to apply them to all bridge projects. This study conducted the collection of vibration signal characteristics of Saigon bridges to investigate the changes in spectral shape and monitor the operational condition of the bridges over time. The results from Figures 4 to 7 show the following issues:

- Spectral moments allows for their calculation in the time domain, frequency domain, or both, making them highly flexible to various measurement problems. This can solve problems across multiple domains, especially in continuous structure health monitoring systems. By providing energy information in the frequency range, spectral moments offers a broader description of a structure’s behavior than traditional parameters, making them an effective tool for evaluating changes. Therefore, the value of spectral moments is also very flexible in determining the important features of signals measured from reality.

- Spectral moments are applicable to both linear and nonlinear problems.When applied to a linear model, changes in physical properties such as mass, stiffness, and dampling of the structure are reflected. In contrast, when applied to a nonlinear model, the value of spectral moments not only indicates changes in structural stiffness, material aging, or state parameters, but also help identify the underlying causes of these phenomena.

- Spectral moments are not dependent on phase oscillation effects, so this method will preserve the important properties of the signal and be less affected by noise. Therefore, when combining the spectral moment value with different algorithms, it will not significantly affect the results obtained.

4. CONCLUSION

Assessing and monitoring the condition of structures is a major issue. Research has used the vibration data of Saigon Bridge as a study model with the following notable results:

- The conclusion from the actual survey process shows that the lowest resonant frequency always appears, even though the value of this frequency range may be lower than that of other ranges. In other words, the lowest resonant frequency value has higher stability than the neighboring ranges. The change and distribution of the PSD shape have not yet reflected the structural behavior under operation time.

- The research results of the article show that using spectral moment analysis to monitor the condition of the bridge is an effective and flexible method in structural assessment. This method allows for the calculation of spectral moments in the time domain, frequency domain, or both, helping to solve various measurement problems and can be applied in health monitoring systems for continuous structures. Therefore, spectral moment analysis can be a useful tool in monitoring and assessing the condition of the bridge.

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