Assessing mechanical responses for damage detection in bridge spans through resonance region analysis

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Abstract:

This article introduces a new method for evaluating the mechanical behavior of structures to detect potential damages in bridge spans. The study enables us to monitor the stiffness degradation of bridge spans over time, operating under different working conditions. The proposed approach suggests monitoring the operational status of bridge spans at different measuring points, corresponding to different levels of applied load, measurement time, and environmental conditions according to the random theory. The study results demonstrate that changes in the area under the resonance regions of the power spectrum density can provide accurate information on the change in the structural behavior during operational periods. Furthermore, the research indicates that changes in the area under resonance regions can identify hazardous points on different spans of a bridge through different measuring points. Overall, in the future, this method can assist in identifying potential damages and warning of potential hazards to improve safety and reliability for people and vehicles crossing the bridge.

Keywords: Mechanical behavior; Bridge spans; Stiffness degradation; Monitoring.

1. Introduction

Bridges always play a crucial role in societal activities, including the passage of people and vehicles. Damage to bridges can lead to terrible consequences, such as traffic congestion, economic losses, and even loss of human life. Therefore, detecting, assessing, and predicting the quality of bridge structures is an important task to ensure their safety during operation, from construction to complete failure. Moreover, visual inspection is subjective and can overlook significant internal damage. Despite these limitations, these methods are still widely used for infrastructure evaluation due to their simplicity, tradition, and low cost in operation [1]-[2].

The actual load evaluation on a bridge, also known as the assessment of changes in structure or changes in load-bearing capacity impacting the structure, is aimed at assessing the relationship between actual loads and the behavior of the structure. In addition, load evaluation has an even more important task when determining overloaded states, abnormal structural states, and different reactions of the structure in these cases [3]-[4]. The behaviors that change the load-bearing state of the structure include tension state, torsion state, and composite behavior [5]. This is caused by load factors that affect the structure, characterized by the magnitude of the load and the load model (static load, dynamic load, impulse load, controlled load, etc.). To assess these situations, we often use the structure verification process – specifically, in this case, the bridge verification process [6]-[7]. To determine the stable working state of the bridge according to the correct process in verification, it is measured by the loads determined. This load model already knows the magnitude of the force, the point of placement, and the method of impact and simulates the behavior of this load on the structure [8]-[10]. This ensures safety for humans and vehicles traveling across the bridge at different times. We can see that except for the basic frequency determined by creating vibration oscillations for the bridge structure, other parameters are usually measured during the static load of the bridge. However, the actual working state of the bridge is always in a state of vibration due to the impact of vehicles and natural conditions. On the other hand, the traditional evaluation process is often expensive and difficult to implement for all bridges in a large area like Ho Chi Minh City. At the same time, the implementation of the verification process also causes traffic congestion due to the need to close the bridge, traffic diversion, and related work. Therefore, according to regulations, management agencies limit the verification frequency to once every one to three years for a bridge. Thus, during the operational period of the bridge, we have overlooked the influences and possible damage that may occur between periodic inspections if only relying on the prescribed bridge verification process. To accurately determine the actual damage that exists in a structure and evaluate its operational status, the current process faces many difficulties. Therefore, the evaluation process is not accurate due to a lack of feedback information on the actual quality status of the structure, the progression of damage over time, and the prediction of its future development. The drawback of relying solely on the verification process was evidenced by the complete destruction of the Mississippi River bridge on I-35W in 2007. Although the bridge had been inspected annually according to design requirements since 1993, it collapsed in 2007, and the management units could not understand the cause of the damage. According to the analysis report, many main causes were identified, including the design not being able to predict the actual development speed of the area, the sudden increase in traffic flow within ten years, and the changing impact load that increased the aging process of the structure. At the same time, the changing environment during the bridge's operation also significantly reduced its lifespan. With the development of current science and technology, the number of high-quality and impressive bridges being built is increasing worldwide. It is extremely important and practical to regularly evaluate the operational status and monitor the quality through structural health monitoring (SHM) systems. These systems record the bridge's behavior under various stimulating conditions caused by the impact load on the bridge under different conditions, including traffic load, wind and sea waves around the bridge, traffic, and sudden conditions. This model is often used by sensor systems directly attached to the bridge surface [11]-[12] or regularly measured by mobile sensors. In the field of Structural Health Monitoring (SHM), exploiting real data obtained from bridges is becoming increasingly popular, especially for detecting damages based on the vibration of the structure (VBDD) [13]-[14]. VBDD methods often rely on the main idea that changes in the structure will lead to changes in related parameters. Currently, major parameters such as fundamental frequency, mode shape, and damping are commonly used. Previous studies [15]-[19] have proposed new methods to monitor the overall stiffness degradation of suspension bridges through direct vibration signals on the bridge. To achieve this, the power spectral density function is generated from the random vibration signals on the bridge, and characteristic parameters are selected based on it for the evaluation process. These parameters can help monitor the stiffness degradation state of the ranges over time and evaluate different defect levels. Furthermore, they will be measured at the same points on the same span or different spans of the same bridge [20]. These studies also propose monitoring changes in the load-bearing capacity of the bridge through the area of the power spectral density. Parameters are based on changes in the shape of the power spectral density function during the operation of the bridge. The goal is to evaluate the momentary density of the power spectral density at different positions on the same span or different spans of the same bridge. This method can provide good results for evaluating project quality during operation and identifying dangerous points on different spans. This is especially important for cable-stayed bridges, which require frequent monitoring of their condition using SHM systems. By using this method, the infrastructure management community can ensure safer operation and avoid costly closures or even bridge collapse disasters such as the I-35W Mississippi River bridge collapse in 2007.

The article presents a new approach for assessing mechanical responses in bridge spans to detect damage. The proposed technique enables the constant monitoring of stiffness degradation in bridge spans by conducting measurements at various locations and intervals. According to the research results, changes in the area under resonance regions of the power spectrum density can provide many advantages in evaluating project quality during operational periods. Moreover, the study highlights that changes in the area under resonance regions can help identify hazardous locations in different spans of a bridge. In summary, this method offers a reliable and efficient way to assess the condition of bridge spans, allowing for timely maintenance and repairs to ensure safe and smooth traffic flow.

2. Theoretical foundations of research

This study performs an analysis of the spectral density function of a structure to evaluate the effectiveness of new parameters in detecting damage using a non-structural approach. The characteristics of the spectral density function include the zeroth-order spectrum, also known as the mean power spectrum; the first-order spectrum, also known as the mean frequency spectrum; the second-order spectrum, which represents the variance of the dataset, the third-order spectrum, which indicates the skewness of the spectrum, and the fourth-order spectrum, which shows the kurtosis of the data set in the frequency domain. The aim of this study is to identify parameters that are sensitive to changes in damage and to combine them with other parameters for the process of identifying structural damage. Specifically, the study will provide power spectral density functions in both the frequency and time domains for real-world data processing:

$$\mu_f^d = \int_{-\infty}^{\infty} f^d . S_{ww}(f) df \tag{1}$$

$$\mu_t^d = \int_{-\infty}^{\infty} t^d . W^2(t) dt \tag{2}$$

Similarly, the central values of the power spectrum can be calculated by subtracting the lowest frequency value from the respective frequency and time domain mean values. This can be expressed as Eqs. (3-4):

$$\mu_f^d = \frac{1}{\mu_f^0} \int_{-\infty}^{\infty} (f - \mu_f^1)^d . S_{ww}(f) df \tag{3}$$

$$\mu_t^d = \frac{1}{\mu_t^0} \int_{-\infty}^{\infty} (t - \mu_t^1)^d . W(t)^2 dt \tag{4}$$

The distances formed from the *d-th* order spectral density function are determined simultaneously in both the frequency and time domains, denoted as μ_{df} and μ_{td}, respectively. Here, $S_{ww}(f)$ is represented by the power spectral density of the structural vibration process of the signal *x(t)* transformed into *W(t)* by the Fourier analysis. $S_{ww}(f)$ is understood as the distribution level of the oscillatory energy of the actual signal being studied in the frequency domain, where f is the frequency of vibration of the signal *x(t)*. For a discrete-time signal, the non-central and central spectral distances in the frequency domain can be expressed as Eqs. (5-6):

$$\mu_f^d = \frac{2}{N} \sum_{l=0}^{\frac{N}{2}-1} S(l) . \left(\frac{l}{N.\Delta l} \right)^d \tag{5}$$

$$\mu_t^d = \frac{2}{N.\mu_f^0} \sum_{l=0}^{\frac{N}{2}-1} S(l) . \left(\frac{l}{N.\Delta l} - \mu_f^1 \right)^d \tag{6}$$

The length of the power spectral density function period is 2/N, where N is the number of samples in the time series and is calculated by dividing the observation time of the signal cycle T by the sampling interval Δt. The moments of the power spectral density function have significant statistical meaning and can provide valuable and accurate information about the structural damage condition. However, the importance of the moment of the power spectral density function should be evaluated based on the sensitivity of the power spectral density function and its correlation with the physical properties of the structure. Therefore, understanding the importance and sensitivity of each type of moment of the power spectral density function to changes in the dynamics of the structure is necessary when using them to determine structural damage. The next section of the article will use statistical terms in mathematics as a standard to define the moments of the power spectral density function and explain their practical significance in determining structural damage.

3. Results and Discussion

During five years of monitoring and observing the operational status of the Saigon Bridge, the main construction material used in the bridge was reinforced concrete, and the load used in the study was the actual traffic load and free vibration of the bridge. Through the process of collecting vibration signals, they were evaluated in six separate measurements, and the results of the first measurement on any concrete span are shown in Fig. 1. Using the Fourier analysis to determine the spectral density function, the analysis from the study revealed four vibration spectral regions with considerable amplitude and area, including the first region ranging from approximately 1-5 Hz, the second region between 5-8 Hz, the third region between 8.5-14.5 Hz, and the fourth region between 15-25 Hz. Similarly, for a different span of the Saigon Bridge constructed using structural steel material, which underwent several tests to ensure the safety and smooth flow of people and vehicles, its vibration spectrum is shown in Fig. 2. Fig. 2 displays five resonance frequency regions with significant amplitude and area, including the first region ranging from approximately 1-3 Hz, the second region between 4-6 Hz, the third region between 9-12 Hz, the fourth region between 13-14 Hz, and the final region between 15-18 Hz.

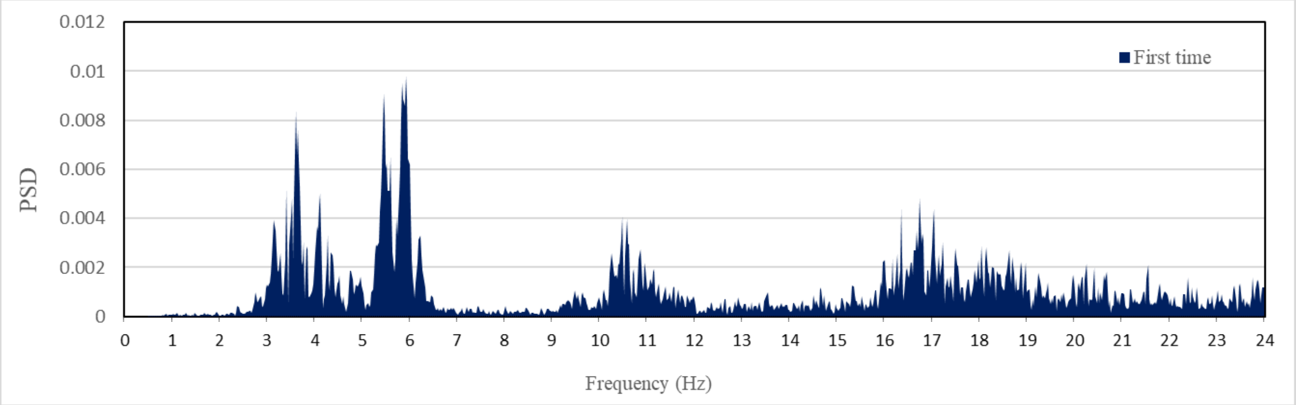


Figure 1. The PSD with prestressed concrete material (first time).

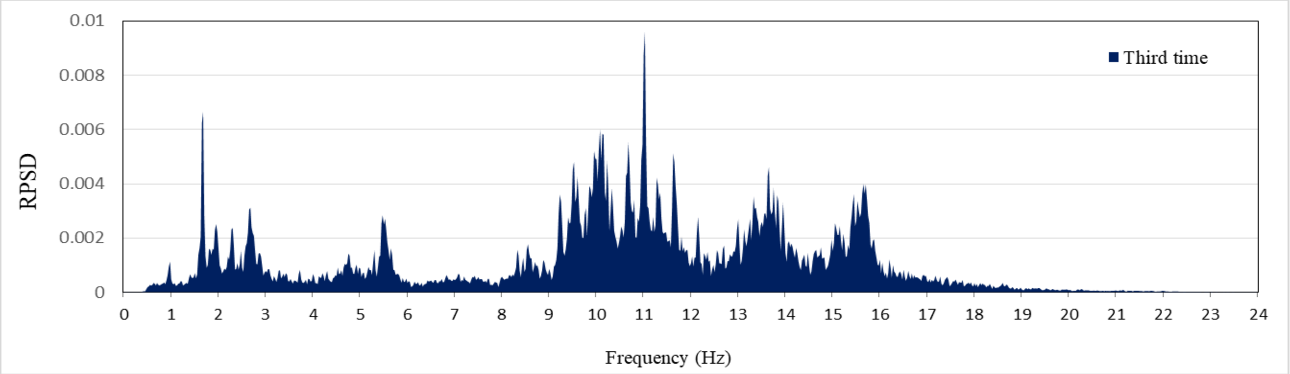
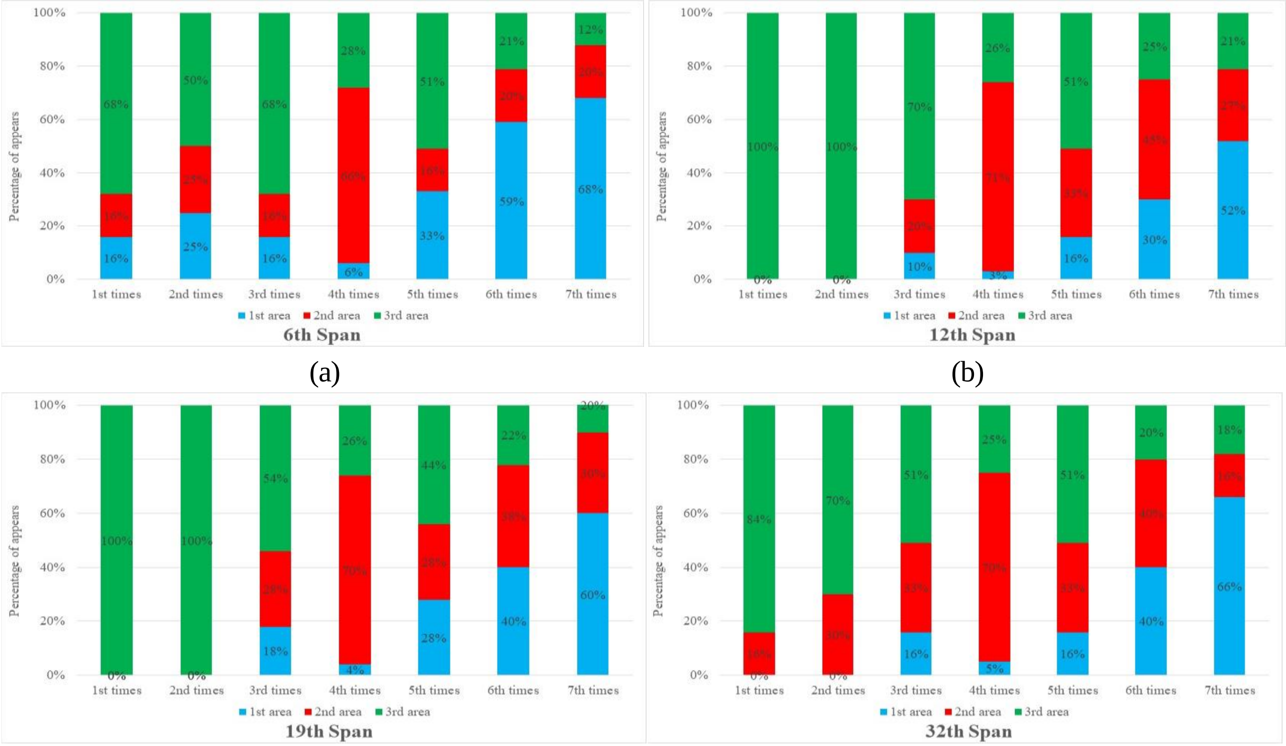


Figure 2. The PSD with structural steel material (third time).

3.1. The behavior of frequency regions in the spectral density function

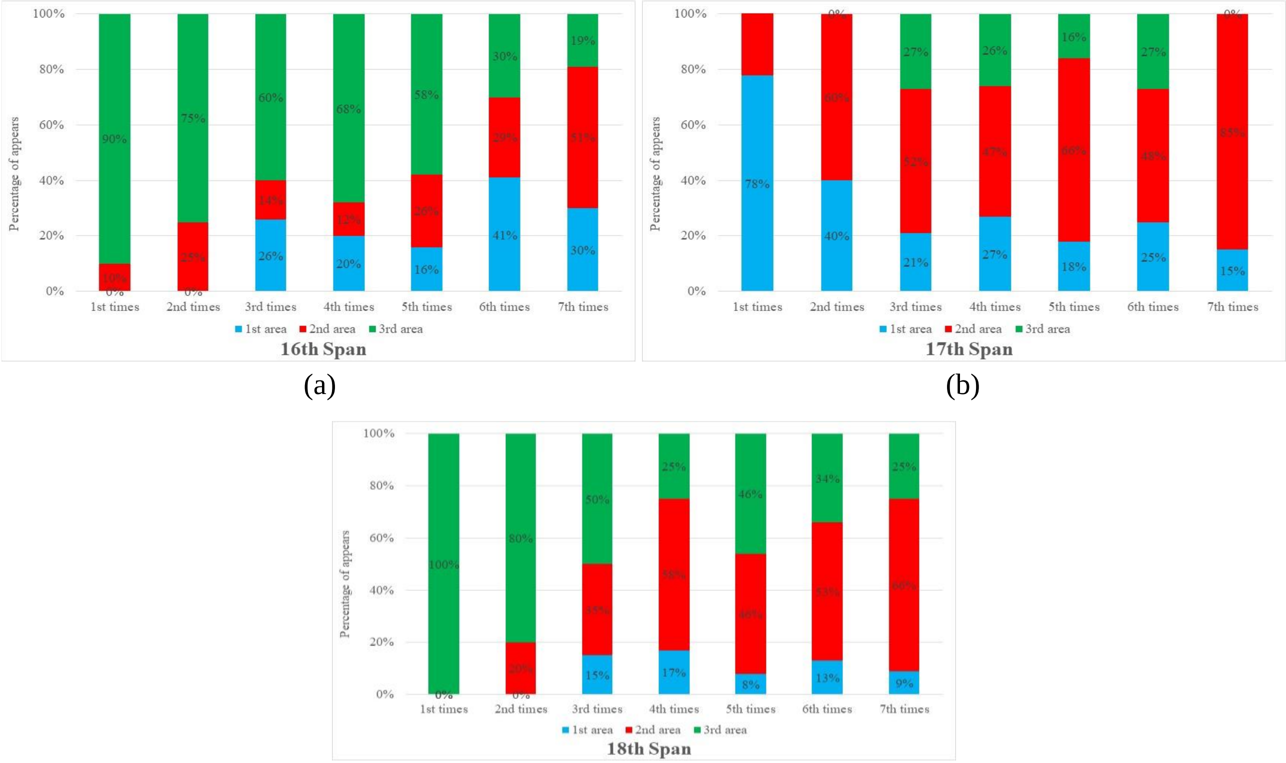
The article describes the results of a study on the PSD of different structural materials (prestressed concrete and structural steel) of the Saigon Bridge over a period of five years. Multiple resonance regions were observed during the measurement times, with some PSDs having one, two, or three resonance regions. Fig. 1 and Fig. 2 illustrate the distribution of the resonance regions for the two materials. The data indicated that over the five-year monitoring period, there was a significant decrease in PSDs with two or three resonance regions and a corresponding increase in PSDs with only one resonance region, despite the constant traffic load. Therefore, the study suggests that the likelihood of PSDs containing resonance regions at high frequencies will decrease over time, replaced by those with only one resonance region.



(a) (b)

(c) (d)

Figure 3. Rate of change between regions in the spectral density function on prestressed concrete structure



(a) (b)

(c)

Figure 4. Rate of change between regions in the spectral density function on steel structure material.

During the monitoring period, the probability density functions (PSDs) with four resonance regions for the concrete span and five resonance regions for the steel span on the Saigon Bridge changed significantly. According to the mechanical theory applied to identifying the changes in the structure, continuous traffic load passing over the span can lead to a decrease in the span's bearing capacity over time due to the aging and wear and tear process, resulting in a reduction in high-level harmonic resonance regions. Moreover, the theory also predicts that the traffic load's vibration power (people and vehicles passing over the bridge) will shift its energy from high-frequency regions to lower-frequency regions until there is only one frequency region left. Figs. 3-4 compared the changes of resonance regions on the spans between steel and prestressed concrete materials of the Saigon Bridge. The results showed that the probability of the highest-frequency region changed more quickly than the lower-frequency regions in the same material structure. However, if comparing two different structures during the same period, the prestressed concrete span model changed much faster than the steel span, which is consistent with the properties of the materials since steel has a longer destruction time compared to concrete. Therefore, this study proposes a new method to evaluate the bearing capacity and monitor the status of a bridge's span during operation using the moment model of the PSD.

3.2. The process of energy transfer of frequency regions in the power spectral density.

This study examined the changes in the shape of resonance regions on the Saigon Bridge as a measure of the change in its structural stiffness. By analyzing the area value of these regions in the power spectral density (PSD), the study showed that this parameter is highly sensitive to structural changes. Random vibration data were collected from a sensor system at different points along the bridge's length. The study determined the area values of the resonance regions by dividing the frequency ranges into 2 Hz widths to observe changes in each region's area. In mechanical engineering, the area value of a resonance region reflects the total vibrational energy of the harmonics within the frequency range. Tracking the change in the area of the PSD over time can determine the level of energy change. Figures 5-6 provide a visual representation of the area changes in some of the Saigon Bridge's spans with different structures. These findings can aid in evaluating the bridge's bearing capacity and monitoring its structural integrity during operation.

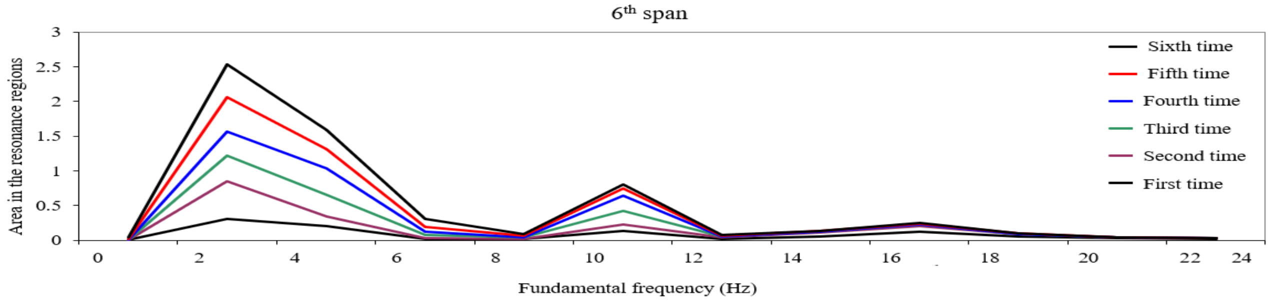


Figure 5. PSD area changes on the 6th span Saigon Bridge.

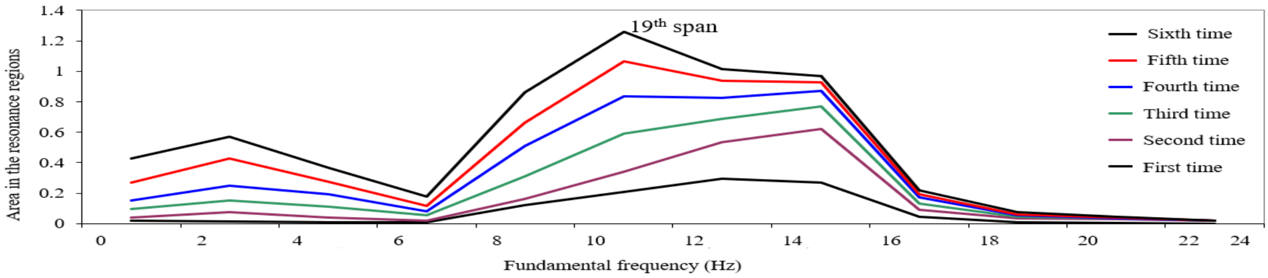


Figure 6. PSD area changes on the 19th span Saigon Bridge.

According to the analysis of random vibration data to form the power spectral density function, changes in the area of resonance zones have revealed some interesting observations and significant implications in determining, evaluating, and predicting changes in the structure over time. For all spans with reinforced concrete materials on Saigon Bridge, the area of high-frequency zones will continuously decrease over time (zones with frequencies above 12 Hz). This indicates that the energy transition process in this area is rapid. Conversely, in low-frequency zones (below 12 Hz), the energy conversion from high to low frequencies is unclear, and the area reduction process in this zone is relatively low. In the case of spans with steel materials, the area in high-frequency ranges also decreases continuously over time, similar to concrete spans. However, the area in other zones (low frequencies) tends to increase slightly. These results have provided valuable insights into the dynamic behavior of different structural materials under operating conditions and may support in evaluating the health and condition of the bridge.

During the monitoring period, the area of the highest frequency resonance (the fourth area) decreased significantly. The fourth area initially had a high energy ratio of about 45% and 35% in the first two measurements in December 2011 and February 2012 and peaked at around 17 Hz. However, in subsequent measurements, including the third measurement in May 2012 and the fourth measurement in August 2012, the area of the fourth resonance decreased significantly to below 7%, indicating that the energy transition of this area had shifted to the second or first resonance area. Unlike the first resonance area, the second resonance area did not show a corresponding increase in a short period of time. From the fifth measurement in July 2015 to the sixth measurement in October 2016, the area of the second resonance decreased significantly, while the area of the first resonance increased rapidly. In the sixth measurement, the common dynamics of the third resonance area in the PSD became very small or non-existent, indicating that the energy was concentrated in the first resonance area and transmitted from the high-frequency areas to the low-frequency areas. Therefore, the area value can provide valuable information about the operational status of the bridge, especially when the load-bearing capacity of the beam decreases.

4. Conclusions

The study conducted led to the following conclusions:

- The PSD measurements showed that multiple resonance regions coexisted simultaneously, and a real vibration graph was generated for each dataset.
- Over time, the likelihood of PSDs containing high-frequency resonance regions decreased and was replaced by PSDs with only one resonance region, even though the traffic load remained constant. The study's innovative contribution is a technique for evaluating the bearing capacity and keeping track of a bridge's span's status during operation.

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