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Evaluating and identifying the decline stiffness spans by moment of the power spectral density

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Abstract

This article proposes a new method which can be used in order to evaluate the mechanical responses of the spans. In fact, this method can monitor the stiffness degradation of spans through the time. These monitoring processes will be conducted at different measuring points on spans, different spans within the same measuring period, or within different measuring times. The obtained results show that the application of algorithms of cumulative functions of moments on power spectral density has brought many positive preliminary outcomes in evaluating the quality of projects during their operational period. The study also shows that this cumulative function allows us to identify the dangerous points on spans or on different dangerous spans of a bridge.

Keywords: Span, Monitoring, Cumulative Functions, Bridge, Power Spectral Density

1. Introduction

These measurement systems are called Structural Health Monitoring (SHM) systems as shown in N. K. Ngo *et al.* (2020) [4]. 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 attracts the attention of many scientists in the world, so the data mining in this field is a group of vibration-based damage detection (VBDD) like T. Q. Nguyen *et al.* (2020) [5]. The basic idea of VBDD methods is that modal properties including natural frequencies, mode shapes and damping are a function of the physical properties of the structure including 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 by. The primary response parameters, parameters affected by a change in the physical properties of a system to the health condition of a structure, are identified. These parameters are also known as damage-sensitive features. The general methodology for detecting damage in structures is to extract meaningful features from the measured data. The features are then monitored in order to detect changes due to damage. With the current trends of vibration based SHM, the impact of the environment can cause changes in the monitored features of an order of magnitude equal or greater than the damage detected. The first phase consists of extracting features strongly sensitive to damage but not very sensitive to the variability of the system and its environment. As an alternative to the current local inspection methods, global vibration-based methods have been widely developed over the years as T. Q. Nguyen *et al.* (2021) [6]. For monitoring of the bridges, actual and future trends in this domain are the use of vibration signals under ambient, unknown excitation due to wind or traffic (output-only data), and the use of very large arrays of sensors (towards the concept of "smart dust"). In the last phase, the relationship between variation of the features and the changes of structure is studied. This study is in the pattern recognition group. The stage is the use of mathematical models as modeling and analyzing a non-existing component of structural systems. The solution in this approach is with model-based methods. The second stage is the use of signal processing of measured responses that will determine the feature, and is called non-model based methods. The feature of model–based methods include deformation, deflection (static), fundamental frequency, mode shapes, mode curvatures, modal strain energy, dynamic flexibility, damping. The parameter selections can be made dependent primarily on two factors: the ability to measure and the level of sensitivity. The first factor shows easily received signals and is cheap. According to the feature shown from vibration data that can be the most appropriate.

In recent years, accelerometers have been used extensively for bridge dynamic monitoring because of low cost and convenience. Accelerometers can be used remotely in the different locations and do not need to determine offset value as strain gages, displacement sensors, etc. Model–based methods identify damage by comparing the value of the feature between the original undamaged state and the current condition. The different values of this feature are the damages. Most methods require a baseline from the undamaged structure, or from a theoretical model (e.g., finite element) of the structure by Colin Ratcliffe *et al.* (2008) [1].

Disadvantages of the model-based methods are difficult to model with real structures, and deviation of the simulation is often greater than deviation of the damage. In the dynamic feature, the fundamental frequency is used more than the other features because it is very easy to extract from the acceleration signal. However, the fundamental frequency is the least sensitive parameter. Vibration signal of the bridge is collected from measured responses to various forms of excitation, including harmonic forced excitation induced by a shaker, impact force excitation by dropping a weight, releasing a force or impact from a hammer, random forced excitation due to traffic, different types of model of truck excitation, free damped vibration of the bridge after random and truck excitation or ambient excitation due to wind and river flow. C. R. Farrar *et al.* (2000) [2] studied the variability in modal parameters related to the excitation source using statistical methods. Field results obtained from a hammer impact test were compared to those obtained from ambient vibration tests. It was also determined that ambient excitation could not identify all the modes that the impact hammer could because of the deficiency of some frequency ranges in the input power spectrum. Zhang (1994) [3] found that the modal data obtained from the impact test were of lower quality compared to those obtained using harmonic forced vibration. However, for large mechanical systems such as the cable-stayed bridge and overpass bridge, to create the harmonic vibration is very costly and difficult. In practice, the most readily accessible sources of dynamic excitation for bridges are traffic and/or wind loading, both of which are random in nature and difficult to quantify. However, the research using this excitation does not require costly. The vibration signal caused by traffic has more advantages than damped vibration and harmonic vibration because it contains more information and the actual behavior of the mechanical system. The view of the methods using power spectrum density is that damage does not affect the energy distribution between the frequencies. The damage is not only shown by the change of stiffness but also by different interconnectedness of the materials. Our research proposed the appearance frequency of harmonic in power spectrum density as shown by T. Q. Nguyen *et al.* (2020) [5] and Lam Q. Tran (2019) [8]. Our research proposed the moment of the power spectrum density that was limited by a graph of PSD with *x*-axis as area phenomenon damage and degradation of the mechanical system. This research shows the sensitive feature in identifying the decline of the bridge stiffness.

2. Materials and methods

The density function in statistical theory points out the distribution of the spectrum amplitude values in the time domain. In the frequency domain, the spectral density function also shows that the energy distribution is satisfied in the frequency domain. The concept of spectral moment *SM* is proposed to investigate the energy distribution characteristics of the signal in each frequency domain

$$SM_{(n)} = \int_0^{\infty} |\omega|^n S_w(\omega) d\omega \qquad (1)$$

in which, $SM_{(n)}$ is the n^{th} spectrum. In the case of the characteristics of the output signal there are many variables such as the decline of beam stiffness problems. Previous studies only stop at defined load objects, which means that the effect load must be completely under control. In our study, we developed this parameter based on the actual survey at the bridge span. In addition, the study listed the featured spectral moment value in assessing the structural stiffness decline. These new proposals include:

- Spectral moments can be calculated in time domain, frequency domain or both in time zone and frequency space. Hence, the concept of Spectral moment is greatly flexible when using the responses in different measurement systems. This creates an opportunity for investigating in a period of time and for applying these health monitoring systems in form of continuously.
- Spectral moment is suitable for both linear and nonlinear problems. Hence, for the main linear model, there are changes in the physical properties of the structure such as mass, stiffness, and damping. On the other hand, when applying to the nonlinear model, these changes are not necessarily caused by changes in the stiffness of materials or the variation of certain parameters, instead the reason of this change is attributed to physical phenomena and dynamic characteristics.
- Spectral moment provides the energy information of the frequency range during the active span. It is almost impossible to use frequency parameters such as natural frequency regarding nonlinear problems. Spectral moment provides information of the frequency range so it describes the characteristics that meet the more generalized structures than response frequency. Moreover, the spectral moment is also incredibly flexible in determining the crucial characteristics of the signal.
- Spectral moments can be calculated from the frequency response function if both the input and output of the system are obtained from the power spectral density function. Therefore, stimuli from natural vibration such as circulation, wind, and tremor can still be used.
- Spectral moment does not depend on the vibration phase effect which will preserve the important properties of the signal. The analyzes, therefore, will not significantly affect the spectral moments.

In Eq.(1), when the coefficient n = 0, the expression becomes the formula for calculating the flat area, it will be created by the power spectrum graph with the frequency axis. We call this the spectrum area or *SSM* spectral moment

$$SSM = \int_{-\infty}^{\infty} S_w(\omega) d\omega \qquad (2)$$

Static moment of a power spectrum is defined when constructing an axis perpendicular to the frequency axis that will divide the spectral graph into 2 regions of equal area as shown in Fig 1. Then, the value of *SSM* is determined by Eq.(3)

$$\int_{-\infty}^{\omega} S_w \, d\omega = \frac{1}{2} \int_{-\infty}^{\infty} S_w \, d\omega \qquad (3)$$

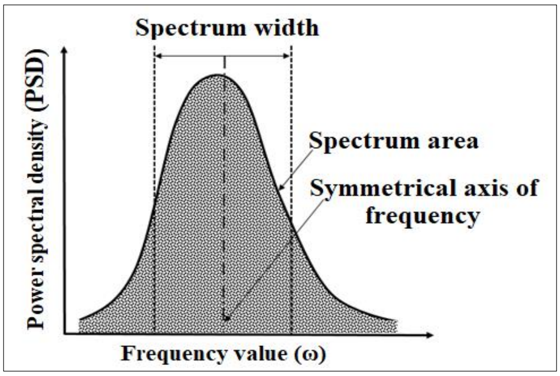


Fig 1: Some characteristics of the power spectral density shape

3. Results and discussion

The PSD moment (PSDM) was calculated by the vertical axis ($\omega = 0$ – symmetrical axis of frequency) of the PSD graph and the resonance region acreage as shown in Fig 2. To represent change in shape of magnitude of the vibration spectrum, we surveyed the magnanimity PSDM of the all Saigon Bridge`s spans in each frequency ranges about 2 Hz. In terms of mechanics, the PSDM value will represent the transmission of vibration energy that becomes fast or slow of harmonics on the resonance region survey. From Fig 2 to Fig 6, this is the PSD moment graph of the equal frequency intervals about 2 Hz of some Saigon Bridge's spans.

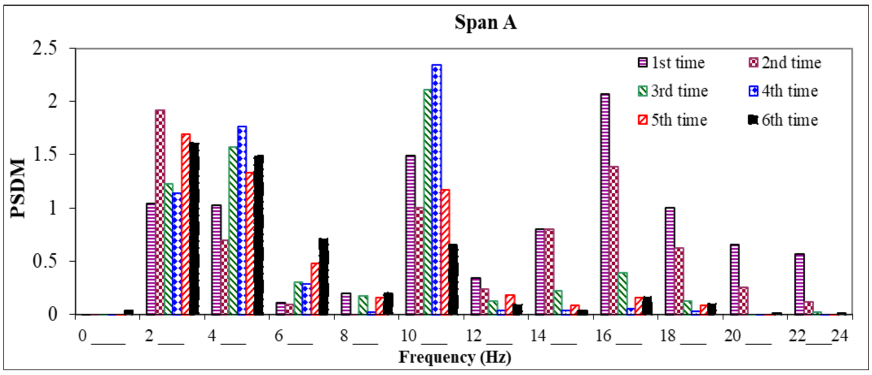


Fig 2: The PSDM change of Saigon Bridge's span A

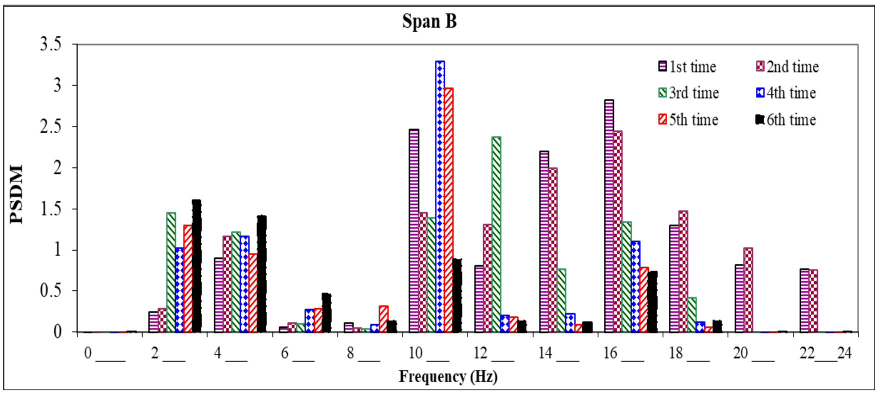


Fig 3: The PSDM change of Saigon Bridge's span B

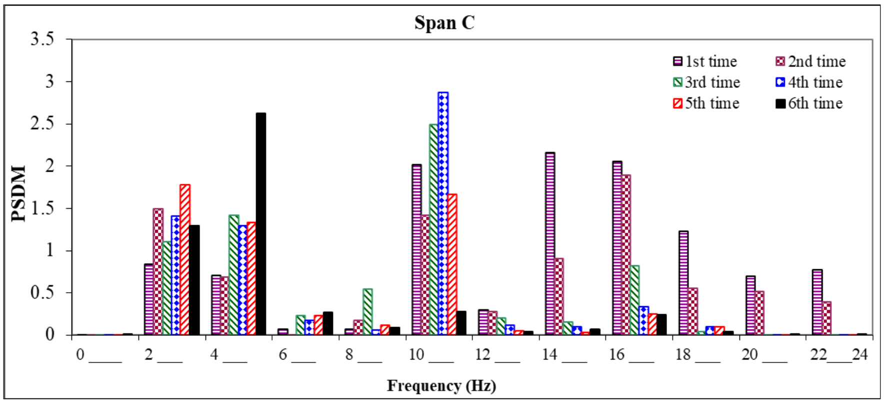


Fig 4: The PSDM change of Saigon Bridge's span C

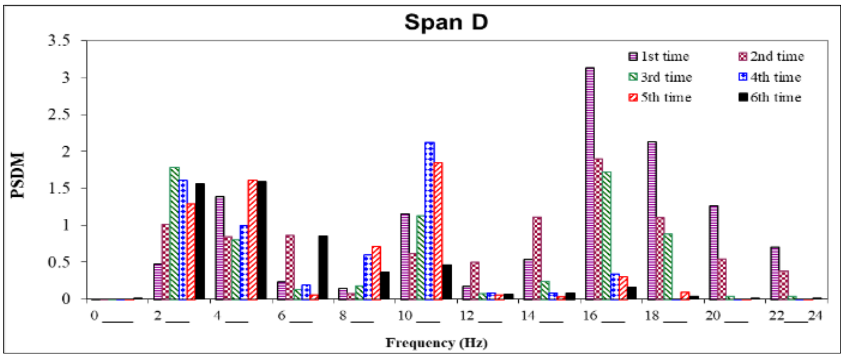


Fig 5: The PSDM change of Saigon Bridge's span D

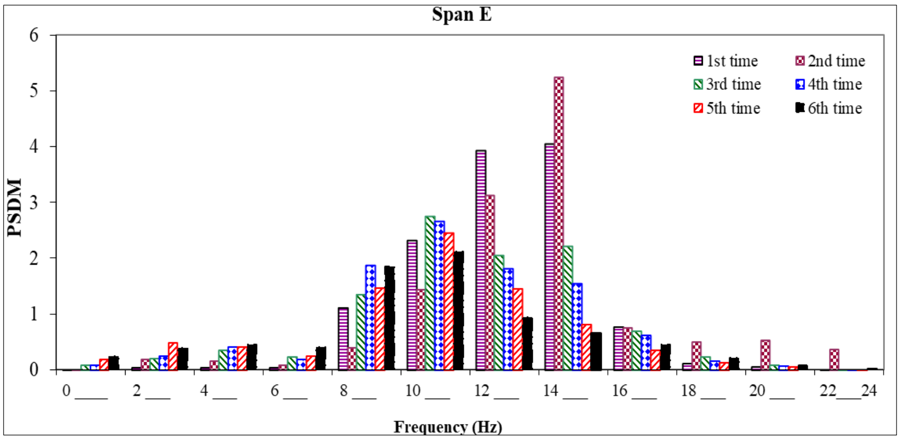
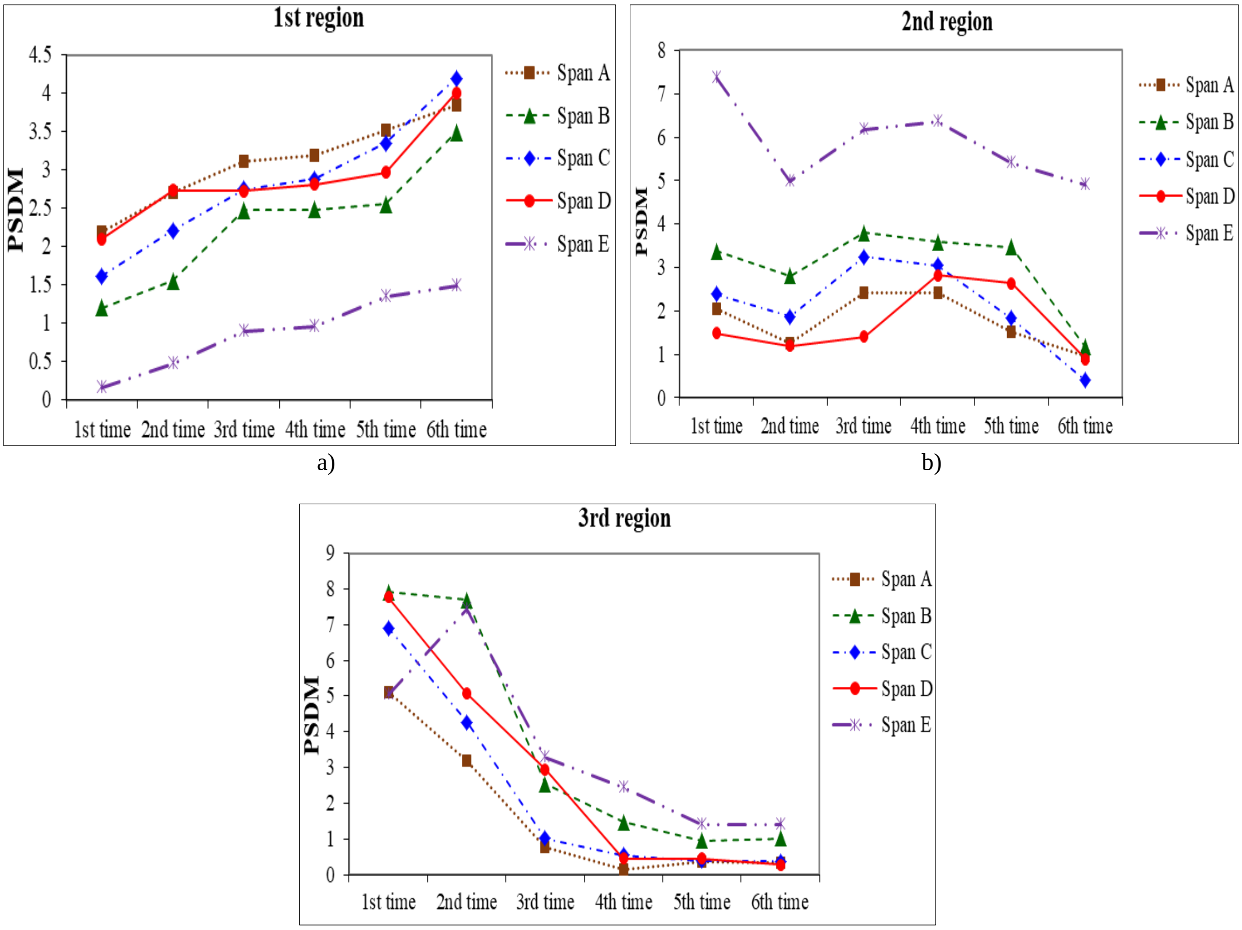


Fig 6: The PSDM change of Saigon Bridge's span E

It can see that the PSDM graphs have a similar shape with the SSM graph at all three resonance regions. However, the change of PSDM over the given period clearly significant than SSM value, including:

- The PSDM value of the first resonance region witnessed an upward trend while the third resonance region experienced a downward trend during the operation time of the bridge.
- The PSDM value of the second resonance region did not change co-variable over time scale; however, in the last of three measurement times, the PSDM value of the second resonance region saw a marked reduction.
- The PSDM value in the first and third resonance region was significantly co-variable, so we would easily use this value in monitoring degradation. Moreover, using PSDM value would be a more general SSM value because it can clearly be used to transmit vibration energy from high frequency region to low frequency region.



a) b)

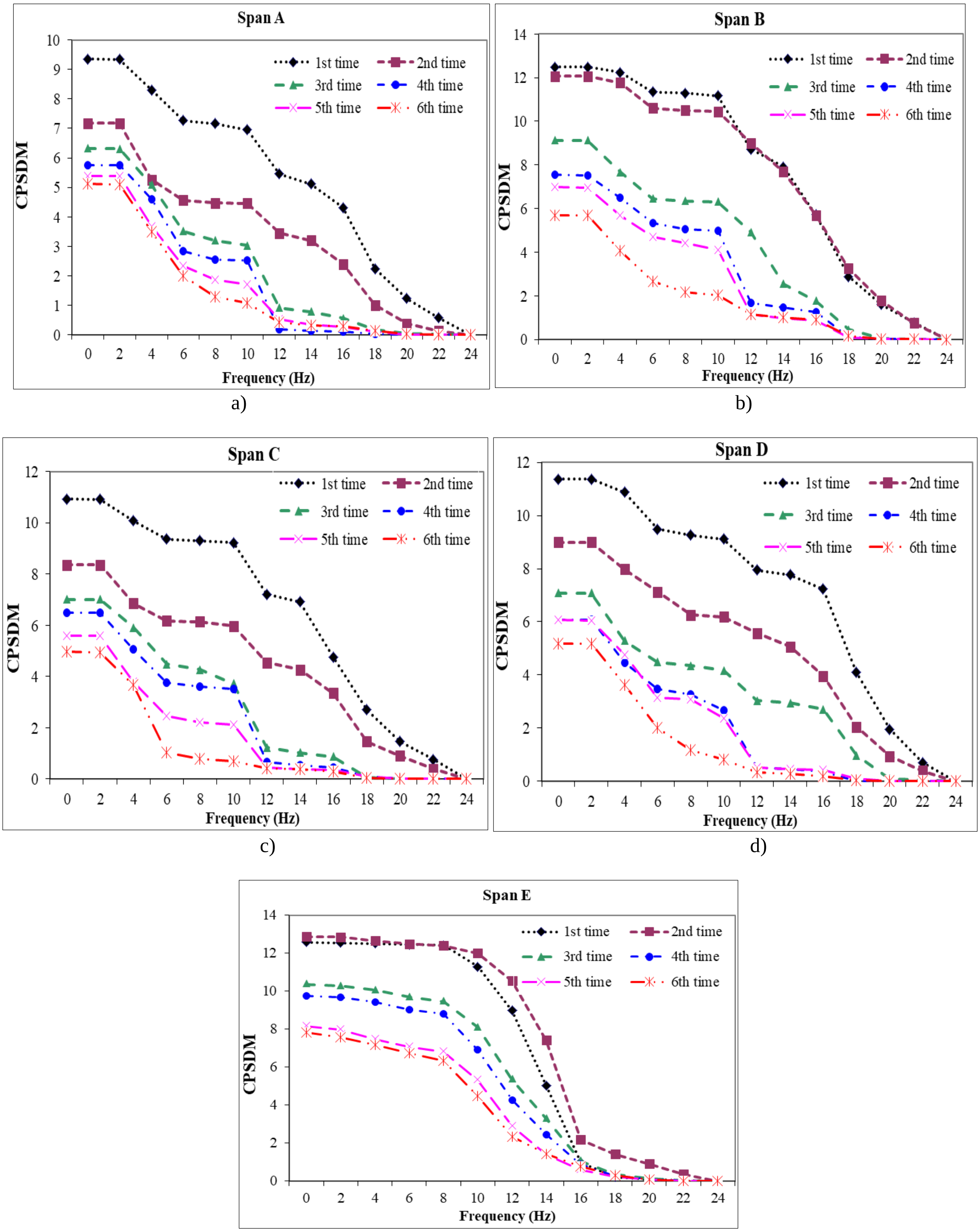
c)

Figure 7: The PSDM with resonance regions of some spans on Saigon Bridge

Although the PSDM value of each resonance region as shown in Fig 7 will allow to monitor the change of spectrum share over the given period, the degradation by this value is only evaluation of impairment in each vibration share. This means that the PSDM value does not allow the overall evaluation of the structure. According to the survey of the PSDM value on some spans, we can see that their value of each bridge`s span on the third resonance region differently declined, for example with the PSDM value of the most spans like A, C and D in last measurement time is very small; however, the others spans (B and E) is still significant value. So, there is the difference in evaluation of impairment between each span over the different measurement times. To assess overall impairment of the spans, we propose to use the cumulative function of PSDM value (CPSDM), the CPSDM function is calculated by the expression (4):

$$CPSDM(\omega) = \int_{\infty}^{\omega} PSDM(\omega)d\omega \qquad (4)$$

On Fig 8, this is the cumulative function graph of some Saigon Bridge`s spans with the different measurement times.



a)

b)

c)

d)

e)

Fig 8: The cumulative function graph of some Saigon Bridge`s spans

- With span A, B and C, there is a similar structure material, according to the graphs as shown in Fig 8, the CPSDM functions show clearly the difference between the measurement times. It can see that the cumulative rule of the spans is similar to each other. These mean that the CPSDM graph will be shown clearly more sensitive than SSM value or PSDM graph.
- The CPSDM graph of the before measurement times are always located below the after measurement times. This rule fixes both concrete and steel structure material spans. Evidence shows that the CPSDM function can a general parameter to monitoring degradation of the bridge.
- During the first 4 times of measurement, approximately three months per measurement time, the CPSDM function graph changes less than the last 2 times of measurement, around over 1 year per measurement time. Therefore, these CPSDM will be sensitive with the operation time because the bearing capacity of the span depends on the operating time.
- Inclination curve of cumulative function will express the PSDM magnitude value and the characteristic of mechanical behavior of bridge`s span. Areas have the high inclination of cumulative function to indicate that the PSDM has the high value. In Fig 8, there are three regions with inclination as 2÷6 Hz; 11÷12 Hz; 14÷24Hz in the first measurement time as 11/2011. Over the given period, the inclination curve of cumulative function of the resonance region at the highest frequency witnessed a downward trend while the region at the lowest frequency experienced an upward trend. These reasons show that the CPSDM function of the different spans are difference and there are conditions to determine or compare the degradation between the spans.
- After 3 months, the CPSDM function of some spans were very different. To compare with other common using parameters to monitor the degradation of the bridge as frequency parameter (change 6%, and shown in Fig 9), damping coefficient, eigenvectors, the CPSDM function value were more sensitive about over 50% between the first and the last measurement time, approximately 5 years. On the other hand, with the vibration signal, the CPSDM function value was more stable than individual frequencies or fundamental frequency because the CPSDM value steadily decreased while frequency value witnessed a slight fluctuation followed by a minimal decline from the first measurement time to the last measurement time.
- In this study, the research direction used the CPSDM function value to monitor the degradation of the bridge`spans that was a significant decrease over the given period as Fig 9. We can see that the CPSDM value dramatically declined between the first and the fourth measurement time on Saigon Bridge around one year, from 2011 to 2012. However, in the last two times, this value was a slight reduction over 4 years. This cause of the phenomenon shows that the Saigon Bridge's span was slightly repaired in 2012. In 2014, the second Saigon Bridge was built and operated. It help the old Saigon Bridge to reduce the traffic flow, so, the degradation level

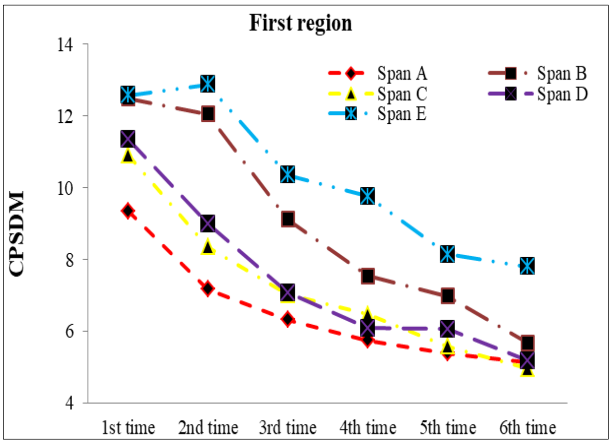


Fig 9: The CPSDM value of some Saigon Bridge's spans in 5 years

Graphical Abstract

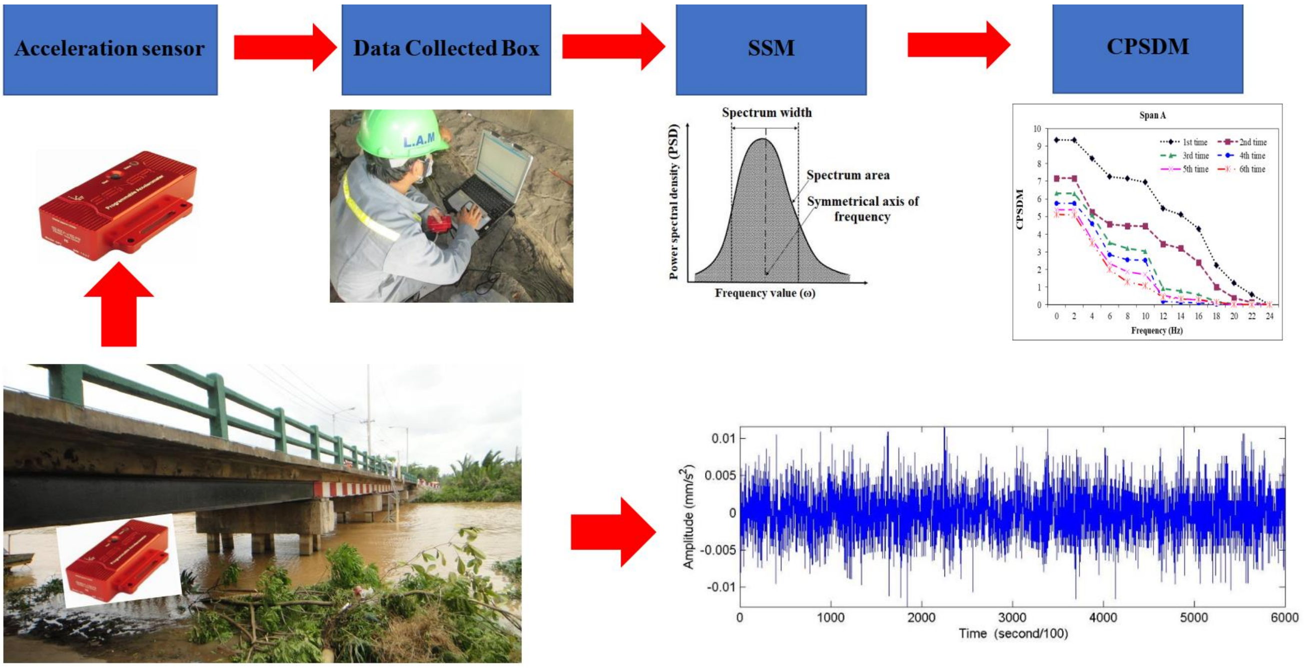


Fig 10

4 Conclusion

The article has proposed the theoretical construction to determine the price of the power spectrum for the *Ox* axis. From this, the research also examined the values of this spectral moment through mathematical accumulation function and is called the moment accumulation function. The results obtained is outstanding:

The lowest vibration frequency measured on different positions of the same span has the same value. However, their power spectral shape may be the same or different. In specific, if their behavior is similar in terms of the mechanical properties of materials, equivalent in terms of stiffness and the level of stiffness degradation over time, the power spectrum form is equal. However, there is always a difference in the shape of the power spectrum across each measurement at different locations in the same span, or different span in the same bridge.

To evaluate the change in geometry on the power spectrum, we use the concept of the spectral moment and the cumulative moment function to identify the differences between measurement points on the same span and between different spans in the same measurement. The change of this momentary accumulation function is the basis for calculating the difference between different measuring points on the same span and the different measuring spans on the same bridge. This suggests that the sensitivity of this moment accumulation function is higher than other parameters in the evaluation of structural stiffness decline.

When evaluating behavior at different points on the same span, the moment accumulation function has shown superiority when fully and accurately evaluated compared to parameters that use other methods. However, the evaluations are only the initial results with a small number of spans, the next research direction will be conducted and distributed in a large number of spans to comprehensively evaluate this parameter.

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