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HYBRID STRUCTURE HEALTH MONITORING TECHNIQUE FOR ENHANCING MODAL PARAMETER IDENTIFICATION ACCURACY.

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1. INTRODUCTION

SHM relies on the possibility of estimating structural modal parameters, such as mode shapes, natural frequencies, and damping, from the structure's measured data. Nevertheless, modal parameter estimation still faces accuracy problems. The identification of bridge and/or vehicle system parameters and vibration characteristics have been studied both numerically and experimentally. The knowledge of bridge vibration characteristics and vehicle system parameters is crucial to the maintenance of bridges. The issue is that the techniques used to identify bridge and vehicle system parameters usually work very well with numerical simulation but present accuracy issues with experimental data due to environmental noise.

Traditionally, measured data were obtained by instrumenting bridges with connected sensor systems, which had issues such as high cost, maintenance problems, safety concerns, and traffic disruption. More recently, indirect SHM (iSHM) methods, such as drive-by using passing instrumented vehicles, have been researched[1,2]. However, these methods still struggle with the accuracy of modal parameter identification, particularly for higher vibration modes sensitive to localized bridge damage, limiting the widespread adoption of iSHM methodologies[1,3].

A combination of indirect and direct monitoring methods is proposed to address these limitations. This approach aims to improve modal parameter identification, including higher vibration modes, for localized damage detection and structural assessment. The proposed method uses GPS-time synchronized sensors for simultaneous measurement of vehicle and bridge vibration data and is verified through numerical simulation assuming multiple runs over the same bridge. The study highlights the potential of this hybrid SHM technique to significantly improve the accuracy of indirect structural health monitoring, providing more reliable and precise modal parameter estimates, especially for higher vibration modes, allowing for the identification of localized bridge damage.

1.1.Basic theory of bridge frequency estimation

The structure health monitoring technique used data collected directly from the structure. For the last decades, an indirect structure of health monitoring has been investigated. It is confirmed that the bridge's natural frequency can be found in the response of vehicle crossing it [2]. This means it is possible to identify those frequencies by simply processing the vehicle's acceleration data by Fourier transform.

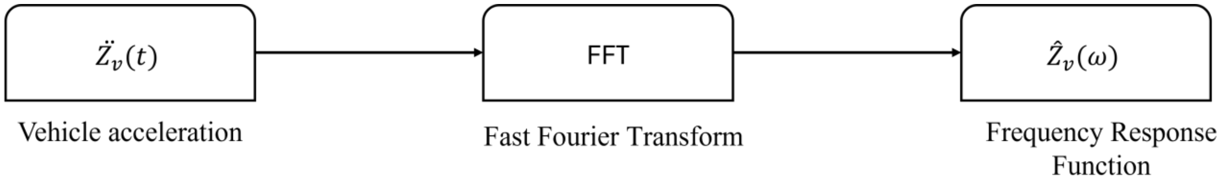

Figure 1. Vehicle acceleration data frequency analysis.

The application of the Fourier transform to the equation of motion of the vehicle, equation 1, enables the calculation of FRF as follows.

$$m_v\ddot{z}(t) + c_v\dot{z}(t) + k_v z(t) = f(t) \tag{1}$$

$$\hat{Z}_v(\omega) = \mathrm{H}(\omega) * \mathrm{F}(\omega) \tag{2}$$

Where $\mathrm{H}(\omega) = \frac{1}{m_v\omega^2 - c_v i\omega + k_v}$ is the frequency response function whereas ω is the angular frequency.

$$H(\omega) = \frac{F(\omega)}{\hat{Z}(\omega)} = \frac{-\omega^2 F(\omega)}{-\omega^2 \hat{Z}(\omega)} = \frac{-\omega^2 F(\omega)}{\hat{\ddot{Z}}_v(\omega)} \tag{3}$$

However, this is only possible for the first natural frequency while this simple treatment can not identify higher bridge vibration frequencies. Figure 2 shows the identified first natural frequency from the numerical simulation of the VBI system with the vehicle moving at 90km/h which is a remarkably high speed for vibration-based SHM-based realization. It is observed that the resolution of the identified frequency depends on the vehicle's speed. Depending on the signal used, the identified frequency is more pronounced in the case of sprung mass acceleration data since the effect of road profile is minimal.

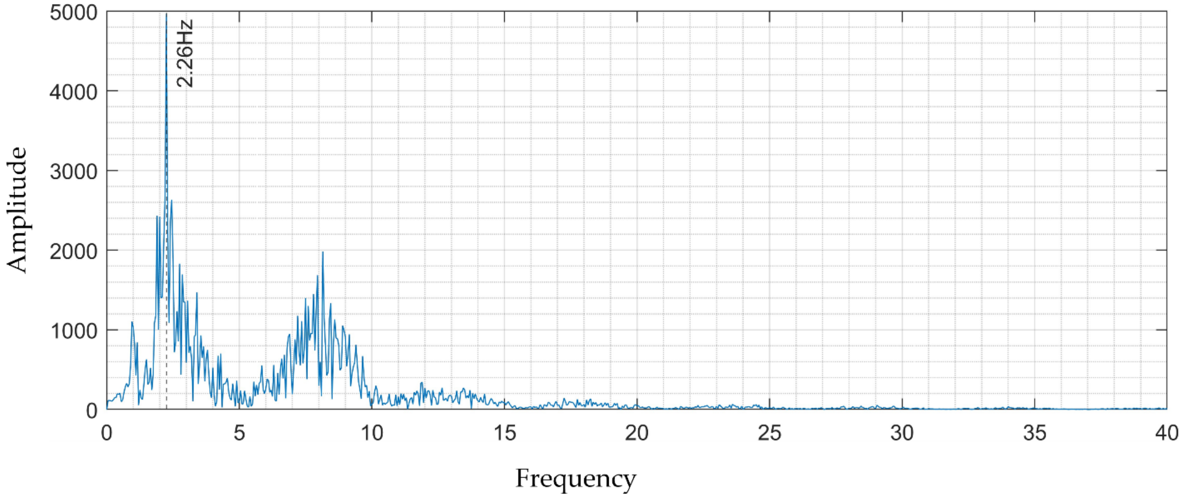

Figure 2. Vehicle acceleration spectrum: Sprung mass.

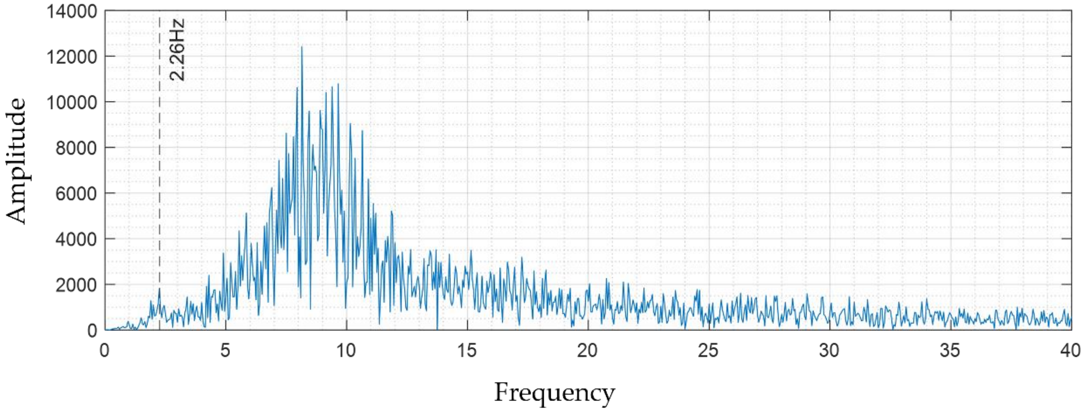

Figure 3. Vehicle acceleration spectrum: Unsprung mass.

a. Bridge Response-Only Based Bridge Natural Frequency Estimation Method

Bridge natural frequencies can be identified from its vibration data by directly applying a fast Fourier transform. The following equation describes the dynamic vibration of a simply supported bridge.

$$\rho A\ddot{y}(x,t)+\frac{\partial^2}{\partial x^2}EI\frac{\partial^2}{\partial x^2}y(x,t)=-\sum_{i=1}^{n}\delta\big(x-x_i(t)\big)\big\{m_{si}\big(g-\ddot{z}_{si}(t)\big)+m_{ui}\big(g-\ddot{z}_{ui}(t)\big)\big\} \tag{4}$$

where x is the position along the bridge, t is time, ρ is the mass density of the bridge, A is the cross-sectional area, E is the Young's modulus, I is the inertia moment, m_{si} is the mass of i^{th} sprung mass of the vehicle body, m_{ui} is i-th unsprung mass of the vehicle, g is the gravitational acceleration, $\ddot{z}_{si}(t)$ is the vehicle's sprung mass vertical acceleration, $\ddot{z}_{ui}(t)$ is the vehicle's unsprung mass vertical acceleration, $y(x,t)$ is the bridge's vertical deflection, and $\ddot{y}(x,t)$ is the bridge's vertical acceleration vibrations. The above equation is transformed, by the Galerkin method, to the general form of the equation of motion below.

$$\mathbf{M}_b\ddot{\boldsymbol{y}}(t)+\mathbf{C}_b\dot{\boldsymbol{y}}(t)+\mathbf{K}_b\boldsymbol{y}(t)=\boldsymbol{f}_b(t) \tag{5}$$

As in the case of vehicle vibration, the direct application of the Fast Fourier Transform enables the estimation of vibration frequency. The same concern remains, only the first natural frequency can be identified. The following are the results of numerical simulations of the VBI system.

As can be seen from Figure 4, the first natural frequency can be genuinely identified with the highest pick at 2.26 Hz. While the others, luckily seen, can be identified with low peaks. The author suggests a method to simultaneously use vibration data from both vehicle and bridge. This approach can enhance the accuracy of natural frequency identification, especially for higher modes of vibration. In typical Vehicle-Bridge Interaction (VBI) scheme field experiments, the bridge vibration data is often recorded to verify the results obtained from vehicle data. By adopting simultaneous measurement of both bridge and vehicle acceleration data, the resolution of higher modes of vibration can be increased. This dual-data approach provides a more detailed and reliable analysis of the bridge's dynamic characteristics, thereby improving the structural health monitoring process.

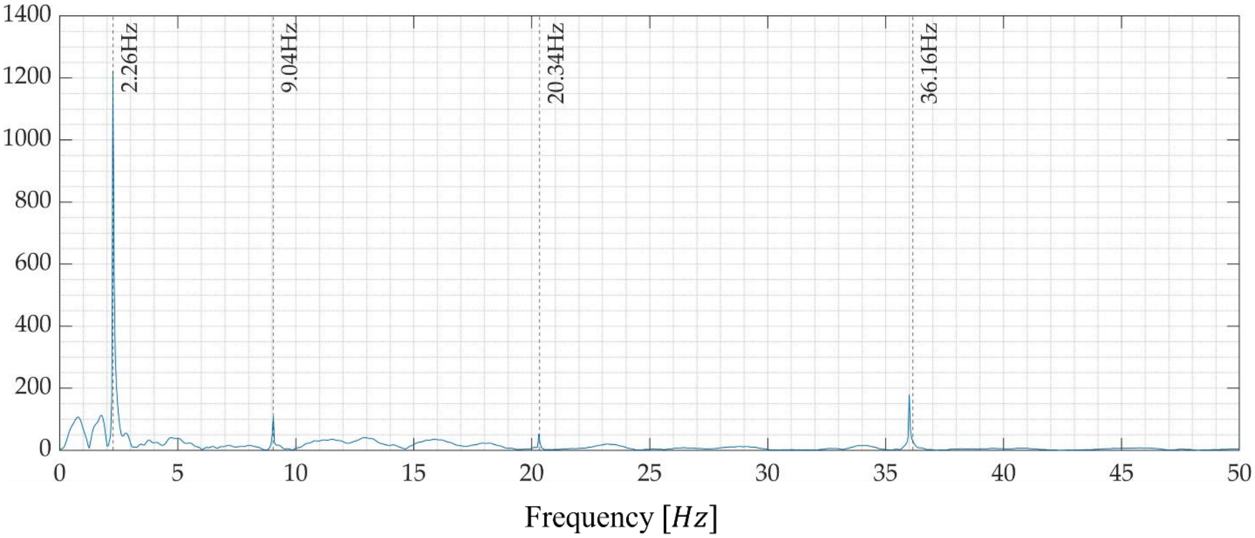

Figure 4. Bridge response-based frequency identification.

2. THE PROPOSED METHOD

2.1.Simultaneous-based monitoring

Simultaneous monitoring enhances the bridge's natural frequency identification by leveraging the acceleration data from both vehicle and bridge taken simultaneously. Equation 4 can be manipulated using the modal analysis theorem into equation 7.

$$\ddot{q}_k(t) + \omega_k^2 q_k(t) = \sum_i^n \frac{m_i}{M} \phi_k\big(x_i(t)\big) s_{vi}(t) \tag{6}$$

Where $\phi_k\big(x_i(t)\big)$ is the window function based on k-th mode shape of the bridge, $x_i(t)$ is the vehicle position, and s_{vi} is the sensor measurement of vehicle vibration given by the equation 8:

$$s_{vi}(t) = m_i\big(g - \ddot{z}_i(t)\big) \tag{7}$$

Where $\ddot{z}_i(t)$ is the measured vehicle acceleration, m_i is the vehicle mass, and g is the acceleration of gravity. This derivation assumes that vehicle vibration, bridge vibration as well vehicle position are simultaneously being measured. The bridge response in equation 4 can be expressed using modal coordinates as follows.

$$\ddot{y}(X_i, t) = \sum_{k=1}^{n_b} \phi_k(X_i) \ddot{q}_k(t) \tag{8}$$

$$F_k(t) = \sum_i^n \phi_k\big(x_i(t)\big) s_{vi}(t) \tag{9}$$

Where $\phi_k(X_i)$ is the window function or modal shape. The right-hand side of equation 7 expresses the input force to the bridge system. This force depends on the vehicle vibrations as it can be seen, rewritten as equation 9 with the influence of mass ratio being ignored.

The modal frequency is estimated as the ratio of the output and input of the system in the frequency domain. The numerical simulation of the above process is shown in the figure below.

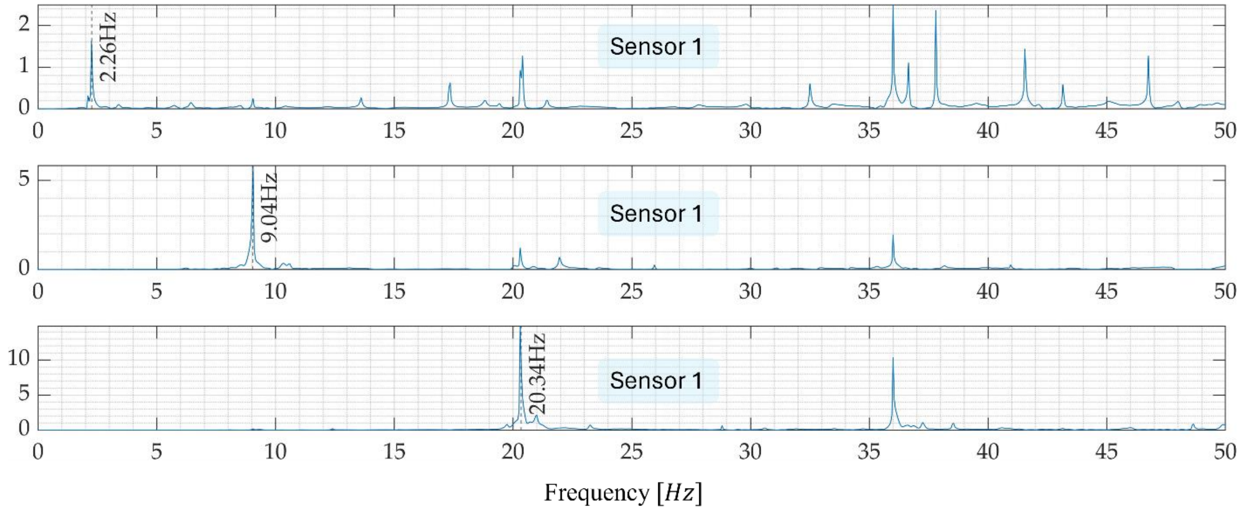

Figure 5. Simultaneous-based bridge frequencies identification.

Figure 5 shows that three different frequencies are identified using three sensors assumed to be attached to the bridge. Unlike the other methods mentioned above, the frequency determined by the simultaneous-based method has good resolution and can easily be identified.

3. FIELD EXPERIMENT

Field vibration measurements are conducted to verify the applicability of the proposed simultaneous method. The vehicle's front and rear axle vibration data are collected, and the bridge structure is equipped with bridge sensors at different locations. This section describes the result obtained by applying the proposed method to the measured data.

3.1.Vehicle Response-Only Based Bridge Natural Frequency Estimation Method

The vibration data recorded from a vehicle crossing a bridge is believed to contain information, such as the natural frequency, of the underlying bridge. This is essential to the drive-by bridge monitoring technology. This technology uses the interaction between the vehicle and bridge and extracts the bridge's vibration characteristics indirectly through the vehicle's responses. Studies have shown that, when analyzed correctly, the vehicle acceleration data can significantly provide information about the bridge it traverses[4]. As Figures 2 and 3 show, applying the FFT algorithm to the vehicle acceleration data identifies the bridge's first natural frequency[2,3,5]. The possibility of extracting the first natural frequency is the main foundation of the drive-by bridge monitoring. However, this methodology is not efficient when thinking about the extraction of higher modes of vibration which are linked to localized structure damage.

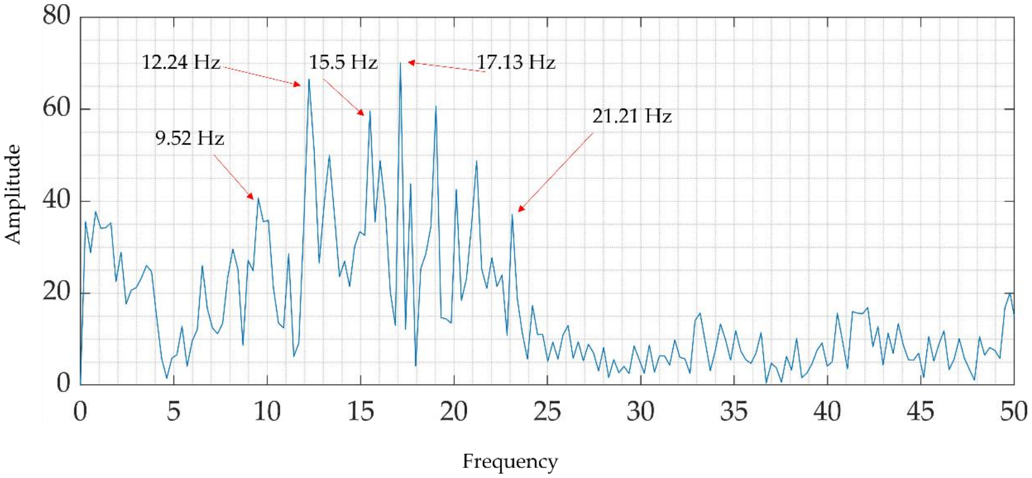

Figure 6. Frequency content of vehicle vibration data, FFT.

Figure 6 shows the result of measured vehicle vibration data frequency analysis using the FFT algorithm. Unlike the numerical simulation results where the first natural frequency is easily confirmed, it is very difficult to confirm whether the dominant peaks in the processed data are related to bridge vibration frequencies. This is primarily due to the lack of exact natural frequency information about the monitored bridge. In addition, the presence of many frequency peaks makes it difficult to decide.

3.2.Bridge Response-Only Based Bridge Natural Frequency Estimation Method

In the same way, the FFT is applied to the bridge vertical acceleration data. Unlike the vehicle vibration, the bridge vibration contains more prominent frequency peaks which are easily identified.

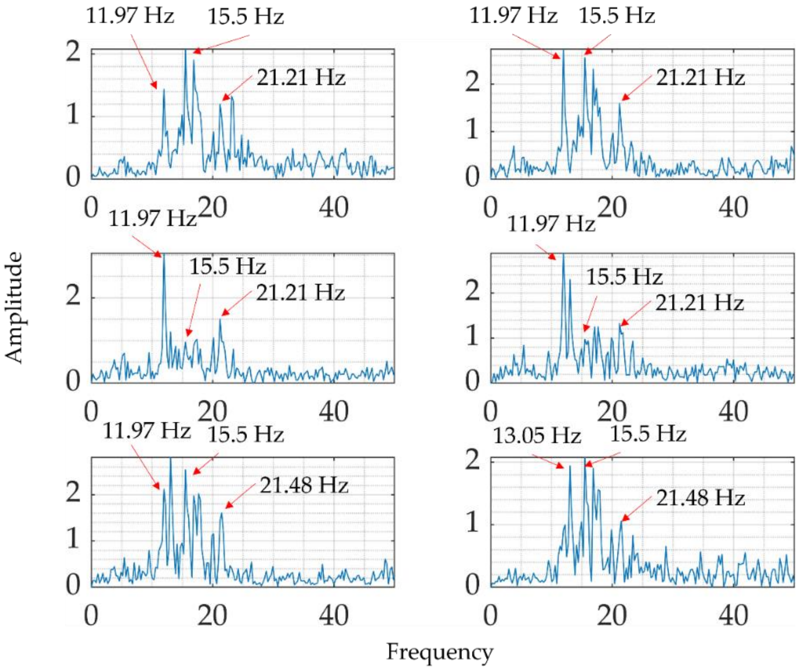

Figure 7. Bridge vibration frequency content, FFT.

Figure 7 presents the bridge vibration frequency content using the FFT algorithm. Each subplot represents one sensor data located at different locations along the monitored bridge. In total 12 sensors are installed with 6 sensors on each side of the bridge. As can be seen from these subplots, the 15.55 Hz frequency is present. This frequency consistently appears in all cases suggesting its stability and significance in the bridge vibration response. However, deciding whether it is the bridge's natural frequency is hard. In addition, many frequency peaks add difficulty to the conclusion.

3.3. Simultaneous Monitoring

Finally, the proposed method is used to analyze measured vibration data from both vehicles and bridges. It should be noted that they are simultaneously recorded. Figure 8 shows a predominant 16.59 Hz. From the information from Figure 7, it can be concluded that the first natural frequency of the monitored bridge is between 15 Hz and 17 Hz.

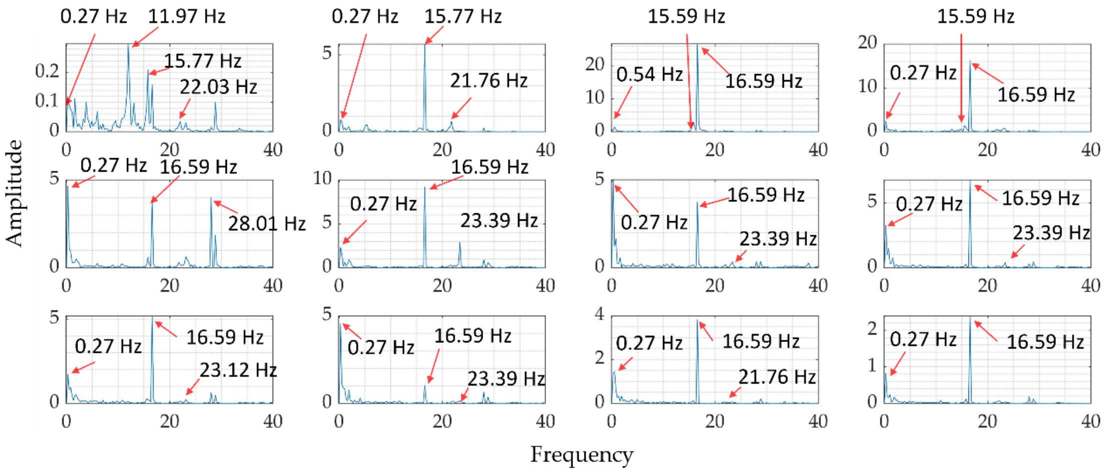

Figure 8. Modal FRF by the proposed method.

Besides the predominant frequency, Figure 8 also shows higher frequencies such as 21.76 Hz, 22. 03 Hz, 23.39Hz, and 28. These frequencies could correspond to the higher mode of vibration of the monitored bridge. This suggests that the simultaneous monitoring technique can identify the first mode of vibration and the higher modes of vibration. The low frequency at 0.27 Hz is believed to be related to the slow environmental factors or inherent low-frequency dynamics of the VBI system. In addition, the variation of amplitude of vibration suggests the effect of change of vehicle speed or bridge condition or higher damping effects during the experiment.

4. CONCLUSION

In this study, three methods of bridge’s natural frequency estimation from vibration measurements are compared. Both numerical and experimental studies are conducted. As the results suggest, the proposed simultaneous monitoring method identifies more modes of vibration compared to the methods of applying FFT directly to the measured vehicle or bridge vertical vibration data. Nevertheless, it is difficult to conclude that the identified frequency peaks correspond to the monitored bridge's natural frequencies since the exact values are not available for comparison. The same method may be tested on the experimental steel bridge with the known frequency of vibration for easy evaluation of this method.

In addition, the simultaneous monitoring reveals other underlying phenomena such as the fact that the speed of the vehicle is changing by looking at the variation of frequency amplitudes and the possibility of low-frequency events such as slow environmental factors or inherent low-frequency dynamics of the VBI system.

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