RESEARCH AND APPLICATION OF INDIRECT MONITORING METHODS FOR TRANSPORT INFRASTRUCTURES TO MONITOR AND EVALUATE STRUCTURAL HEALTH

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Abstract. Currently, bridge constructions in Vietnam, as well as in the world, are regularly monitored and evaluated to ensure safety in the exploitation process and to prevent damage. The traditional method of monitoring by geodetic tools through monitoring cycles often brings results with significant errors, thus not really representing the performance of the structure and potential damages on it. Recently, to overcome the factors observed by geodetic methods, sensors are directly located on the construction to monitor the change of parameters, such as stress, deformation and vibrations. From that monitoring it is possible to assess the mining safety level of the structure through the data collected continuously from the sensors. However, the funding needs for each monitoring system and for each specific project may be very large, not to mention the need to spend a large amount of resources to maintain the monitoring system for many projects, including high prices from experts and exclusive distributors. Instead of using sensors and machines on constructions, the research and application of sensors placed on a vehicle that often passes on a traffic structure may present several benefits. In this case, the structures are indirectly monitored through equipment placed on vehicles moving along the structure. In this work, focus is given on researching and application of indirect monitoring methods by installing sensors on vehicles to identify frequency and evaluate bridge structures' performance.

Keywords: Indirect monitoring, Drive-by, Sensor on vehicle.

1 Introduction

Using mobile sensors for bridge assessment through an instrumented vehicle is a promising indirect bridge inspection technique, commonly designated by "drive-by". The drive-by technique is an indirect vibration-based method for bridge assessment that has emerged over the past decade. In the proposed method, instrumented vehicles were used to gather the dynamic properties of a bridge. In this case, through the drive-by technique, the vehicle can be considered as both exciter and receiver [1] to obtain these dynamic properties.

Yang et al. [2,3] first introduced this technique using the dynamic response of a passing vehicle to extract the dynamic properties of a bridge. Variation in natural frequencies of a passing vehicle was used as a damage feature for the proposed drive-by technique. Since then, drive-by methods have been investigated by many researchers [4, 5, 6]. For instance, Lin and Yang [7] used an experimental case study of passing instrumented vehicles over a highway bridge to confirm the feasibility of this method in a real case study. The authors employed a tractor–trailer system passing over a prestressed concrete bridge. It was stated that lower vehicle speeds result in a lower influence of road surface profile and lower variation in the extracted damage feature. By using a heavy truck, it was found that it would improve frequency peak detection. Yang et al. [8] and Chang and Kim [9] showed that the bridge frequency of a vehicle–bridge interaction (VBI) system is different from the one obtained for the direct methods. In another study, Yang et al. [10] investigated the reliability of using a test cart to extract bridge frequency under various service conditions.

Overall, the indirect bridge monitoring methods using mobile sensory devices have a great potential for drive-by damage detection. Drive-by methods are still in the research and technological development phase but they are possibly viable candidates for specific applications of health monitoring of bridges. These methods suffer from the uncertainty caused by mobility parameters of vehicles and lots of influential parameters among which are the physical parameters of the vehicles and the contact surface, that significantly degrade the performances of these methods for real-life applications. The low accuracy of these methods makes them unreliable solutions as a standalone tool for the health monitoring of bridges. Moreover, due to the lack of an effective platform for the implementation of these techniques, these methods have a low capacity for commercialization and attracting business-driven investment.

2 Research Methods

The method used to perform indirect monitoring of the structure is based on the use of sensors installed on vehicles that pass through the structure. The data collected during the vehicle movement (especially vibration data) is used to monitor and evaluate its structural health condition. The collected information contains many different data and influence of different sources, including vibration characteristics of the structure, vibration characteristics of the vehicle and noise data during implementation. In order to use these data, it is necessary to establish a relationship or interaction between the vehicle and the structure. From this correlation, it can be used to evaluate the structure indirectly through monitoring the vibration characteristics of the vehicle installed with the sensor.

To simplify the analysis of the bridge-vehicle interaction, a car model (2DOF model) is used for analysis and calculation (Figure 1).

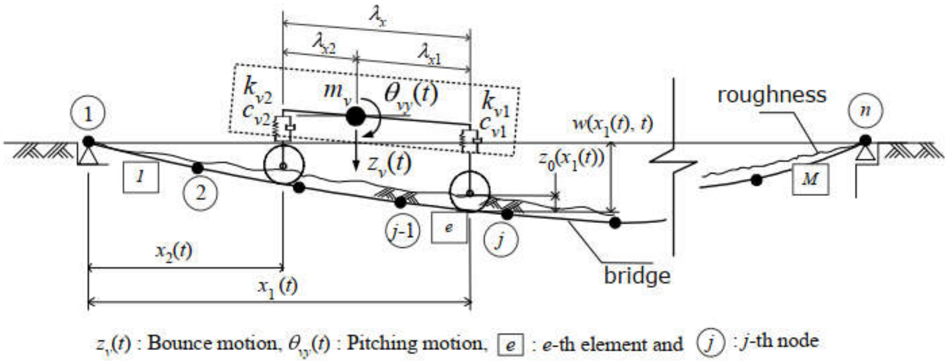


Fig. 1. Bridge-vehicle interaction model.

In this, $z_v(t)$ and $\theta_{vy}(t)$ are respectively representing the vehicle's bounce and pitching motions, m_v denotes the vehicle mass; k_{vs} and c_{vs} respectively denote the spring constant and damping coefficient at the *s*-th axle of the vehicle; *s* indicates the position of an axle: $s = 1$ and $s = 2$ respectively signify the first (or front) and second (or rear) axles. λ_{x1} and λ_{x2} are the distances from the vehicle's center of gravity to the respective axles; $z_0(x_s(t))$ indicates the roadway surface roughness at a position of $x_s(t)$ from the bridge entrance which is assumed as the reference position.

The equation of motion of the car model (2DOF model) is established as follows:

$$\begin{aligned} m_v\ddot{z}_v(t)+\sum_{s=1}^{2}c_{vs}(\dot{z}_v(t)-(-1)^s\lambda_{xs}\dot{\theta}_{vy}(t)-(\dot{\mathrm{w}}(\mathrm{x}_s(t),t)-\dot{z}_0(x_s(t)))) \\ +\sum_{s=1}^{2}k_{vs}(z_v(t)-(-1)^s\lambda_{xs}\theta_{vy}(t)-(\mathrm{w}(\mathrm{x}_s(t),t)-z_0(x_s(t))))=0 \end{aligned} \tag{1}$$

$$\begin{aligned} m_v\lambda_{x1}\lambda_{x2}\ddot{\theta}_{vy}(t)-\sum_{s=1}^{2}(-1)^s\lambda_{xs}c_{vs}(\dot{z}_v(t)-(-1)^s\lambda_{xs}\dot{\theta}_{vy}(t)-(\dot{\mathrm{w}}(\mathrm{x}_s(t),t)-\dot{z}_0(x_s(t)))) \\ -\sum_{s=1}^{2}(-1)^s\lambda_{xs}k_{vs}(z_v(t)-(-1)^s\lambda_{xs}\theta_{vy}(t)-(\mathrm{w}(\mathrm{x}_s(t),t)-z_0(x_s(t))))=0 \end{aligned} \tag{2}$$

Combining the interaction force at the contact point of a vehicle wheel with the dynamic equation of motion of a bridge provides equations of motion for the bridge-vehicle interactive system. The dynamic equation of a bridge under a moving vehicle is defined as:

$$M_{br}\ddot{q}_r(t)+C_{br}\dot{q}_r(t)+K_{br}q(t)=\sum_{s=1}^{2}\Psi_s(t)P(t) \tag{3}$$

In which, M_{br}, C_{br}, K_{br} correspond to the mass, damping, and stiffness matrices of the bridge; $q_r(t)$ is the displacement vector; Ψ_s (t) is a load distribution vector to each node of the element on which a tire contacts; $P_s(t)$ is the wheel load at a tire and can be defined as follows:

$$P_s(t) = \left(1 - \frac{\lambda_{xs}}{\lambda_x}\right) m_v g + c_{vs}\dot{\delta}_s(t) + k_{vs}\delta_s(t) \tag{4}$$

With

$$\delta_s(t) = z_v(t) - (-1)^s \lambda_{xs}\theta_{vy}(t) - [\mathrm{w}(x_s(t), t) - z_0(x_s(t)] \tag{5}$$

Equations (1) and (2) show that changes of bridge's dynamic features can be extracted from the vehicle vibrations since dynamic equations of motion of the vehicle traveling on a bridge clearly contain bridge's responses ($w(x_s(t), t)$. It means that if dynamic properties between the vehicle and bridge are clearly different and moreover the amplitude of the bridge response is big enough then detecting the bridge's frequencies becomes theoretically feasible.

3 Case study – monitoring at Chuong Duong bridge

3.1 Chuong Duong bridge (Vietnam) structure

Chuong Duong bridge (Figure 2) across the Red River was built from 10/10/1983 to 30/6/1985 by Vietnam engineers. It connected Hoan Kiem district with Long Bien district in Hanoi (Vietnam). It carries a four-lane bridge (No. 1A National Road) two lanes in the middle for cars, buses and others for motorcycles.

Fig. 2. Chuong Duong bridge in Ha noi, Viet Nam

The main structural system is a truss bridge with 21 spans with 11 steel truss spans and 10 concrete spans. The main bridge consists of 11 truss spans: 8 simply supported spans and 1 module with 3 continuous spans. Each span is almost equal length (90m).

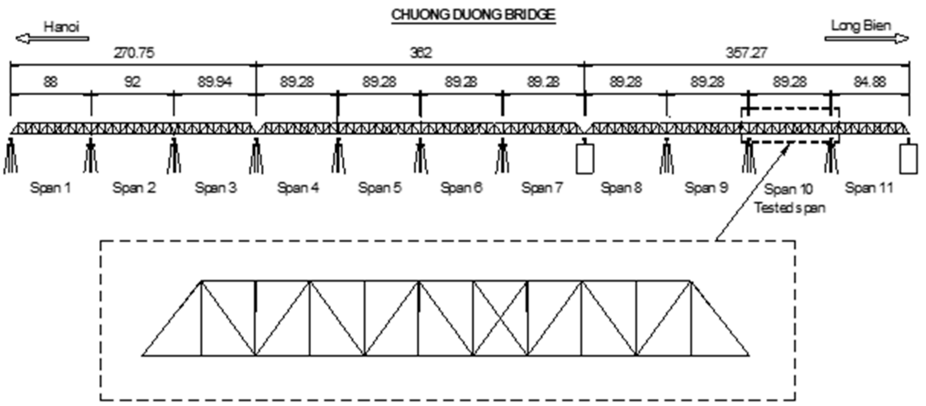


Fig. 3. Front view of Chuong Duong bridge

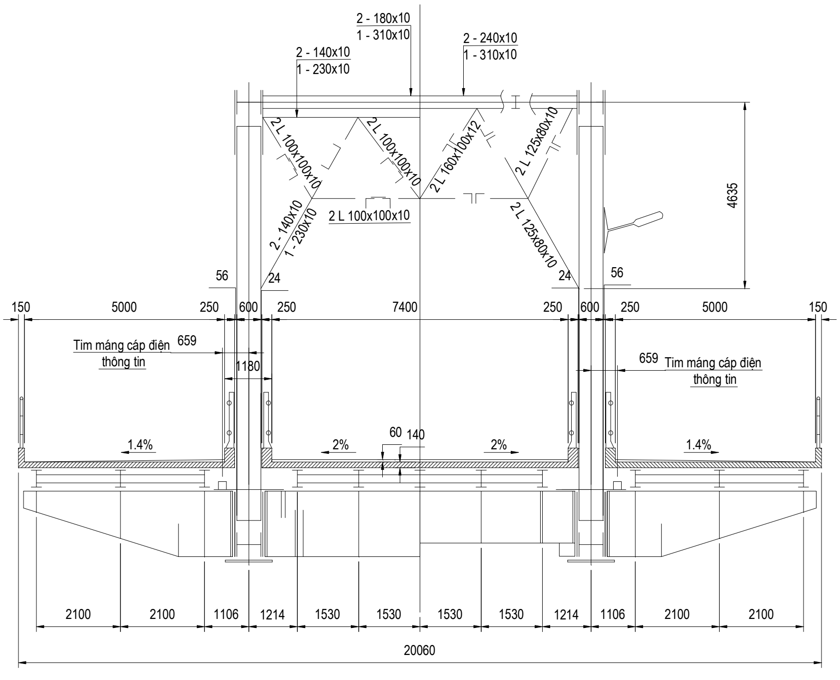


Fig. 4. Cross section of Chuong Duong Bridge

The entire width of the bridge is 19m and its length is 1.230m. The main welding bar has an H-shaped welded cross-section, the width is 600mm, the top plated bar is above and below is 600mm, the top oblique bar is 640mm, the other oblique bars and the vertical bar are 600, 460, 420, 260 mm. The largest steel plate length is 32mm. The master board buttons are 16mm thick. The length of the bar ends is 550mm.

3.2 Direct monitoring on Chuong Duong bridge

To perform direct monitoring of the Chuong Duong bridge, measurements of the vibration of the entire bridge under the effect of random loads was made.

The measurement system consists of eight high sensitivity accelerometers of type PCB, a 8-Slot CompactDAQ Chassis (cDAQ-9178) with two NI-9234 modules, a laptop installed MACEC (Figure 6). The sensors with labels 31, 34, 37, 38, 39, 40, 41, 42 have sensitivities 1.077, 1.051, 1.069, 1.059, 1.073, 1.039, 1.051, 1.063 [V/g] respectively.

Fig. 5. The measurement system used to direct monitoring

The full-scale operational modal analysis (OMA) test was performed on the span 10 (Figure 3) by measuring the vibration under ambient excitation. The campaign used eight different setups to cover all measurement points and recording time was 30 minutes per each setup. The measurement points were set on the lower and upper layer to distinguish different modes (torsion, vertical/horizontal bending,..). For the determination of the coordinates in a setup, a Cartesian coordinate system is the z-axis is vertical with the positive direction upwards, the y-axis is in the transversal direction of the bridge and the x-axis in the longitudinal direction. At each bearing, two sensors with x-axis and y-axis were installed. At other points, the sensors were placed in y-axis or z-axis or y and z-axis. To combine all the setups, the reference points (point 103) were used. A detailed description of all setups can be found in Figure 6.

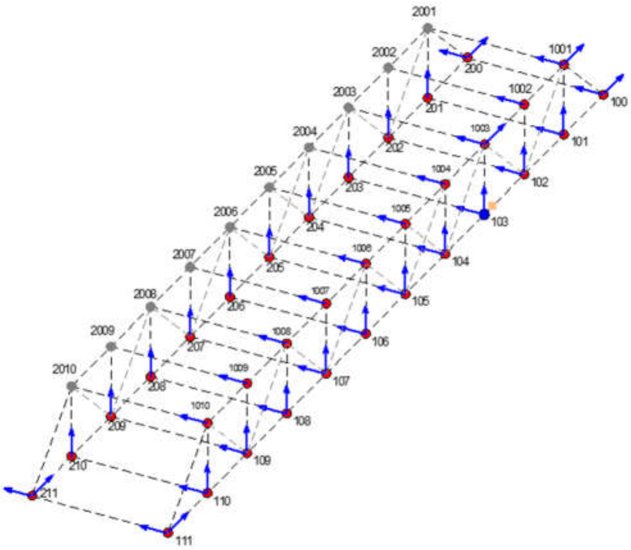


Fig. 6. Placement of measurement points on Chuong Duong bridge (direct monitoring method)

In order to collect vibration data of the bridge, the system DAQ was employed to connect accelerometers and a laptop. The sample rate (or sampling frequency) for collecting vibration data was 1651Hz.

Fig. 7. Carry out direct monitoring by vibration method

Fig. 8. One of the sensor installation position at truss node

Due to the long time needed to collect all vibration data of simple span of Chuong Duong bridge, the whole work was completed after 4 days of continuous measurements. All data was stored in the laptop for processing using MACEC software.

3.3 Indirect monitoring on Chuong Duong bridge

For the onsite measurements, the considered instrumented vehicle was a car with the technical information given in Table 1.

Table 1. Test vehicle specifications

No	Technical information	Value	Unit
1	Type of vehicle	Car (Vinfast SA 2.0)	
2	Length x witdth x height	4940 x 1960 x 1773	mm
3	The standard long	2933	mm
4	Weight	2140	kg
5	Clearance	195	mm
6	Power steering	Hydraulic, electric control	-

Fig. 9. Vehicle used for indirect monitoring

On the test vehicle, a measurement system is installed including 4 accelerometers: 2 sensors located at the front of the vehicle and 2 sensors located at the end of the vehicle (Figure 11). At each installation position, the sensor is placed in two directions (horizontal (y) and vertical (z) in the Cartesian coordinate system). Installation details of the sensors are shown in Table 2.

Table 2. Installation details of the sensors

No	Sensor’s label	Direction	Location	Sensitivity[V/g]
1	31	Horizontal (y)	Front of the vehicle	1.077
2	34	Vertical (z)		1.051
3	37	Horizontal (y)	End of the vehicle	1.069
4	38	Vertical (z)		1.059

Fig. 10. Installation of sensors on the monitoring vehicle

Carry out monitoring by driving vehicles through Chuong Duong bridge. During the bridge crossing process, record the time and mark the timestamp when crossing the module of the bridge to be monitored and use that link's data only for future processing purposes, other data will be discarded. All data collected during monitoring is transmitted to the CompactDAQ Chassis (cDAQ-9178) and stored on a dedicated computer.

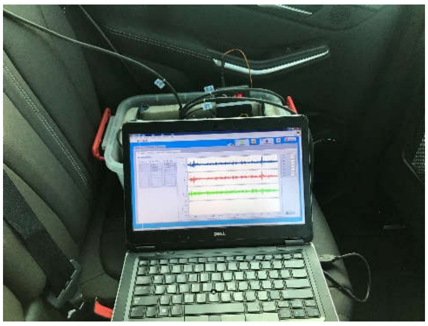


Fig. 11. Collecting data during monitoring

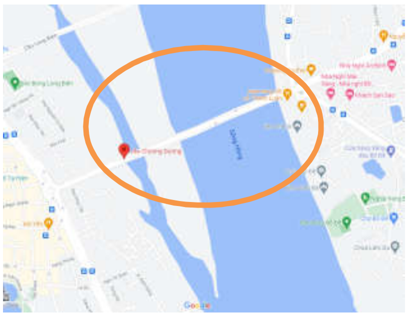


Fig. 12. Location and distance taken

Unlike the direct method, the indirect method took place in a very short time. In this case, an average of 2 minutes for each structural monitoring measurement was required. Using this advantage, it was possible to collect continuous monitoring data many in different times as to obtain a better data quality and monitoring efficiency, as well as to discard outlier measurements. In this case, a total of 6 runs across Chuong Duong Bridge were made. With each monitoring, the vehicle moved with different velocities and the details are shown in Table 3.

Table 3. Vehicle speed in tests

Times	1	2	3	4	5	6
Velocities (km/h)	25	30	35	40	45	50

4 Results and discussion

In MACEC, the Stochastic System identification (SSI) method is used to determine the natural frequencies and mode shapes for this bridge. Among time domain techniques, stochastic subspace identification (SSI) is a robust and efficient modal identification algorithm. Commonly, two implementations of SSI can be found: (i) data-driven SSI (SSI-data); and (ii) covariance-driven SSI (SSI-cov). The main difference is that SSI-data directly deals with raw output data while SSI-cov works on the output correlations. Similar results can be obtained from SSI-data and SSI-cov, but SSI-cov provides a faster way to obtain the results.

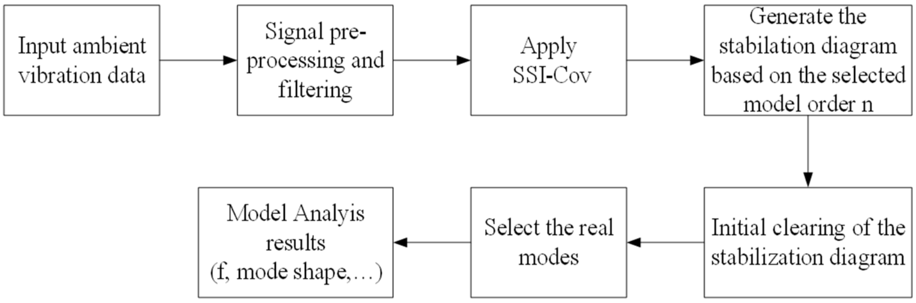
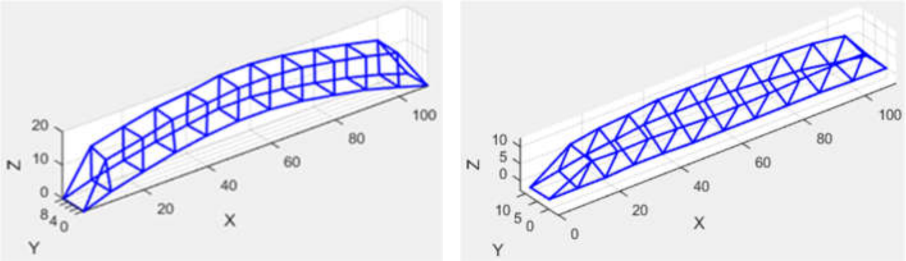


Fig. 13. Process of system identification

4.1 Direct monitoring method

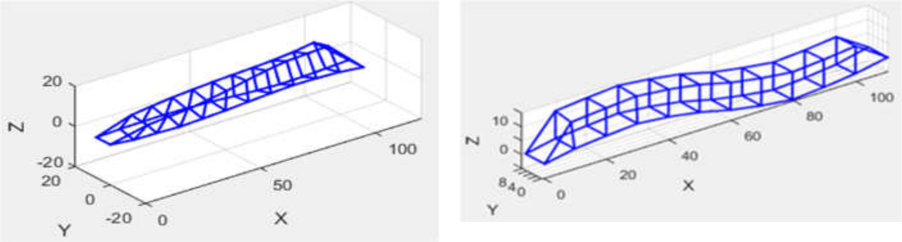
In this study, the analysis and evaluation of direct observation data was not considered and the results were included after the data processing and selection process. With the data collected from the data collection process direct monitoring of Chuong Duong bridge structure, processing and combining the data, the corresponding modes shape and frequency will be obtained.

There are 7 identified modes in the campaigns. Natural frequencies and the corresponding mode shapes from 8 setups are shown in Figure 14.



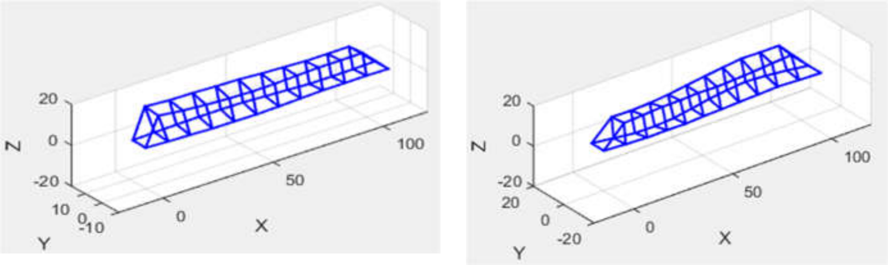
Mode 1: f = 1.79 [Hz]
(1st vertical bending)

Mode 2: f = 2.25 [Hz]
(1st lateral + torsion)



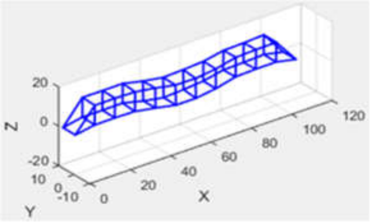
Mode 3: f = 3.57 [Hz]
(2nd torsion)

Mode 4: f = 4.30 [Hz]
(2nd vertical bending)



Mode 5: f = 4.60 [Hz]
(lateral movement)

Mode 6: f = 5.03 [Hz]
(2nd lateral bending)



Mode 7: f = 8.09 [Hz]
(3rd vertical bending)

Fig. 14. Identified mode shapes

The results are selected from the stabilization diagram by criteria which corresponds to 1% for frequency, 5% for damping, 1% for mode shapes (Figure 15).

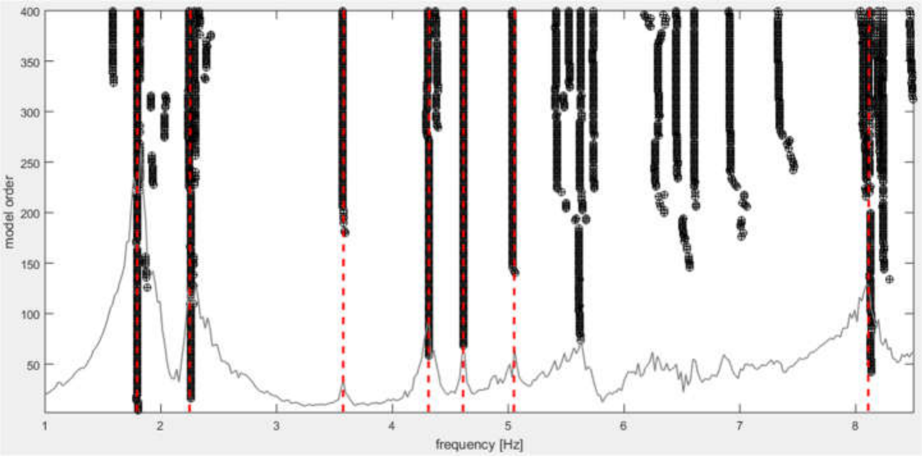


Fig. 15. Stabilization diagram of direct monitoring from 1 - 8.5 Hz.

Table 4. Summarization of frequency values of the 9 identified modes

No	Frequencies [Hz] (measurement)	Damping ratios [%]	Modal phase collinearities	Mode type
1	1.79	1.50	0.999	1st vertical bending
2	2.25	1.06	0.997	1st lateral + torsion
3	3.57	0.77	0.999	2nd torsion
4	4.30	1.21	0.996	2nd vertical bending
5	4.60	0.40	0.997	lateral movement
8	1.79	1.50	0.999	1st vertical bending
9	2.25	1.06	0.997	1st lateral + torsion

Modal phase collinearities (MPC) values are greater than 0.9 which leads to the smooth mode shapes.

4.2 Indirect monitoring method

Eliminate the high frequencies of the vehicle, determine the frequency domain of the structure and performing the same data processing analysis as for the direct monitoring method from the data obtained from the indirect method, the results are obtained as follows:

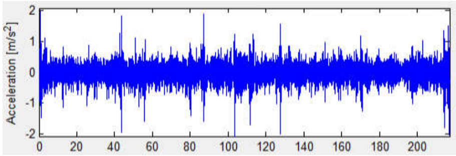


Figure 16. The data in the time domain

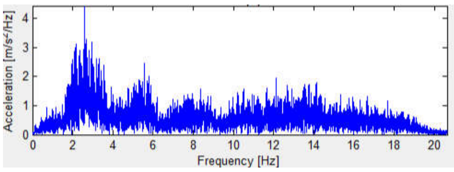


Figure 17. The data in the frequency domain

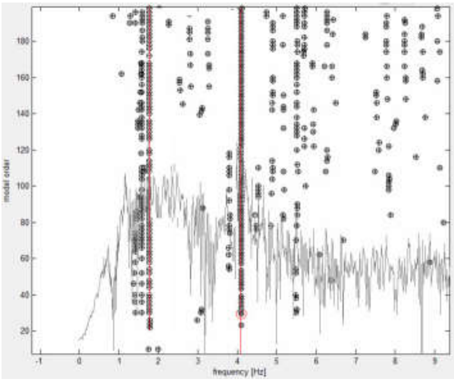


Figure 18. Stabilization diagram in the second time monitoring

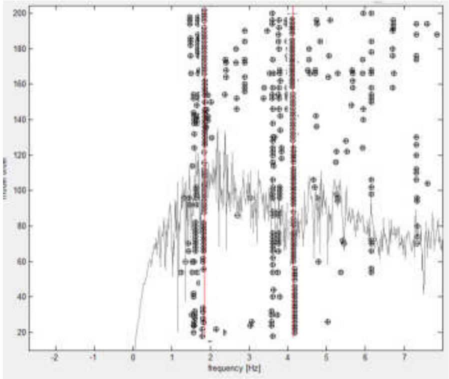


Figure 19. Stabilization diagram in the third time monitoring

Since the collected data does not identify the movement at the positions corresponding to the steel truss, the identification of the mode shapes is still difficult. At the same time, the received frequency of the structure after removing noise signals, the two most vibration frequencies of the structure are shown in the table below (Due to research limitations, in this paper the authors only evaluate and compare the frequencies obtained from the sensor in the vertical direction):

Table 5. Frequency values for indirect monitoring

No	Frequencies [Hz] (measurement)	Damping ratios [%]	Modal phase collinearities
1	1.836	1.8	0.91
2	4.141	1.6	0.90

4.3 Comparison and discussion

A table comparing the frequencies determined from the two methods is made with the results in table 6:**Table 6.** Frequency values comparison

Mode	Direct monitoring	Indirect monitoring	Error
1	1.79	1.836	2.56%
4	4.3	4.141	3.69%

Comparing the results between the two methods, it can be seen that the determination of the structural vibration frequency through indirect monitoring method achieves relatively accurate results (for mode 1 the error compared to direct observation is only 2.14%, for mode 2 it is only 3.69%). The indirect monitoring method does not accurately determine as many frequencies as the direct method. Here, the indirect observation can only identify 2 frequencies corresponding to 2 modes of vertical oscillation.

Considering the implementation time, direct monitoring method of the structure through vibration measurement will consume a very long time (to measure Chuong

Duong bridge takes at least 4 days for 1 simple span). Meanwhile, each indirect monitoring only uses an average of 3 minutes for all bridge. From the advantage of time, it is possible to regularly and continuously perform the indirect monitoring process to evaluate the structure, and at the same time obtain a very large amount of data that can serve long-term construction monitoring goals. Not only that, indirect monitoring will bring great benefits in terms of implementation costs by reducing time.

The system for performing direct monitoring is very complex, requires a large number of sensors, preparation and field manipulation is quite difficult if the monitoring conditions are not favorable. With the use of a small number of sensors (only 4 sensors are required for Chuong Duong Bridge), indirect monitoring can be easily performed.

The velocity of vehicle moving on the structure also substantially affects the effects received inside the indirect monitoring technique. The tests result show that, for a car velocity of 30 km/h with the gadget parameters as described above, the best signal and monitoring result are obtained among the tested speeds

The direct monitoring method with obtaining the long-term responses of the structure gives clear results through the shape modes with the corresponding frequencies. Meanwhile, the indirect monitoring method only gives results in the form of frequencies and does not determine the mode shape. This is one of the shortcomings of the indirect monitoring method that needs to be studied further.

5 Conclusion

It is possible to monitor the structural health by recognizing the frequency of the structure through a vehicle-mounted sensor system. The indirect monitoring system helps to quickly carry out structural monitoring, and at the same time can regularly and continuously observe, without spending significant resources.

Through testing on the actual construction (Chuong Duong bridge), the results show that the indirect method has high accuracy. The signals obtained from indirect monitoring are best received when the vehicle speed over the bridge is 30km/h. At the same time, the flatness of the road surface is also a factor that greatly affects the noise of the signal. Indirect monitoring will be really effective when applied in railways because of the stable speed and flatness in the movement of the train. Further studies are needed when applying indirect monitoring in railway bridges.

With a large amount of data obtained from indirect monitoring through the device, it can be used to train an intelligent system that automatically recognizes damage. In this perspective, it is possible to combine direct and indirect monitoring to improve the accuracy of data by determining the initial state of the structure by direct methods, then performing indirect monitoring through periodic check.

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