Method Assessment of Bridge Conditions Using Vibration Mode Patterns

by Sukamta Sukamta

Submission date: 06-Sep-2022 10:51AM (UTC+0700)
Submission ID: 1893433110
File name: Fullpaper_Method_Assessment_of_Bridge_Conditions.pdf (489.07K)
Word count: 4867
Character count: 24031

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Sukamta, Bagus Acung Billahi, Susilo Adi Widyanto, and Han Ay Lie

Abstract The current bridge structure maintenance method is done by visual observation only, this often has limitations and the results obtained are less accurate. This research was conducted to obtain a vibratory mode data base which will be used as a basis for compiling the failure patterns of the bridge structure. Vibration mode measurements are carried out on the prototype and the bridge model using an accelerometer sensor mounted on the bridge structure. Accelerometer installed at several points to get variations in the vibrate mode. Dynamic load frequency variations are given to get vibrational mode variations. The results of the vibration mode measurement analysis show the similarity between the prototype and the model, so that the bridge model can be used to study structural failure patterns.

Keywords Dynamic characteristics · Prototype model · Scale model · Vibrate mode · Experimental analysis

1 Introduction

The development of bridge technology has continued to experience rapid increases over the last few years in line with the increasing demand for land and air transportation. This can be seen from the increase in bridge plan load classes, understanding of bridge construction planning/implementation technology, and the use of various kinds of software to support statistical analysis and dynamics of bridge structures. A maintenance system is needed to see and ensure that the bridge is still fit for use or

Sukamta (✉) · H. A. Lie
Department of Civil Engineering, Diponegoro University, Semarang, Indonesia

H. A. Lie
e-mail: hanaylie@live.undip.ac.id

B. A. Billahi
Master Program in Civil Engineering, Diponegoro University, Semarang, Indonesia

S. A. Widyanto
Department of Mechanical Engineering, Diponegoro University, Semarang, Indonesia

S. Belayutham et al. (eds.), *Proceedings of the 5th International Conference on Sustainable Civil Engineering Structures and Construction Materials*, Lecture Notes in Civil Engineering 215, https://doi.org/10.1007/978-981-16-7924-7_51

commonly known as Structural Health Monitoring. Bridge performance needs to be considered over its service life. The old bridge structure, the uncertain environmental conditions, and the increasing load of the vehicles in its path must be monitored for bridge maintenance.

Bridge detection monitoring is needed to determine structural deformations caused by regular operation or environmental impacts such as temperature, humidity, and heavy vehicle loads. It is also necessary to monitor the entire structure after extreme conditions, such as earthquakes. A system that can measure the performance of structures, especially truss bridges, is Structural Health Monitoring (SHM). The current maintenance system can be used and is considered an interesting topic because it can be carried out by routine monitoring and evaluation of civil construction's integrity through the use of sensor network technology, both wired and wireless. Structural Health Monitoring System refers to the in-service monitoring process embedded to effectively manage structured systems with various possible failures. The goal of a Structural Health Monitoring (SHM) system is to reduce security operating costs by providing more accurate condition-based maintenance [1].

Currently, the Structural Health Monitoring System is still limited to data collection and direct testing of structural elements, so it is time-consuming and relatively expensive. The bridge itself, has not yet developed an automatic monitoring system and a more accurate and efficient maintenance system. The main requirement for monitoring that is currently needed is an effective method to collect data from a structure and process the data for the benefit of performance measures such as the health level of a bridge, which correlates with its vibration mode. An automatic vibration sensor system is required, without the need for constant monitoring by human operators. The use of an accelerometer measuring device is very suitable for maintenance or maintenance with a vibration-based structural health monitoring system on this bridge structure. The accelerometer device will generate vibration mode data, which will later be converted from an analog signal to a digital signal, for easy reading. The obtained vibration mode signal will be processed using Fast Fourier Transform (FFT) analysis, which will obtain a graph of the frequency relationship to changes in amplitude. Through this graph, the bridge structure failure pattern can be analyzed, with several variations in the condition of the bridge structure. Variation of several dynamic load positions related to the condition of the bridge structure will be carried out.

According to this study's type of structure, a single degree of freedom system is used, meaning that mass or objects are limited in motion to only one axis, namely the x-axis or the y-axis. The vibration system used in this research is forced vibration with damping, which means that there is an excitation force (F), which is a sine function with amplitude (Fo) and frequency (ω) as shown in Fig. 1 [2]. The equation for the motion of mass m in response to this force can be determined from the analysis of the force acting on mass m when its position deviates by (x) from its position of static equilibrium [3]. Under conditions of dynamic equilibrium, Eq. 1 can be constructed.

$$m\ddot{x} + c\dot{x} + kx = Fo \sin \omega t \quad (1)$$

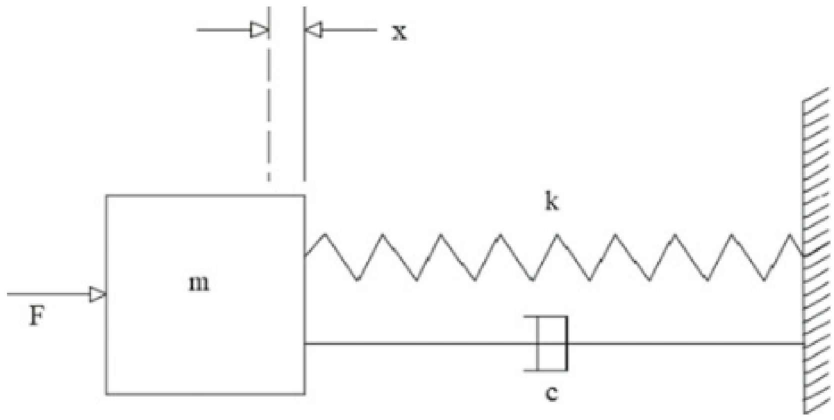

Fig. 1 Schematic forced vibration with damping

where

$m\ddot{x}$ Inertia force (N)
$c\dot{x}$ Viscous Damping
kx Spring force (N)
Fo Centrifugal force (N).

The centrifugal force is obtained from Eqs. 2 and 3 as follows:

$$F = m\omega 2r \tag{2}$$

$$\omega = (2\pi n)/60 \tag{3}$$

where

F Centrifugal force (N)
m Mass unbalance (kg)
ω Angular speed (rad/s)
r Turning radius (m).

Using the model's scale analysis calculations, we can combine the variables to become "comfortable" groups, called "Piterms", and result in a subtraction from the number of unknowns involved in the problem. Buckingham's Pi theorem says any homogeneous equation involving a specific physical quantity can be reduced to an equivalent equation involving a complete set of dimensionless products. In general, the theory states that Eq. 4 is below:

$$F(X_1, X_2, \ldots X_n) = 0 \tag{4}$$

Can be expressed equivalently in the form of Eq. 5:

$$G(\pi_1, \pi_2, \ldots \pi_m) = 0 \tag{5}$$

The pi terms are dimensionless product of the physical quantities $X_1, X_2, \ldots X_n$, a complete set of dimensionless product are the $m = n - r$ independent product that can be formed from the physical quantities $X_1, X_2, \ldots . X_n$. Generally, it can be stated that the number of dimensionless products (m) is equal to the difference between the number of physical variables (n) and the number of fundamental measure (r) that are involved. Buckingham's Pi theorem occupies a very important place in the theory of dimensional analysis. Before moving on to dimensional analysis applications, the next section discusses some details of the procedures used to get the dimensionless product that goes into Buckingham's Pi Theorem equation [4].

Analysis of the scaling model aspects calculated using the Pi Buckingham Theorem results in the scaling aspect for dynamic loads or vibration loads used in the bridge prototype and bridge models. Classification of the resulting vibration or dynamic load is one type of deterministic vibration, where the excitation quantity or load frequency can be known at a specific time. Vibration or dynamic load both work based on frequency, understanding the dynamic load frequency can certainly prevent resonance in the prototype structure or bridge model which is related to natural frequencies. The results of the Pi Buckingham theorem analysis for the load scale aspects given for the bridge model and bridge prototype are compiled in Eq. 6:

$$W_m = \left(\frac{\rho_m \cdot \ell_m^3}{\rho_p \cdot \ell_p^3} \right) W_p \tag{6}$$

where

Wm	The dynamic load of the bridge model
Wp	The dynamic load of the bridge prototype
ρ_m	Density of the material bridge model
ρ_p	Density of the material bridge prototype
ℓ_m	Length of the bridge model
ℓ_p	Length of the bridge prototype.

Studies on the dynamic characteristics of structures have been carried out by several practitioners such as Wei-Xin et al. [5]. Wei-Xin et al. study on the vibration testing, which carried out on bridge cables in Fuzhou China. The study is related to dynamic response, particularly in constructing these structures. The research was conducted in 2 ways, namely by using modal analysis and experimental analysis to obtain the natural frequency of the structure, aiming for the health of the structure. The analytical capital analysis was carried out with a 3-dimensional finite element program, namely ANSYS. Experimental analysis of direct vibration vibrations on the bridge, installed a total of 180 accelerometer sensors that are placed in separate places. The experimental analysis will perform three vibration tests: vibration, free vibration and ambient vibration. The vibration test uses force, impulse, weight loss, and electrodynamic excitation.

The free vibration test is carried out by releasing a load or mass suddenly. Test for ambient vibrations caused by wind, traffic, and pedestrians. The test results show that the analytical and experimental vibration tests have been tested on the bridge prototype. The results of the analysis are created a good correlation between analytic capital and experimentally tested directly in the field. The natural frequency produced in the direct vibration test is 0.36 Hz for the longest cable and 1.97 Hz for the shortest cable [5].

Seno et al. tested the structural response system based on dynamic response structures using wireless sensor networks. The parameters tested for vibration are the natural frequency and shape of the bridge vibrational mode. The test is carried out on a prepared model and then validated using finite element method software (FEM). The method used to validate the success of the system is used two ways, namely using the FEA as a standard reference to determine the behavior of the structure and analysis of the Capital Assurance Criteriation (MAC). Analysis of the finite element method was carried out using the CSi Bridge 2015 software to measure the natural frequency of the test-bed bridge built. The finite element method analysis results showed that the natural frequency of the test-bed bridge was 22.24 Hz, while the system developed to measure the average natural frequency of the bridge was 20.26 Hz. It is concluded that the value obtained by the finite element method analysis is close to the value obtained from the measurement system that has been built. The second way is to use it. MAC has calculated the correlation between the shape modes obtained from the finite element method analysis with those obtained by the system being developed. If the MAC value is close to one, both calculations have a strong correlation, so that the data obtained from the measurement system from the wireless sensor used is valid. The MAC value for finite element analysis (FEA) and measurement by the wireless sensor system is 0.8, so it is concluded that the two measurement parameters have a strong correlation [6].

Cristian et al. conducted research related to the Structural Health Monitoring System of Bridges on one of Romania's bridges. Visual inspection and incorporating several sensors were carried out for integrated monitoring of the bridge's durability. Some aspects observed were steel corrosion, concrete carbonation, freeze-liquid cycle, chemical reactions, mechanical damage, and changes in structural behavior such as deformation, strain, cracking, vibration. The success of the Structural Health Monitoring System depends on two stages of the procedure, namely design and implementation. By creating a dynamic sign database for all bridges, the conclusion is that enabling the Structural Health Monitoring (SHM) system to provide complete, accurate, and real-time data on the feasibility of the entire bridge network being monitored [7].

Cristiano et al. examined the dynamic response of a small-scale bridge model that is subjected to running loads. The basis of modeling is Buckingham's theory, which states that any homogeneous dimensional equation that involves a certain physical quantity can be reduced to an equivalent equation involving a dimensionless series of products known as the term pi terms.

Physical variables that involve modeling here are length (l), flexural stiffness (EI), mass density (p), load ($P = mg$) and longitudinal velocity ($v = \varsigma$). Several parameters are determined through analysis, such as the transverse deflection (w) and the natural frequency of vibration ($fr = \omega r/2\pi$) by defining the pi terms [8].

This paper presents the correlation between vibration response in the form of vibration mode on the prototype bridge structure with a 1: 23 scale bridge model.

2 Material and Method

2.1 Prototype and Model

The truss bridge used as a prototype is the steel frame bridge Sendangmulyo Rowosari, located on Jl. Rowosari Raya, Semarang City, Indonesia. The prototype bridge structure has a total length of 53 m, a width of 9.3 m, and a bridge height of 5 m shown in Fig. 2. The thickness of the gusset plate is 21 mm and uses M24 bolts. The top, side, and bottom steel profile types are IWF 300.300.10.15, then for the upper bracing section use the type IWF 200.200.8.12.

The 1:23 model scale is selected and produces the dimensions of the bridge structure model scale (Fig. 3) as follows: 2315 m long, 0.389 m wide, and 0.217 m high. The bridge model's scale is 1:23, and is made using a hollow profile steel structure of 15 × 15 mm. The structural components are bolted by using M4 bolts, to represent the road area, the bridge model uses a 2 mm thick plate and is coated with a 2 mm thick rubber sheet.

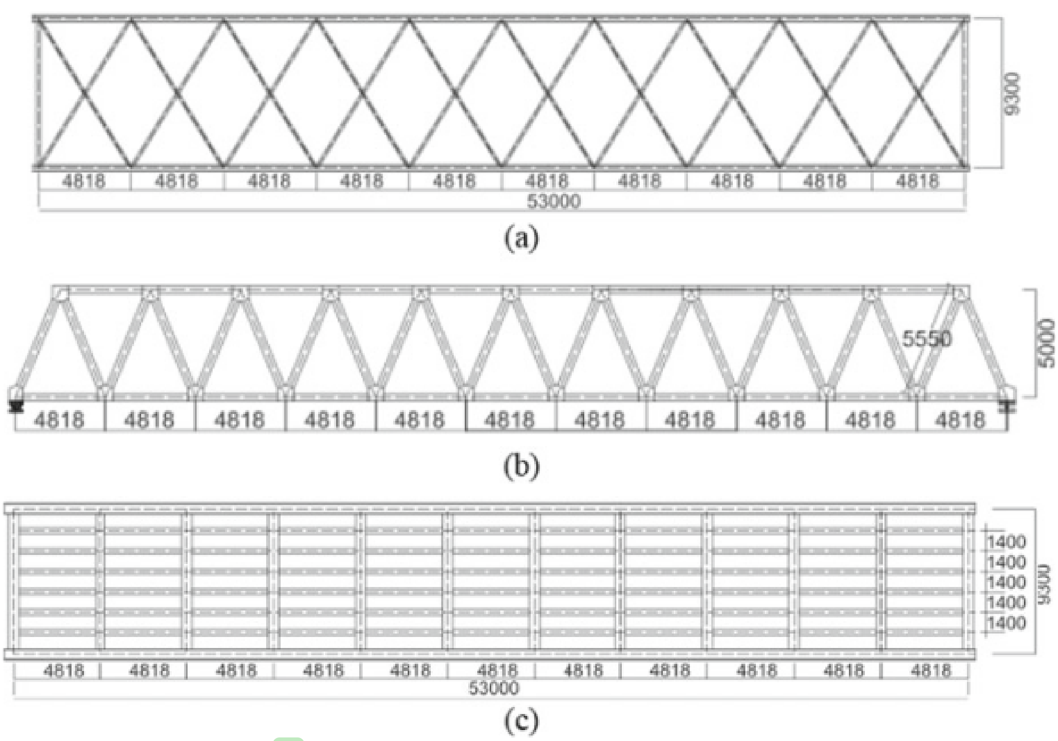

Fig. 2 Prototype bridge: **a** top view, **b** side view, **c** bottom view

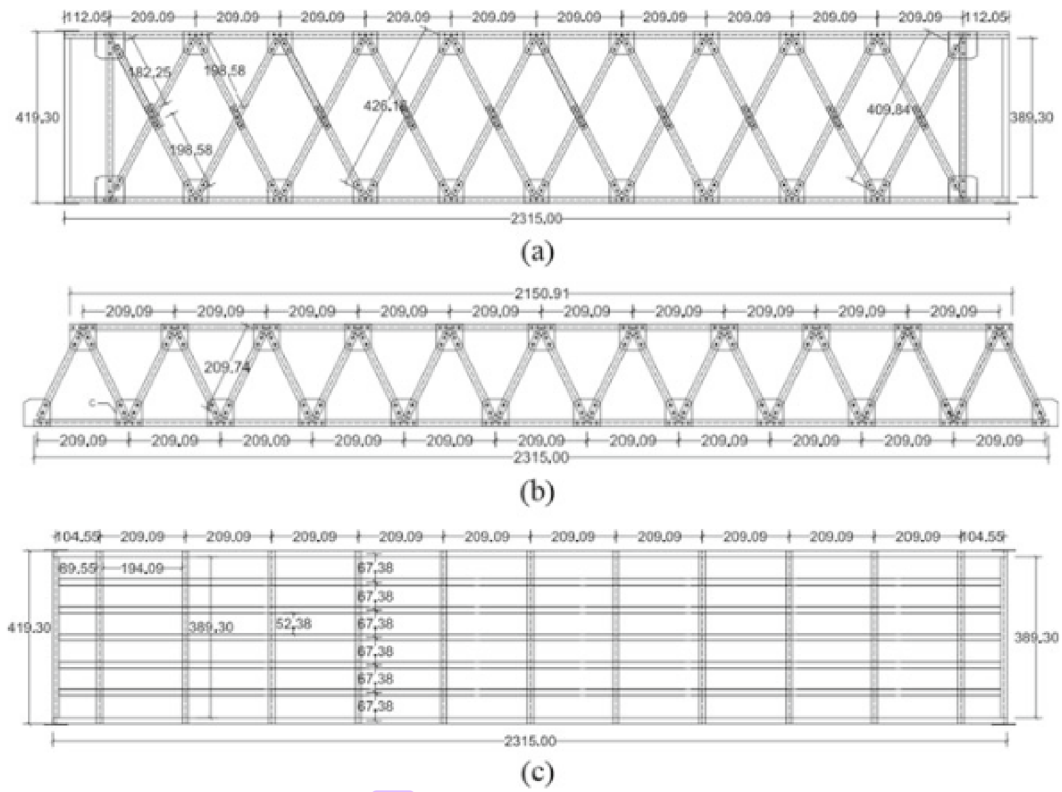

Fig. 3 Model bridge: **a** top view, **b** side view, **c** bottom view

2.2 *Dynamic Loading System Prototype and Model Bridge*

The dynamic loading of the bridge prototype uses a tamping rammer machine with 12,209 N impact force, as shown in Fig. 4. The dynamic loading model data from the tamping rammer machine can be seen in Table 1 [9].

The tamping rammer produces a deterministic vibration output whose value or amount of excitation can be known at a specific time and has a particular frequency to be used as test analysis. The tamping rammer works based on the rotor's centrifugal force, which is present in the machine. The direction of the excitation issued is vertical, the vibration can be adjusted to produce the desired frequency as a test basis for the prototype bridge.

The dynamic loading of the model uses the rotating unbalance mass (Fig. 5). The characteristics of unbalanced mass are as in Table 2.

2.3 *Sensor Accelerometer*

The accelerometer used is the ADXL 335 brand with a sampling rate of 100 Hz. This sensor is of type small, low power, 3-Axis as shown in Table 3.

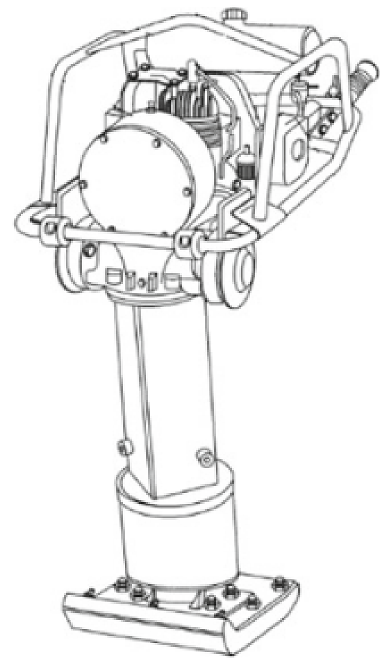

Fig. 4 Tamping rammer machine

Table 1 Dynamic load testing data for prototype bridge structures

Experimental data	Value	Unit
Weight	74	kg
Force	12,209	N
Frequency	30	Hz
Jumping stroke	50–70	mm

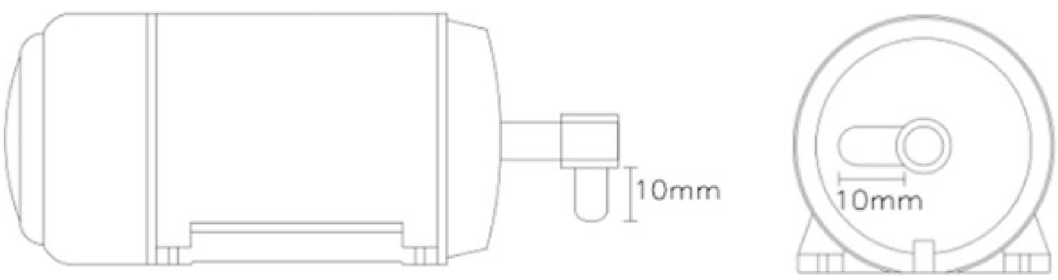

Fig. 5 Mass unbalance

Table 2 Unbalance mass characteristics

Experimental data	Value	Unit
Mass *unbalance*	3	g
Force	1.064–1.449	N
Frequency	30–35	Hz
Turning radius mass *unbalance*	10	Mm

Table 3 Spesifikasi accelerometer

Size: 4 × 4 × 1.45 mm
3-axis sensing and single-supply operations: 1.8–3.6 V
Full scale measurement range can beset to ±3 g
Low power: 350 µA (typical)

2.4 *Experimental Set Up*

The test set-up circuit is shown in Fig. 6. In Fig. 6a is the test set-up used to determine the correlation of the prototype bridge structure and the bridge model structure. Figure 6b is the test set up used to determine the response due to frequency variations. The test was carried out at five position points, which later obtained the vibration mode results, which was used to determine the condition of the bridge structure. The resulting vibration mode will be measured and processed using fast Fourier transform (FFT) analysis, then a frequency domain graphic pattern is generated for changes in amplitude that can represent the feasibility of the structure.

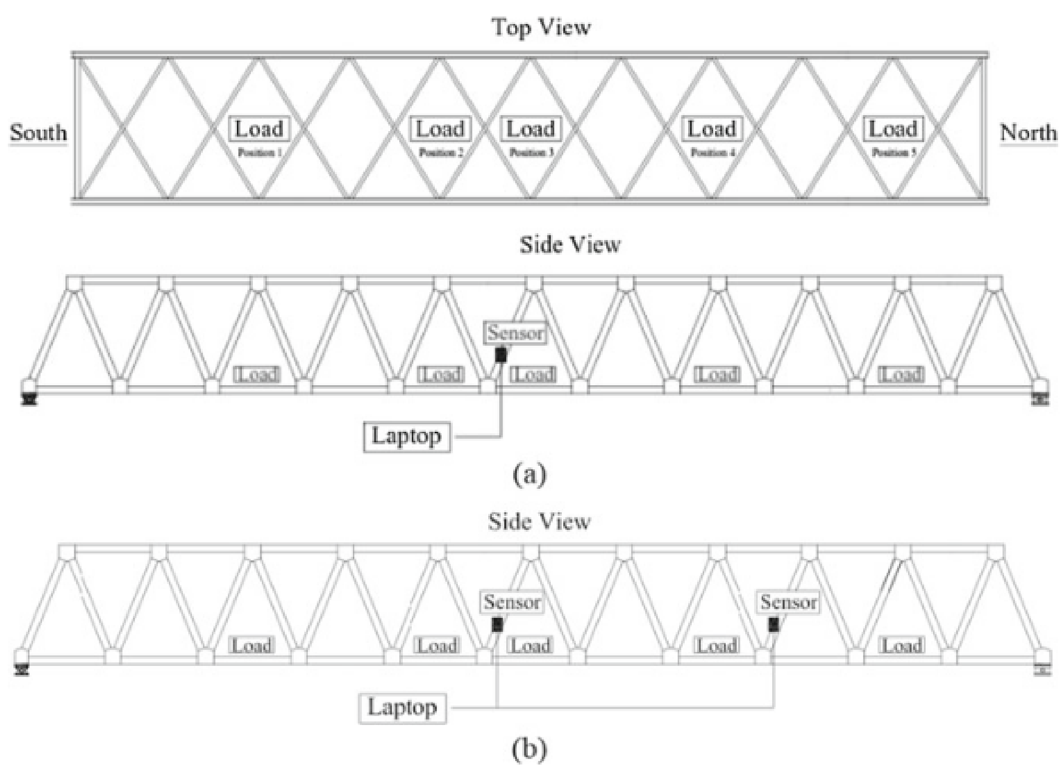

Fig. 6 Experimental set up

2.5 Research Stages

1. Identify problems regarding the vibration mode using the vibration-based Structural Health Monitoring (SHM) method on the bridge's upper structure as in the problem formulation. Prepare literature and theories related to the method of measuring the vibration mode on bridges. Collecting bridge data such as structural geometry, girder dimensions that will be used as a reference for making the bridge model scale.
2. Testing due to dynamic loads on the prototype bridge structure and model scale can be done when the test object has been completed. Tests will be carried out with several variations of dynamic load frequency and dynamic load position variations to obtain the actual vibration mode data of the bridge structure and the scale of the model. Vibration data is read through data acquisition software, from the software is obtained a graph that is still in the form of a vibration measurement curve that will be processed again.
3. Processing the measured data with data acquisition software, data processing using a program with the Fast Fourier Transform (FFT) analysis method. The results of the data processing produced a graph of the frequency domain relationship to changes in amplitude. Through the graph of the frequency domain relationship to changes in amplitude, the failure pattern of the bridge structure can be analyzed.

3 Results and Discussion

3.1 Dynamic Prototype Bridge Load Response

The test results of the bridge prototype structure due to dynamic load at position 1 can be seen through the FFT graph in Fig. 7, and the test results in other positions can be seen in Table 4. Variations in dynamic load positions are carried out to determine the variation in the vibration mode. The Z-axis is chosen as a reference for the variation of the vibrating mode, because the direction of the dynamic load is vertical.

From Fig. 7 and Table 4, it can be seen that the magnitude of the amplitude value is influenced by variations in the placement of dynamic load positions.

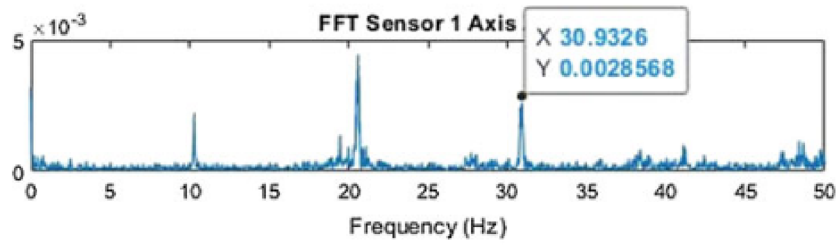

Fig. 7 Position 1

Table 4 Experimental result

Position	Frequency value (Hz)	Amplitude value (mm)
1	30.932	0.00285
2	30.957	0.00383
3	30.639	0.00668
4	30.908	0.00337
5	30.468	0.00247

The largest amplitude value of 0.00668 mm occurs in position 3, where position 3 is the position of the dynamic load closest to the accelerometer sensor. The smallest amplitude value of 0.00247 mm occurs in position 5 which is the farthest position from the accelerometer sensor. This shows that the position of the dynamic load has an effect on the value of the resulting amps. The closer the dynamic load position of the accelerometer sensor, the greater the resulting amplitude value, while the farther the dynamic load position from the accelerometer sensor the smaller the resulting amplitude value. The results of the FFT graph from all dynamic load positions also show that there are frequencies other than the excitation frequency given to the structure, namely frequencies between 20 and 50 Hz, which means that it can be seen that the condition of the prototype bridge structure has been damaged at several points of the structure.

Dynamic Load Response of Bridge Models

The results of testing the structure of the bridge model due to dynamic load at position 1 can be seen through the FFT graph in Fig. 8 and for the results of testing at other positions can be seen in Table 5.

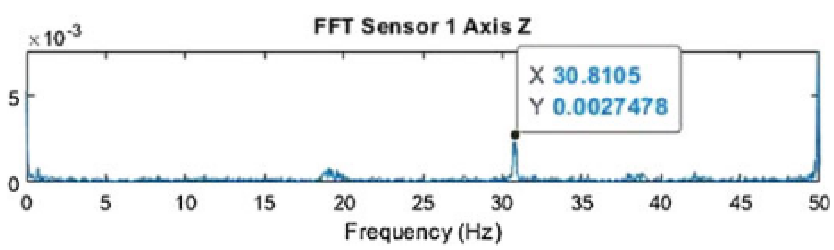

Fig. 8 Position 1

Table 5 Experimental result

Position	Frequency value (Hz)	Amplitude value (mm)
1	30.810	0.00274
2	30.127	0.00370
3	30.957	0.00628
4	30.957	0.00359
5	30.615	0.00254

The largest amplitude value with a value of 0.00628 mm occurs in position 3, where position 3 is the dynamic load position closest to the accelerometer sensor. The smallest amplitude value with a value of 0.00254 mm occurs in position 5 which is the furthest position from the accelerometer sensor.

Analyses

The comparison of the vibration mode response measurement results due to dynamic loads on the prototype of the bridge structure and the bridge model is quite good, the difference in amplitude values is relatively small, and the error shown is still below 10% as shown in Table 6 and Fig. 9.

The comparison of the amplitude value of the bridge prototype structure and the bridge model shows that the highest error value is 6.128% in position 4 with the amplitude value of the prototype bridge structure 0.00337 mm and the amplitude value of the bridge model structure 0.00359 mm. The comparison of the amplitude value of the prototype bridge structure and the model scale bridge shows that the lowest error value is 2.756% in position 5 with the amplitude value of the prototype bridge structure 0.00247 mm and the amplitude value of the model scale bridge structure 0.00254 mm.

Table 6 Comparison of the prototype bridge vibration mode and model scale

Position	Amplitude of bridge prototype (mm)	Amplitude of bridge scale model (mm)	Error (%)
1	0.00285	0.00274	3.860
2	0.00383	0.00370	3.394
3	0.00668	0.00628	5.988
4	0.00337	0.00359	6.128
5	0.00247	0.00254	2.756

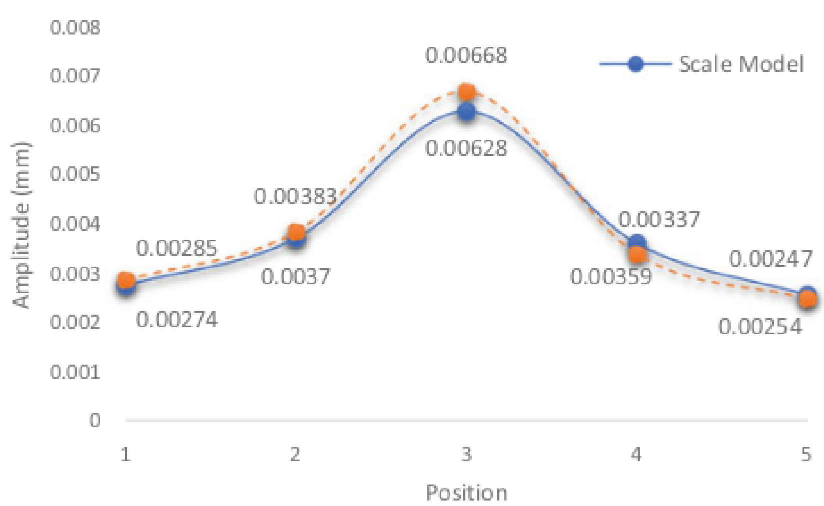

Fig. 9 Comparison of vibration mode response graph prototype model and scale model

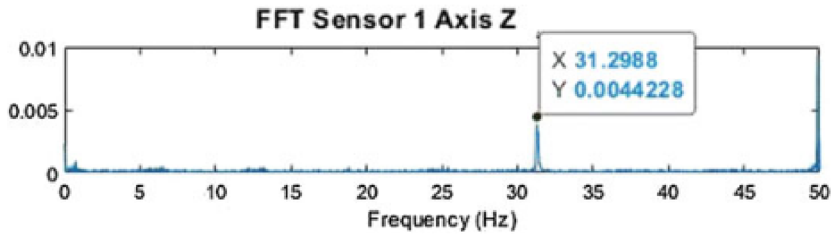

Fig. 10 Position 1

The amplitude value of the prototype structure and the bridge model shows similarities because previously the scaling model aspect has been calculated between the prototype structure and the bridge model using Buckingham's theory.

Frequency Variations in Bridge Model

Vibration mode testing with dynamic load frequency variations in the bridge model structure is done after the similarity of the vibration mode measurement results between the model and prototype is obtained. Unbalance mass frequency is set 31–35 Hz. The test results with a frequency of 31 Hz in position 1 are shown in Fig. 10. And for the results of testing in the frequency and other positions recap in Table 7.

The amplitude value that occurs can be determined from the analysis of the force acting on the mass (m), when the position of the mass deviates as far (x) from its balanced position. The force exerted is in the form of centrifugal force which is related to the rotation frequency of a machine [2]. The relationship between load frequency variations and amplitude values shows that if the greater the load frequency is given, the resulting amplitude will be greater as well. The dynamic load frequency that has increased, automatically the calculation of the centrifugal force load also increases so that the response of the structure will also be different, that is, it is certain to have an increase in the amplitude value as well. This can be proven from the load frequency of 31 Hz to the load frequency of 35 Hz, from the output of the accelerometer sensor number 1 and the accelerometer sensor number 2.

The lowest amplitude value for position 1 is at a frequency of 31 Hz, namely 0.00442 mm for sensor number 1 and 0.00409 mm for sensor number 2, while the highest amplitude value for position 1 is at a frequency of 35 Hz, namely 0.01893 mm for sensor number 1 and 0.01838 for sensor number 2. The lowest amplitude value for position 2 is at a frequency of 31 Hz, which is 0.00659 mm for sensor number 1 and 0.00714 mm for sensor number 2, while the highest amplitude value for the position is at a frequency of 35 Hz, namely 0.01391 mm for sensors number 1 and 0.01128 for sensor number 2. The lowest amplitude value for position 3 is at the 31 Hz frequency, namely 0.00797 mm for sensor number 1 and 0.00602 mm for sensor number 2, while the highest amplitude value for the position is at a frequency of 35 Hz, namely 0.02219 mm for sensor number 1 and 0.02136 for sensor number 2. The lowest amplitude value for position 4 is at a frequency of 31 Hz, which is 0.00471 mm for sensor number 1 and 0.00491 mm for sensor number 2, while the highest amplitude value for the position is at a frequency of 35 Hz, namely

Table 7 Experimental data

Position	Frequency value (Hz)	Amplitude value (S1) (mm)	Amplitude value (S2) (mm)
Frequency 31 Hz			
1	31	0.00442	0.00409
2	31	0.00659	0.00714
3	31	0.00797	0.00602
4	31	0.00471	0.00491
5	31	0.00319	0.00367
Frequency 32 Hz			
1	32	0.00845	0.00647
2	32	0.00917	0.00743
3	32	0.01796	0.01571
4	32	0.007163	0.00716
5	32	0.007413	0.00869
Frequency 33 Hz			
1	33	0.01177	0.00881
2	33	0.01091	0.00924
3	33	0.01508	0.01211
4	33	0.00908	0.00624
5	33	0.00939	0.00876
Frequency 34 Hz			
1	34	0.01316	0.01010
2	34	0.01119	0.01077
3	34	0.01781	0.01441
4	34	0.00845	0.00687
5	34	0.01009	0.01122
Frequency 35 Hz			
1	35	0.01893	0.01838
2	35	0.01391	0.01128
3	35	0.02219	0.02136
4	35	0.00968	0.00774
5	35	0.01485	0.01933

0.00968 mm for sensor number 1 and 0.00774 for sensor number 2. The lowest amplitude value for position 5 is at frequency 31 Hz, which is 0.00319 mm for sensor number 1 and 0.00367 mm for sensor number 2, while the highest amplitude value for the position is at a frequency of 35 Hz which is 0.01485 mm for sensor number 1 and 0.01933 for sensor number 2.

4 Conclusion

The results of the analysis of the vibration mode measurement show the similarities between the prototype and the model, so that the bridge model can be used to study structural failure patterns. A comparison of the amplitude value of the bridge prototype structure and the scale of the bridge model shows that the error that occurs is less than 10% at all given load positions. Variations in the dynamic load position in the bridge model structure indicate that the amplitude value can change due to the load position's influence on how close to the accelerometer sensor position. The amplitude value will be greater if the load position is closer to the accelerometer sensor position, and vice versa, the amplitude value will be smaller when the load position is far from the accelerometer sensor.

The variation of the dynamic load frequency in the bridge model structure shows that the greater the dynamic load frequency given, the greater the resulting amplitude value. The value of the centrifugal force increases when the dynamic load frequency value increases, so that the structural response results in an increasing amplitude value as the load frequency increases. The situation is different when it comes to natural frequency structures, because the highest amplitude values are at the moment of resonance which corresponds to the natural frequency.

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