Temperature Changes Effects to Dynamics Performances of a Pinned-Supported Steel-Arch-Bridge

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Abstract. Seldom is temperature changes effect taken into account in structural design and monitoring. However, in some cases temperature may be the governing load case, especially for a long span bridge. Moreover, statistics have shown that the world's temperature is gradually increasing nowadays and may cause the temperature effect to increase. This may cause an alteration to dynamics parameters of the structure, which will be a highlighted object in this research. These parameters are directly corelated to physical parameters, e.g. mass and stiffness. Hence, as the physical parameters has any kind of change, dynamic parameters will also immediately change. This alteration may modify the health index of the structure. In some regulations, the deviation of the value of natural frequencies, as one of dynamics characteristics, is limited to be 10%. This research is aimed to observe the health index of a determined case study bridge and to observe the effects of temperature changes to dynamics performances of a pinned-supports-arch bridge in the Province of Riau, Indonesia, and it was found, by modeling the structure in Finite Element (FE) Model and performing vibration testing, that temperature difference has caused the natural frequencies of the bridge to vary up to 3.63%.

1. Introduction

Structural failure may occur in a couple seconds for many reasons, one of those is due to strength and stiffness degradation, since it may lead to resonance condition. To avoid this to happen, applying structural monitoring system is considerably a good choice. Some parameters are usually selected and observed to monitor the health index of a structure, such as natural frequencies of the structure. Natural frequencies may be occupied as a governing parameter since it is directly related to the physical parameters, i.e. structural mass and stiffness [1]. Hence, as the physical parameters have any kind of alteration, the natural frequencies of the structure will also definitely be modified.

However, the presence of temperature change may also modify natural frequencies of the structure, since the material of the structure has a thermal coefficient, that may lead the structure to elongate and then change the stiffness of the structure due to elongation and the resulting forces [2,3]. Therefore, temperature effect should be thoroughly observed to justify, if the natural frequencies of the structure are modified due to structural deterioration or temperature change [4].

This research is aimed to observe the health index of a determined case study bridge in the Province of Riau, Indonesia. Furthermore, the effects of temperature changes to the case study bridge will also be analyzed by employing finite element model and vibration testing to the real bridge, and both results will be compared to justify structural health index and the effects of temperature changes to structure.

2. Dynamics parameters of structure

In general, dynamic parameters of structure consist of natural period of vibration, natural frequencies, and mode shapes. Natural period of vibration is the total time needed for a structure to oscillate in a full cycle, and natural frequency is the number of cycle in a range of time of a second. And mode shape is the dynamic characteristic of the structural deflection due to the corresponding modes and frequencies.

In dynamic analysis, structure can be divided into two classifications, single degree of freedom (SDOF) and multi degree of freedom (MDOF). Degree of freedom is the number independent displacements required to define the displaced positions of all the masses relative to their original positions [2]. The number of natural frequencies of the structure depends on the number of modes, which is also the number of the degree of freedom.

Theoretically, dynamic parameters of structure can be obtained by using the dynamic equilibrium equation, which is a second order differential equation. Here it is:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{p(t)\} \quad (1)$$

Equation above can be solved by using matrices operation, square matrices with an ordo n x n, depends on the number of modes. For SDOF structure, this equation can be simply solved by performing an ordinary differential equation analysis.

The natural frequencies of structure can also be experimentally obtained by conducting vibration testing. This kind of testing intend to record the vibrational behavior of the structure as a function of time and then to transform it into frequency domain data by performing Fast Fourier Transform (FFT). FFT is a powerful tool to analyze the behavior of a structure in a frequency domain, since the result may provide the peak response of the structure in the corresponding frequency.

Fourier transform is commonly used to analyze the frequency of a series of signal. Basically, signal is a combination of several sinusoidal functions, hence Fourier Transform is used to decompose the complex function into a simpler function to solve.

If the input domain in Fourier Transform is a time domain function, then the output of the calculation will be a frequency domain function. This transform can be mathematically expressed as follow:

$$F(\omega) = \sum_{-\infty}^{\infty} f(t) e^{-i\omega t} \partial t \quad (2)$$

3. Temperature and heat analysis

Steel bridges responds to changing temperature quickly. Steel structure may react differently during heating and cooling periods. Temperature different between the inside and outside may cause the steel structure to react differently [5].

Several previous researches have been conducted to observe the relationship of temperature and responses of structure, and many of those have concluded that the amplitude of the structural response may increase as the temperature increases. Structural responses can be either static or dynamic, and can be either displacement, velocity, or acceleration.

Here is the governing equation to analyze the heat transfer on structure in case of conduction:

$$Q_x = -KA\frac{\partial T}{\partial x} \quad (3)$$

Where:

Q_x = Rate of heat transfer
K = Thermal conductivity
A = Area
$\frac{\partial T}{\partial x}$ = Temperature gradient

4. Research design

This research is classified as the combination of case study and experimental study research, since it occupies a bridge as a case study object and holds an experimental field testing to fulfill this research.

The case study bridge is located in the district of Bangkinang, Province of Riau, Indonesia. This bridge spans over Kampar River, with three main spans with a total span length of 200 m. The side spans of the bridge are 50 m each, and the middle span 100 m. This bridge is 7 m wide and pinned in every supports it has. It has two lanes of one-way traffic flow.

The first thing to do was to model the structure in FE model by employing MIDAS Civil Software. The objective of conducting a finite-element analysis modelling is to determine the parameters of the structure, in this case are natural frequencies, in the ideal condition, however, the real condition will not show the exactly the same value to the result of the modelling, since the condition in the real structure may not be as ideal as in the finite element model. And here are the real and the modelled structure.

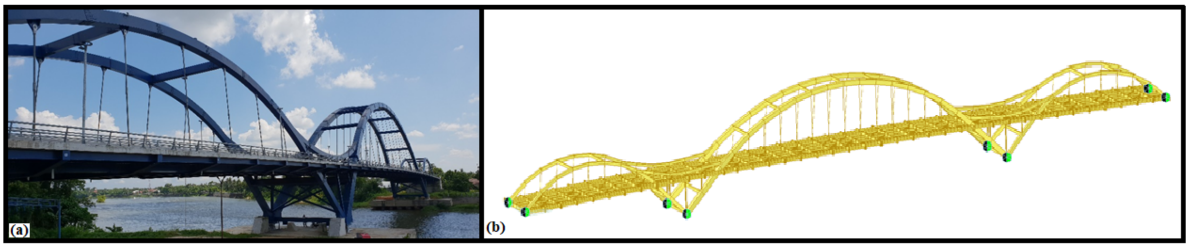

Figure 1. (a) Case Study Bridge; (b) Modelled Case Study Bridge.

After modeling the structure, the next step to do is to conduct vibration testing to extract the real natural frequencies of the bridge. Vibration testing will be conducted by occupying ambient loadings of the bridge to be the source of excitation, since the bridge has been already accessible by the people of the city. Ambient forces here mean the functional loadings of the bridge causing the bridge to vibrate, in this case is dominated by transportation loadings. The transportation loadings will be the source of excitation and vibrate the bridge.

To conduct this vibration testing, several equipment and instrumentations will be occupied, such as vibrating wire strain gauges to measure the strain and temperature of a specified point, a set of vibration sensors, to transmit the mechanics displacement and movement of the structure into electrical or digital signal which will be acquired by operator, in this case is a set of computers. Here are several used instrumentations to conduct this testing.

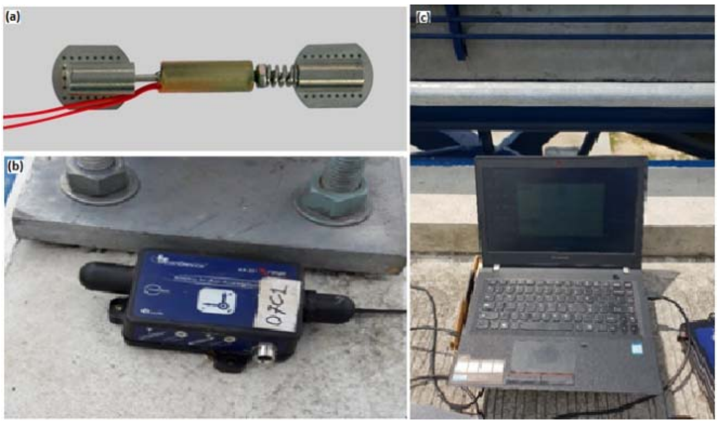

Figure 2. (a) Vibrating Wire Strain Gauge; (b) Vibration Sensor; (c) A set of Laptop.

Vibration testing were conducted in five different times of the day, at which the history showed that the temperature different is the most extreme. The testing was conducted at 5^{th} – 6^{th} of June 2018, at 12 pm, 6 pm, 3 am, 9 am, and 2 pm. At these point of times, the system temperature, showed by the sensor of the installed sensors, varied in a range of 23.4^{o} C – 45.1^{o} C, which has a deviation of 21.7 centigrade.

This research employed four wireless sensors installed in the mid span of the bridge in order to observe the maximum bending response under an exact same excitation. This position was also selected due to the limitation of the sensors, where it can only be installed in a range of around-fifty-meter length. to Figure below shows the locations of the installed vibration sensors.

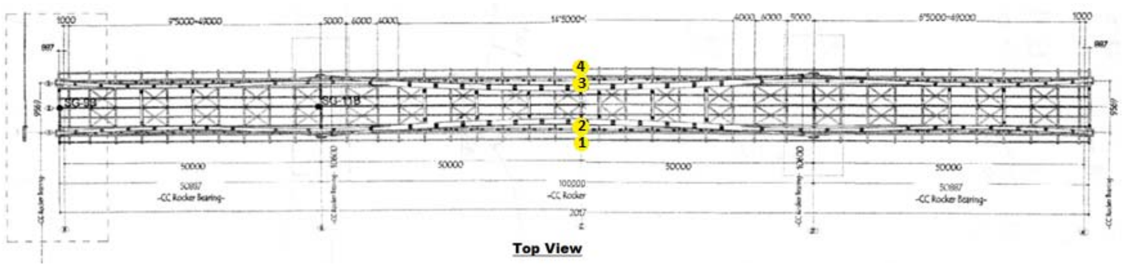

Figure 3. Vibration Sensors Installation Layout.

The structure was excited by employing the travelling vehicle over the bridge as it ambient loading, and the vibrational behavior was recorded before and after the vehicle pass over the bridge. However, the measurable vibration was coming from the travelling truck, and another vehicle might not have enough power to vibrate the whole bridge at once. Sampling frequency of the sensors was set to be 200 Hz (at 12 pm) and the others 600 Hz.

This research is also aimed to observe the health index of the specified case study bridge. Some regulations stated that the allowable difference value of the natural frequencies is limited to be 10%. If the natural frequencies' fluctuation more than 10%, the structure is supposed to be in a fit condition.

5. Results and discussions

5.1. Finite element result

In this section, the result of finite element analysis of the bridge will be provided. The observed output of the MIDAS Civil software is limited only in natural frequencies and mode shapes. The number of mode is also limited up to the first 12 modes. These results will then be employed as a benchmarking value to vibration testing result. This table below sums up the first 12 natural frequencies of the structure.

Table 1. Natural Frequencies and Natural Periods of Vibration from FE Model.

Modes	**Frequency**		**Period**
	(rad/sec)	(cycle/sec)	(Sec)
1	4.329929	0.689130	1.451106
2	6.121680	0.974296	1.026383
3	7.295267	1.161078	0.861269
4	10.278603	1.635890	0.611288
5	11.100667	1.766726	0.566019
6	11.304089	1.799102	0.555833
7	11.659843	1.855722	0.538874
8	11.676054	1.858302	0.538126
9	14.841583	2.362111	0.423350
10	15.856338	2.523615	0.396257
11	16.565074	2.636413	0.379303
12	16.645014	2.649136	0.377482

And figure below shows the corresponding mode shapes from the twelve modes.

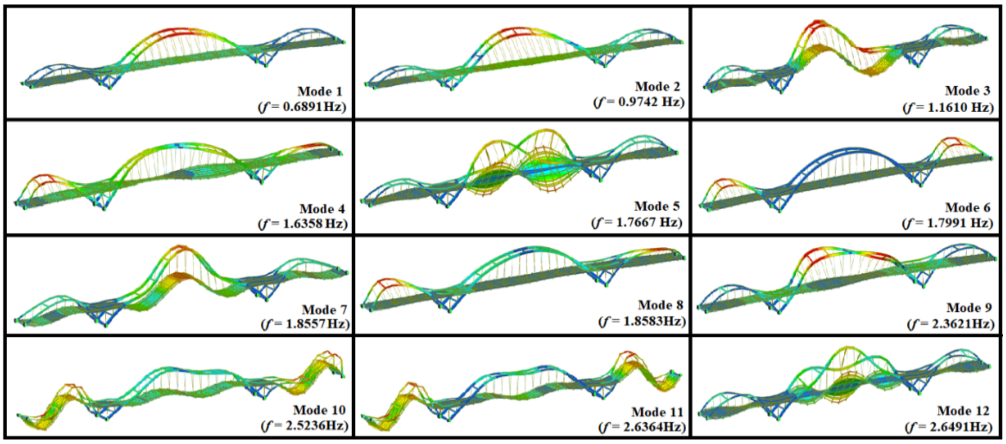

Figure 4. Mode Shapes from FE Model.

Default condition modeling of the structure shows that the structure has the highest response in Z direction (gravity direction) at the local installation point of the sensors, that is in the midspan of the bridge, is in the seventh mode, which has the natural frequency of 1.8557 Hz. Therefore, the first peak response of the FFT operations will then be assumed to be the seventh mode, since the structure was excited in the gravity direction during the vibration testing, so that the dominant response of the structure will also be recorded in the gravity direction.

5.2. Vibration testing result

Vibration testing was conducted by employing the passing vehicle over the bridge as the source of the excitations. However, the structure may adequately vibrate only if a big truck pass by. Private car may also create vibration, however it may be poorly recorded by the sensor, since the vibration induced is not great enough to consider.

To observe the behavior of the structure, vibration signal must be extracted or cut, so that the data only shows the vibrational behavior of the structure. To generate this, the signal must be cut in the range of time, when free vibration took place. Here is the picture of the cut signal, where free vibration took place, and the corresponding FFT result respectively.

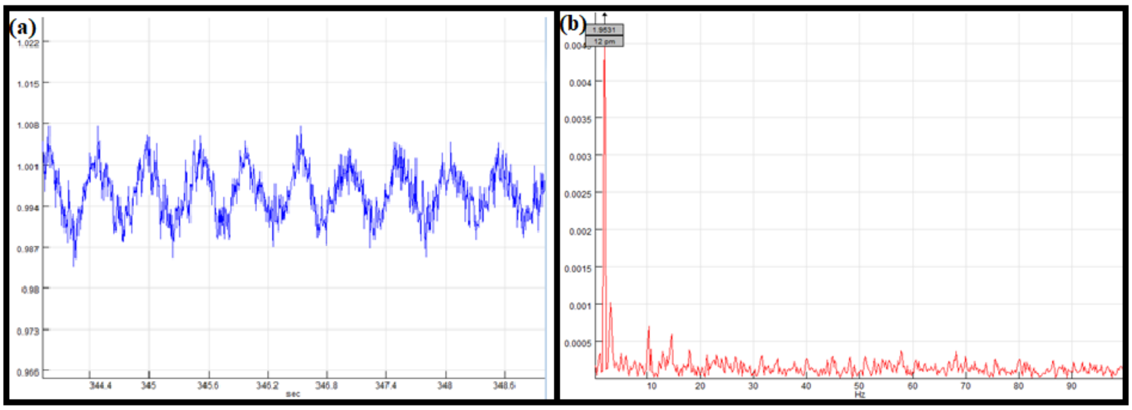

Figure 5. (a) Cut Signal; (b) Corresponding FFT Result.

From this FFT result, it is known that the first peak response is in the frequency of 1.9531 Hz. This may show the dominant mode of the bridge in bending direction. This may not be the first mode of the structure in global, since the first mode of the structure is known to be a lateral movement, and in the frequency of 0.5397 Hz.

This table below sums up the summary of the results of vibration testing, which shows the deviation of the obtained natural frequencies to 1.93 Hz, as a previously-pre-obtained natural frequency of the bridge.

Table 2. Summary of Obtained Frequencies of the Structure.

No.	Time	Temp. (°C)	Natural Freq. (Hz)	Deviation to Previous Vib. Testing (Hz)	Deviation (%)
1	12:14 PM	42.8	1.9531	0.0231	1.20
2	5:57 PM	37	1.92	0.01	0.52
3	3:19 AM	23.4	1.875	0.055	2.85
4	9:41 AM	32.6	1.9097	0.0203	1.05
5	1:52 PM	45.1	2	0.07	3.63

Table above shows that the natural frequency of the real bridge obtained by vibration testing was higher than of that by FE model. This may indicate that the real bridge has higher value of strength and/or stiffness. This may happen, since the stiffness of the concrete slab was neglected in the FE model. This plot below may show the effect of temperature changes to natural frequencies of the case study bridge, comparing the vibration testing results to FE model result.

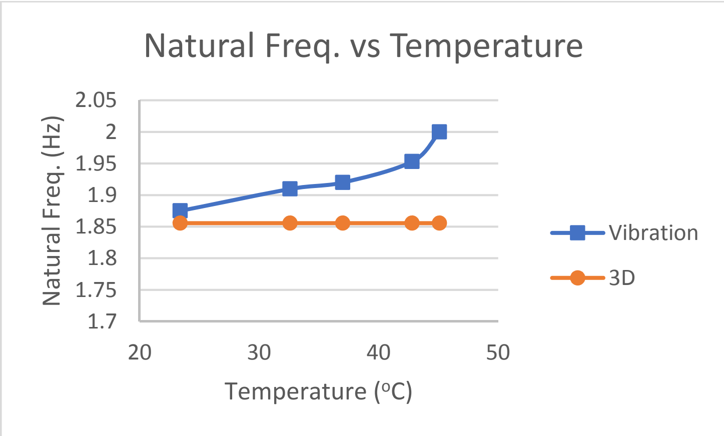

Figure 6. Natural frequency to the change of temperature.

Figure above shows that natural frequencies of the case study bridge rises up as the temperature increases. This may not be as the same as another previous researches about the effect of temperature changes to natural frequencies. Previous researches found that the natural frequency of a simple beam is inversely proportional to the changes of temperature. This may happen because the simple beam structure has pin and roll support, where elongation is allowed. However, in this case study bridge, elongation is prohibited, since the bridge has pin supports in all of the boundary condition, where the point must stay there.

This condition may lead the structure to experience an additional axial force due to the boundary condition. The structure itself wants to elongate, due to the temperature appraisal, however it may not be possible, due to the boundary conditions. Hence, according to the geometry theory, the structure may have additional stiffness in the stiffness matrices components.

Finally, the health index of the structure will be justified by using equation below, by calculating the different value of the natural frequency of the bridge in the daily average temperature of the bridge, that is in 32-33°C, so that the experimental natural frequency is taken to be 1.9097 Hz. Hence, the fitness ratio of the structure can be determined by utilizing this equation, proposed by Thomas (2009) [6].

$$FR = 1 - \left|\frac{1.8557 - 1.9097}{1.8557}\right| = 0.9709 = 97.09\% > 90\%$$

Hence, the structure is still in a health condition, since the fitness ratio is more than 90%.

6. Conclusions

These conclusions may be generated from this research:

1. The observed structure is still in a health condition, since the fitness ratio of the structure is more than 90%.
2. The natural frequencies of the real structure may have higher values than of it in the FE model, which means the real structure is stiffer than the modelled structure. And the observed structure is still in a safe and healthy condition by the time of the vibration testing.
3. Temperature changes may cause the natural frequencies of the case study bridge to change too in directly proportional way, due to the boundary condition of the structure.
4. Temperature changes may cause the natural frequency of this bridge to vary up to 3.63% to the common condition of the case study bridge.
5. Effect of temperature changes should be put into account to conduct structural health monitoring (SHM), since the alteration due to temperature changes itself might reach 3.63% in a range of 10% permission of the structure to change in natural frequencies according to the regulations.

Acknowledgement

This research is financially supported by the Directorate of Research and Community Engagement of Universitas Indonesia (DRPM UI) through Hibah Publikasi Internasional Terindeks Untuk Tugas Akhir Mahasiswa (PITTA) UI 2018 No. 7185/UN2.R3.1/ HKP.05.00/2018.

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