Estimating deterioration rate of a bridge using changes in natural frequencies

Maizuar and S J Akbar
Department of Civil Engineering, Universitas Malikussaleh, Aceh, Indonesia

Corresponding author: maizuar@unimal.ac.id

Abstract. Significant increased demand in heavy traffic loads towards heavy and long vehicles on roads could lead to an increase rate of bridge structural deterioration. This paper presents a methodological framework which can be utilized to estimate deterioration rate of a bridge using accelerometer sensor measurements. Deterioration rate is quantified using changes in natural frequencies of the bridge because it correlates with the reduction in structural capacity of a bridge. Using a case study bridge in Aceh Indonesia, the results of study show that dynamic monitoring framework using accelerometer sensor can be utilized to estimate deterioration rate of a bridge and ultimately it can be further used in the prediction of bridge residual life.

1. Introduction

There are around 93,000 bridges in Indonesia and most of them being over 50 years old [1]. It indicates that many of bridges may be experiencing structural deterioration due to the ageing process. Ageing bridge structures with accumulating damage from increased demand of domestic road freight and overweight vehicles have led to an increase in accelerating bridge structural deterioration [2]. In general, structural deterioration is closely correlated with a reduction in structural capacity of a structure. Such reduction could considerably reduce the service life of a bridge and ultimately the total collapsed of bridges [3,4]. Therefore, inspecting and monitoring bridges over time are required to ensure they have sufficient strength to withstand loads imposed on bridge structures. Further, developing a methodological framework that allows early detecting the structural deterioration of bridge would result in large cost savings attributed to structural maintenance and replacement.

In recent decades, numerous studies have been performed mainly aimed at developing practical approaches for evaluating structural performance deterioration of bridges, and in particular, to predict the condition assessment of structures [5]. Among these, the application of vibration measurement techniques was commonly used. This method was established based on modal dynamic characteristics of a structure e.g. natural frequency, modal shapes and damping ratios. Compared to modal shape testing, frequency measurement has several advantages such as relatively simple to measure and only requires a single measurement point. Therefore, frequency measurement allows monitoring structural performance deterioration in effective and efficient manner [3,6].

The structural performance of a structure can be quantified in term of capacity of the structure (e.g., resistance of material) [7]. The material resistance was closely related to characteristic modal parameters (e.g., natural frequency). Change of material resistance would change stiffness of a structure and so its natural frequency. When a structure put in operation, the structural capacity of the
component decreases because deterioration increases due change in material resistance (e.g., reduction of strength and stiffness). This may change natural frequencies of a structure because stiffness is proportional to material properties (e.g., elastic modulus, inertia). Therefore, change of natural frequencies can be used to estimate the structural performance deterioration of a structure.

Accelerometer sensor is a versatile and robust device that capable of monitoring structural movement and deformations. This sensor has been extensively used for estimating response of a structure (e.g., displacement, natural frequency) [8]. Structural responses obtained from accelerometer sensors are in the form of time histories of acceleration. It is therefore to compute structural response, the measured acceleration data need to be further processed. While the displacement of a structure can be easily determined by using double integration, natural frequency can be computed by assigning the measured acceleration data into Fast Fourier Transform (FFT).

Structural deterioration caused by traffic loading is a time-dependent phenomenon that continuously depleted at a rate over structural lifetime. The structural performance deterioration of bridges can be evaluated by its dynamic parameters (e.g., natural frequency). Although structural performance deterioration of bridges have been extensively researched (e.g., corrosion) [9], there is little research in which experimental study has been used to investigate changes of the natural frequencies of a bridge as a result of structural deterioration of bridges (e.g., traffic condition). The purpose of this study is to estimate the deterioration rate of bridges using changes in natural frequencies of a bridge. Changes in natural frequencies can be further used to predict bridge residual life.

2. Structural performance deterioration of bridges

The structural performance of bridges is affected by both external and internal factors such as the increase of traffic loading. Bridge is dynamically loaded by traffic loads travel on it [10]. The induced dynamic effect on bridges is greater than static load which result in excessive movement of bridges and so it can led to accelerating bridge deteriorating process.

Figure 1. Structural performance deterioration model of a bridge caused by traffic loads [11]

Figure 1 shows the structural performance deterioration of a structure. It can be clearly shown that the structural capacity of the structure decreases because of deterioration increases. It is quite obvious that structural deterioration is a time-dependent phenomenon that continuously depleted at a rate over structural lifetime. In this case, the failure of bridge might be caused by the accumulating damage from instantaneous degradation rate. The structural lifetime is usually characterized by threshold
values (e.g., $s^*$). Threshold $s^*$ represents the limit state performance level where the system cannot provide service in any circumstances and needs to be replaced. Then, the cumulated damage at a particular time is given as follow,

$$ D(t) = \int_0^t r(\tau) d\tau $$  \hspace{2cm} (1)

Where $D(t)$ is damage accumulation and $r(\tau)$ is rate of instantaneous degrading structure. It should be noted that the instantaneous degradation rate of a bridge is not always available at hand. Therefore, the degradation rate can be estimated by well-known methods (e.g., Jump Processes). Here, time-dependent degradation or damage rate is assumed as a sequence of small countable discrete changes in structural systems [11]. If $Y^p_i$ represents damage rate which occurs at a certain fix time interval ($\Delta t^p_i$), the accumulat ing of damage $D_p(t)$ is given by,

$$ D_p(t) = \sum_{i=0}^{n} Y^p_i $$ \hspace{2cm} (2)

Where $n$ is number of small countable discrete changes in structural systems. In this study, deterioration rate due to decrease in structural capacity is quantified based on changes of natural frequencies of the bridge as follow,

$$ Y^p_i = \frac{f_2 - f_1}{f_1} $$ \hspace{2cm} (3)

Where $f_1$ and $f_2$ are the measured natural frequency obtained from experimental tests.

2.1. Monitoring dynamic response of bridges using accelerometer

Over recent years, accelerometer sensors have extensively been used to measure shock and vibration of structures. These sensors have been evolved from traditional device to latest advanced based-sensing technology which allows not only capturing but also storing and transmitting a large volume of the measured accelerometer raw signal data. Vibration measurement using accelerometer usually consists of accelerometer sensors, analog or digital converter, microcontroller, battery and a laptop or PC [8].

The principle of accelerometer measurements were based on producing a force in the sensor and generating a small change in the current. When a signal created by a sensor, the area under the signal can be calculated. Generally, the force and mass are known, thus the acceleration can be easily calculated. The output signal from an accelerometer is in the form of accelerations time series. The displacement can be determined by integral method (Equation 4),

$$ s(t) = s_0 \times v_0 \times t + \int_0^t a(t) dt $$ \hspace{2cm} (4)

Where $s(t)$ is the displacement, $a(t)$ is the measured acceleration, $s_0$ is the initial displacement, and $v_0$ is the initial velocity. Accelerometer drift can be eliminated by signal-filtering to delete unwanted low frequency content in time-domain series.

Bridge structural deterioration can be evaluated using changes of the natural frequency because it correlates with the reduction in stiffness of bridge structures. The natural frequency is usually determined using spectral analysis method. In this method, the Fourier transform is used to convert signal from time-domain based ($f(t)$) to frequency-domain series ($F(\omega)$), which based on the following equation,

$$ F(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt $$ \hspace{2cm} (5)

For transforming the discrete measurement, the Fast Fourier Transform (FFT) method with the Hamming spectral windowing application can be used. FFT is an algorithm to calculate the discrete Fourier transform (DFT) for converting discrete measurement from its original domain (often time or space) to frequency domain, the DFT ($\hat{X}_k$) of $N$ sampled data is given by Equation 6 [12],
Where \( y \) is discrete measurement data and \( w \) is windowing functions. Another modal characteristic which can be used to estimate bridge dynamic behavior is its mode shapes. However, modal shape measurement requires multiple locations. Modal shape describes how the structure vibrates in each frequency. At a particular time, modal shapes can be identified more than one. A schematic diagram showing steps for determining natural frequency of a bridge is shown in Figure 2.

\[
X_k = \sum_{j=0}^{n-1} y_j w(j)e^{\left(\frac{2\pi i j k}{n}\right)}
\]  

(6)

Figure 2. A schematic diagram showing steps for determining natural frequency of a bridge

2.2. Proposed framework

The proposed framework for assessing bridge structural health is shown in Figure 3. It can be described step by step as follow:

- Collecting and analyzing the measurement of dynamic behavior of a bridge using Non Destructive Test (NDT) techniques (e.g. accelerometer).
- Computing the deterioration rate of bridges using changes in natural frequencies.
- Estimating the bridge residual life under prescribed load (e.g., traffic load) using life-cycle structural deterioration model. The structural capacity of the existing bridge structure subjected to the current and future demand in terms of probability is determined. Degrading structural capacity of the existing bridge structure can be estimated based on measurement data, i.e. changes in natural frequencies.
- Determining the bridge health condition and retrofit works if required. The bridge health condition is evaluated in term of maximum observed displacements and changes in natural frequencies. If the maximum observed displacements are under the allowable serviceability state requirement of the bridge specified in the code, then the bridge is considered in good condition. Although frequency measurement using accelerometers have been extensively used, their performance for bridge monitoring has some drawbacks such as expensive, time consuming, and accessibility problems.
2.3. Case study

The selected bridge in this study is Alue Raya Bridge. The bridge is one of the national highway bridges located in Aceh Indonesia. It was constructed in 1990 with two traffic lanes. The bridge is a 25.5m long and 8.75m wide PCI girder bridge. This bridge is constructed by five normal-I girders between two abutments. For the purpose of monitoring dynamic behavior of bridge, an accelerometer sensor was positioned underneath the bridge girder with the sensors location at the midspan of the bridge to capture the fundamental frequency of the bridge (Figure 4). In this measurement, the configuration of sensor with the output range of +/-2g and a sampling rate frequency of 100Hz were used. The measurements are taken during operational hours with traffic loads under operational conditions. Measurements were conducted several times for accuracy of the data measured.

Figure 3. The proposed framework for assessing bridge structural health

Figure 4. Measuring dynamic response of the bridge using accelerometer sensor
3. Results and discussion

The analysis of results provided by the accelerometer sensor measurements first can be observed through the output raw data of structural response. The data obtained from the measurement may include noisy signals. In this case, the measured accelerometer data should be processed by signal filtering. Signal filtering is used to eliminate noisy signals and to determine the natural frequencies via peak picking method. Signal filtering procedures can be found in many literatures [13]. The accelerometer sensors can provide acceleration measurement in 3-axis direction. The measurements and data storage are controlled through a laptop or computer for further analysis. The velocity and displacements were then computed by using numerical integration. Figure 5 shows samples of the measured data which include original raw data before and after signals filtering.

![Figure 5](https://via.placeholder.com/150)

(a) Before filtering  
(b) After filtering

**Figure 5. Measured accelerometer measurement data (a) Before filtering (b) After filtering**

Natural frequencies which characterize dynamic behavior of bridges were be determined by converting acceleration time series into the FFT analysis. In frequency spectra, natural frequencies are identified by the peak amplitude in the spectrum response. Table 1 shows the natural frequencies of the bridge structure obtained from measurements for six months. It can be seen that changes of natural frequencies of the bridge is around 0.065% per month. Changes in natural frequencies of the bridge obtained are consistent to that of previous theoretical and experimental studies [14]. The vibration of the bridge is below the allowable serviceability limit state requirements of the bridge (e.g., L/480) and so the bridge is in good condition [15].

| Measurement period | Natural frequency (Hz) | Deterioration rate (%) |
|--------------------|------------------------|------------------------|
| Month 1            | 4.32722                | 0.00000                |
| Month 2            | 4.33002                | 0.06470                |
| Month 3            | 4.33282                | 0.06466                |
| Month 4            | 4.33565                | 0.06531                |
| Month 5            | 4.33848                | 0.06527                |
| Month 6            | 4.34131                | 0.06523                |

Table 1. Deterioration rates of the bridge using changes in natural frequencies

It has been known that structural deterioration correlates with the reduction in structural capacity that continuously degraded at a rate over structural lifetime. The rate of deterioration (damage rate) is
usually used to estimate residual life of bridges. Here, the reduction in structural capacity of bridges is evaluated by its dynamic parameters (e.g. natural frequency). Using Equation 3, deterioration rates of a bridge which is quantified based on changes in natural frequencies within six months measurement period (Table 1). It can be seen that damage rate of the bridge increase proportionally with time.

4. Conclusions
A structural monitoring framework for assessing the dynamic behavior of bridges was presented. The application of accelerometer sensors is utilize to predict health condition and deterioration rate of a bridge caused by the increased demand of heavy traffic loads. Dynamic characteristic of a bridge (e.g., changes in natural frequencies) was used to estimate deterioration rate of the bridge. Changes in natural frequencies correlate with the reduction in stiffness of a structure. Using a case study bridge in Aceh Indonesia, the results of the study show that deterioration rate of the bridge caused by increased demand of traffic loads is approximately 0.065%. While results obtained in this study are very promising, further model development is clearly required to estimate the residual life of bridges.

References
[1] Imran, I., D. Hoedajanto, and I. Zarkasi, 2014. Bridges in Indonesia: Present and future, in International forum, JSCE century anniversary. Tokyo, Japan.
[2] Maizuar, M., et al., 2020. Structural health monitoring of bridges using advanced non-destructive testing technique, in ACMSM25. Springer.
[3] Maizuar, M., et al., 2017. Detecting structural damage to bridge girders using radar interferometry and computational modelling. Journal structural control and health monitoring, 24(10): p. 1-6.
[4] Maizuar, M., L. Zhang, and S. Miramini, 2018. Structural monitoring of Eltham Rail Trestle Bridge using advanced non-destructive testing techniques, in 9th International conference on bridge maintenance, safety and management. Melbourne.
[5] Kafle, B., et al., 2017. Monitor the dynamic behaviour of the Merlynton creek bridge using interferometric radar sensors and finite element modelling. International journal of applied mechanics., 9(1): p. 1750003-1750023.
[6] Zhang, L., et al., 2016. Monitor the dynamic behaviour of concrete bridges using non-contact sensors (IBIS-S). Applied mechanics and materials, 846: p. 225-230.
[7] Zhang, L. and M. Maizuar. 2018. Reliability-based model to determine the residual life of bridges. in Symposium on Reliability Engineering and Risk Management (6ISRERM). Singapore.
[8] Maizuar, S.J. Akbar, and Salahuddin, 2020. Developing a low-cost vibration measurement system prototype for bridges using accelerometer sensors: A review. International journal of psychosocial rehabilitation, 24(2): p. 12-19.
[9] Sánchez-Silva, M. and G.-A. Klutke, 2016. Reliability and life-cycle analysis of deteriorating systems. Springer series in reliability engineering. Springer.
[10] Maizuar, L.Z., R. Thompson, and H. Fithra, 2017. Life-cycle performance of a bridge subjected to multiple heavy vehicle impacts. Proceedings of MICoMS, p. 13-18.
[11] Maizuar, et al., 2018. A reliability-based approach for highway bridges subjected to progressive deterioration, in 1st International Conference on Multidisciplinary Engineering (ICoMdEn): Advancing engineering for human prosperity and environment sustainability. Lhokseumawe - Aceh, Indonesia. p. 1-7.
[12] Kohaupt, L., 2015. Introduction to the discrete Fourier series considering both mathematical and engineering aspects - A linear-algebra approach. Cogent education, 2(1): p. 1-29.
[13] Moschas, F. and S. Stiros, 2011. Measurement of the dynamic displacements and of the modal frequencies of a short-span pedestrian bridge using GPS and an accelerometer. Engineering structures, 33(1): p. 10-17.
[14] Peeters, B. and G. De Roeck, 2001. One-year monitoring of the Z24-Bridge: environmental effects versus damage events. *Earthquake engineering & structural dynamics*, 30(2): p. 149-171.

[15] Standard, I., 2002. Standard Specifications for Concrete Structures, SNI 03-2847-2002. BSN Indonesia: Jakarta. (*In Bahasa*)

**Acknowledgement**

The authors wish to thank Hibah Penelitian Dasar Kemristek Dikti 2019 research grant, BMKG Stasiun Geofisika Banda Aceh, Balai Pelaksanaan Jalan Nasional-I Aceh, LPPM Universitas Malikussaleh, David Firmando, Sri Ganti, Firman Hidayat and Agem Neneng Kasmiani for their support.