Developing a low-cost vibration measurement system prototype for bridges using accelerometer sensors: A review

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ABSTRACT--*Bridges are invariably subjected to several types of hazards such as traffic loading, aging condition and sudden extreme events. However, under the increase heavy traffic loading, the structural damage of a bridge could be accelerated. Excessive vibration and displacement induced by moving vehicles could considerably effect on the reduced service life of bridge structures. This paper presents a low-cost vibration and displacement measurement system prototype on bridges using wireless accelerometer-based sensing technique. In particular, this study reviews the advantages and capabilities of the measurement used in the recent studies. The results of this study could provide an alternative method in the selection of the appropriate approaches related to the bridge dynamic monitoring.*

Keywords--*low-cost; vibration measurement; accelerometer; bridges.*

I. INTRODUCTION

Bridges are critical transport infrastructure networks. It also provides subtantial benefits in economic, environmental, and social aspects for our society. In general, bridges are designed on overage 50-75 years and so the structure may be exposed to several types of hazards (e.g., traffic condition, sudden extreme events, etc.) [1-3]. Consequently, the bridge structures may deteriorate or possibly fail (*e.g.*, unable to perform its designated function) before completion of the mission. Further, structural deterioration can be more vulnerable especially for ageing bridges subjected to an increased traffic condition. Therefore, the development of innovative way for assessing and monitoring the bridge structural health is of paramount importance [4, 5].

Structural health monitoring techniques and methods of bridges have been developed in the past decade. Such methods include vibration testing of bridges (*e.g.* accelerometers) [6]. These sensors have been successfully and widely used in monitoring dynamic behavior of bridges under operational condition due to its relatively inexpensive, simple and accurate [7]. Other devices such as Linear Variable Differential Transformer (LVDT) which uses data logger usually require hardwiring from transducer to a data acquisition system. It also disrupts the

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traffic flow during field test. Laser sensors have limitation in detecting the overall deformation of a bridge and are very sensitive to dust and change of environmental conditions [8].

Monitoring dynamic behavior of bridges under operational conditions is becoming more popular in recent years and hundreds of bridges have been tested worldwide [9]. Such dynamic tests are generally conducted using piezoelectric sensors or accelerometers. These sensors are capable of determining time histories of acceleration of structures. It also can estimate the displacement of a structure. The natural frequency of a structure can be obtained as structural response caused by induced vibration such as vehicles movement.

Over recent years, monitoring vibration and displacement induced by moving vehicles using accelerometer have been thoroughly researched. In this context, many design accelerometer system prototypes for bridges has been developed [10]. Among these, the application of a monitoring device equipped with Micro Electro-Mechanical Systems (MEMS) has been considered to be a cost-effective way of monitoring the structural integrity of a bridge based on the dynamic characteristics of a structure [11, 12]. Testing of various civil engineering structures worldwide has demonstrated high accuracy of MEMS accelerometers for prediction of the modal parameters over traditional testing instruments. It was also reported that MEMS is a good alternative device to standard vibration measurements because they do not require heavy electrometric amplifiers [13]. Given the large amount of bridges in Indonesian road network, employing a reliable tool for structural health monitoring of bridges at low-cost, on-site monitoring and real-time simultaneous analyzing of vibration are needed. Therefore, this paper is aiming at developing a vibration and displacement measurement system prototype for structural health monitoring of bridges using wireless MEMS accelerometer-based sensing technique. The vibration signal acquisition system is based on the Arduino micro-controller connected with wireless networks and transmitted data to a personal computer. The acquisition data in real-time is displayed and processed by a developed code under LabVIEW software.

II. LOW-COST SENSING SYSTEM FOR STRUCTURAL MONITORING OF BRIDGE

A low-cost accelerometer and low-cost Arduino Uno formed a cost-effective system of monitoring dynamic behavior of bridges. Accelerometer is a sensor device which can be used to detect vibration, measure acceleration, velocity, distance or position of a structure. The accelerometer sensor system has been extensively used for the analysis of a broad range of experiment in the field of automobile, buildings, security, computer, communication, seismic and navigation applications. If a signal generated by a sensor can be obtained, the area under the signal at a particular time can be determined using Integration method (Figure 1).

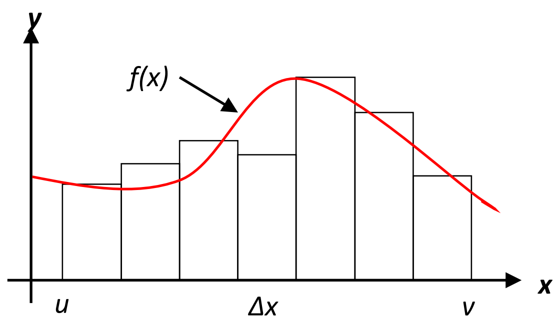

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Figure 1: Integration of a signal at a particular time [14]

$$\int_{u}^{v} f(x)\ dx = \lim_{n \to \infty} \sum_{i=1}^{n} f(x_i)\, dx \tag{2}$$

$$\Delta x = \frac{v - u}{n} \tag{3}$$

The integral solution for Equation 2 may contain error. However, it can be optimized and solved numerically by using well-known approach (e.g., Runge-Kutte).

In this study, a low-cost accelerometer MMA8452Q is used. It is a capacitive accelerometer produced by NXP Semiconductors. The sensitivity of this accelerometer is less than 1mg/LSB with selectable measurement ranges ±2 g, ±4 g, and ±8 g. It is also a low-power consumption device and use low-pass filters to eliminate unwanted high frequencies in time series. Figure 2 shows sample of MMA8452Q accelerometer.

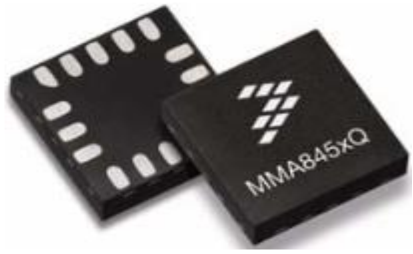

Figure 2: View of the MMA8452Q accelerometer [15]

Figure 3: The Arduino Uno microcontroller hardware [16]

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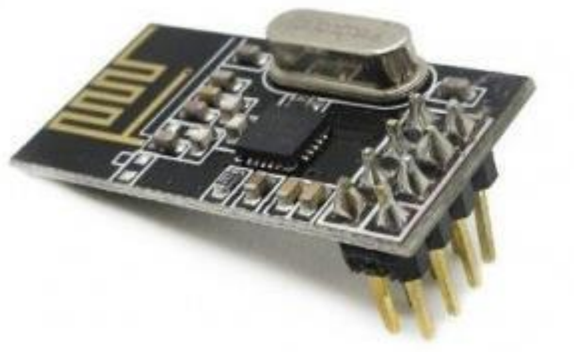

Figure 4: The wireless transceiver NRF24L01 module [17]

The Arduino Uno board is a low-power microcontroller that runs as the data acquisition unit (Figure 3). It operates at voltage of 5V, 14 digital input/output pins, and 6 analog input/output pins. A USB cable or an external power supply can power the Arduino board. The Arduino Uno consists of a micro-controller (programmable circuit board) and a bit of programming software, or Integrated Development Environment (IDE) that acts on a personal computer, used to write and transmit PC code to the physical board. It has been used in many different projects and applications [18]. Compared with many other micro-controllers, the Arduino language programming is convenient and flexible for both beginners and advanced users. Some advantages of Arduino controller include: (1) inexpensive (2) Cross-platform (e.g., Windows, Linux, and Macintosh) (3) Simple, clear programming environment (4) Open source, extensible software and hardware. Data collected by the micro controller is transmitted to a PC via the transceiver module of nRF24L01 to store the acquired signal, process the data, and view the initial results in real-time.

The nFR transceiver is a wireless communication device using radio frequency wave. This device is an ultra-low power which operates in the 2.4GHz ISM frequency band with 2Mbps radio frequency transceiver as shown in Figure 4. It can be used both as transmitter and receiver data. The nFR is also a low-cost wireless transceiver designed for long distance measurement as well as high speed communicating data. The approach for processing and displaying the data of the accelerometer measurements is developed using LabVIEW code.

III. METHODS

Bridges are dynamically loaded by vehicles travel on it. As a consequence, bridges will undergo vertical displacement which is proportional to load given. The magnitude of displacement is detected by an accelerometer sensor (e.g., MMA8452Q). To measure the vertical displacement, only vibration in z-direction is recorded. The accelerometer sensors measure change of voltage and transmit it to micro-controller for signal processing. Then, the recorded data is transmitted to a personal computer using nRF wireless device. **Figure 5** shows a schematic diagram of block system for monitoring dynamic behaviour of bridges. In a personal computer, data can be displayed using well-known application program such as LabVIEW. The measurement output can be displayed as time-history displacement at a particular time. Changes of displacement are measured in *cm* while changes of time are measured in *second*.

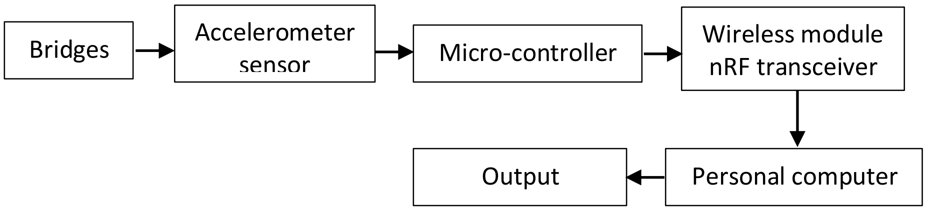

Figure 5: Schematic diagram of block system for monitoring dynamic behavior of bridges

IV. RESULTS AND DISCUSSION

A design prototype for vibration and displacement measurement using accelerometer sensor is developed. The capability of this sensor system is to analyze the dynamic behavior of the bridge using the data's collected from the accelerometers which are mounted on bridge. Accelerometer is a widely used device for application such as wrecking of bridges and damage of bridges for bridge monitoring. Figure 6 shows a design prototype of vibration measurement. It consists of an accelerometer, a microcontroller, a radio transceiver, two antennas, a battery and a personal computer. This system has simple structure, low-cost manufacturing and low-power consumption. Also it is sensitive to the low frequency vibration which is the prominent characteristics of the vibration occurring by vehicles moving across a bridge.

Structural dynamic deformations by accelerometers can be analyzed in term of determining the relative displacements and a spectral analysis of the vibrations in the frequency domain. The output signal of accelerometer sensors is generated in the form of accelerations time series. To obtain relative displacement that are of particular interest can be determined by double integration method. For determining a spectral analysis of the vibrations in the frequency domain, the Fast Fourier Transform (FFT) algorithm with application of Hamming spectral window function is used. The Fourier transform is the common method for the transformation a signal from a time domain to a frequency domain. The result of accelerometer may contain long-period components of the measured signal which can be eliminated by high filter of low frequencies in time series. In this study, the Kalman filter method is adopted. Kalman filter is a relative simple form and an efficient recursive filter that has capability of estimating the internal state of a linear dynamic system from a series of noisy measurements. It has been used in particular for minimizing the correlated noise of MEMS sensors [19]. Peak frequencies from the discrete frequency spectrum can be estimated by known statistical test of periodicity (*e.g.*, the Fisher's asymmetric test). A schematic diagram describes steps for data processing is shown in Figure 7. In a personal computer, the acquired data be viewed by developing algorithms using well-known application program such as LabVIEW software (Figure 8).

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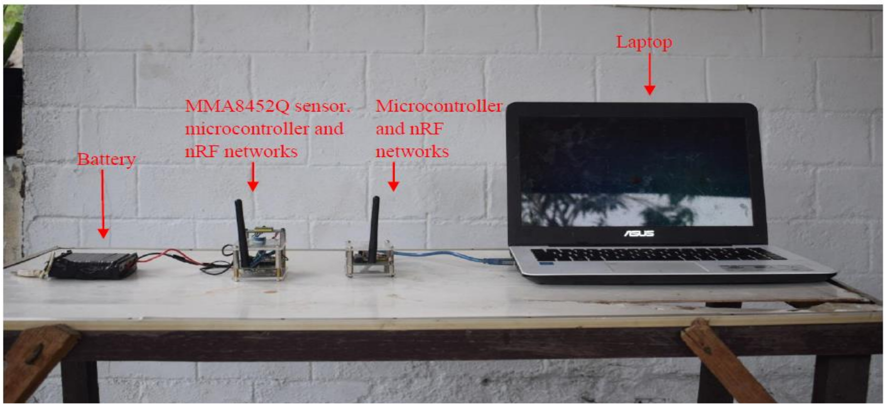

Figure 6: Design prototype of vibration measurement

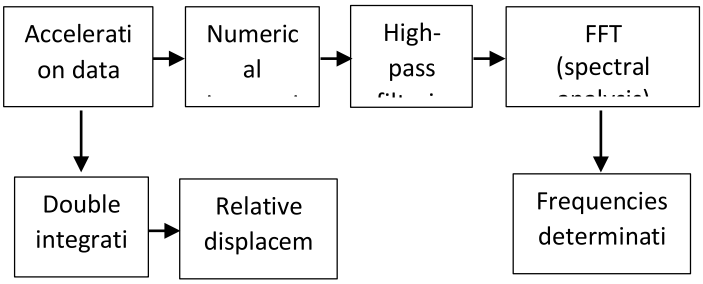

Figure 7: Steps for data processing of output signal generated by an accelerometer

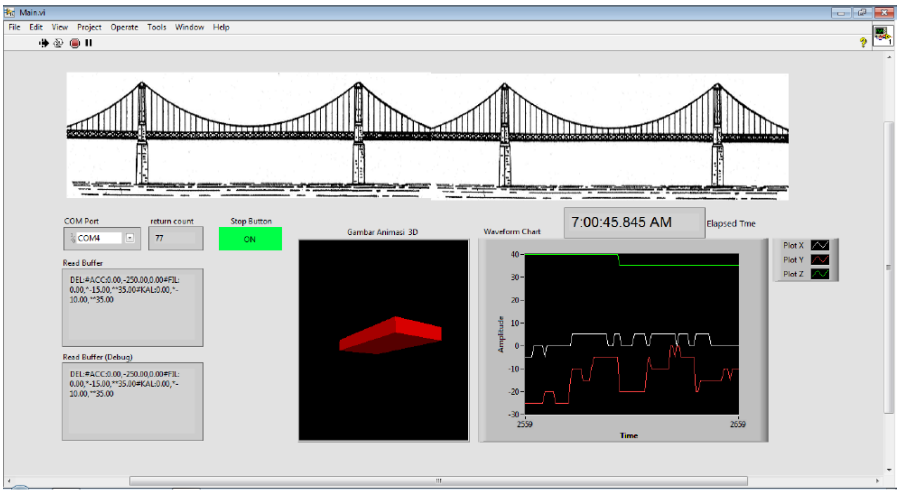

Figure 8: View of initial results developed by LabVIEW code

V. CONCLUSIONS

A design of vibration and displacement measurement system prototype on bridges using accelerometer sensing technique was developed. The model has capability of monitoring dynamic behavior of bridges such as displacement and natural frequency. While the model outcomes are very encouraging, further development on the capability of the model for long-term monitoring is clearly required. The results of the study could provide an alternative method in the selection of the appropriate approaches related to the bridge dynamic monitoring. Further, the development of low-cost vibration measurements also has the potential to reduce structural health monitoring costs which allow transport authority to perform rapid assessment of the structural health of bridges, detection of ongoing damages and thus enabling refined and safe transport infrastructures. For a long term real-time monitoring dynamic behavior of bridges, an appropriate and sufficient power supply is required.

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