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Three-dimensional Visualization of Dynamic Oscillation of Structural Components using Inhomogeneous Wireless Sensors

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Abstract

A three-dimensional visualization system was developed to investigate the dynamic state of bridge components using portable sensors located at multiple points. The system utilizes wireless data transfer and real-time signal processing for on-site output of the dynamic oscillation of bridge components. Vibrational modes (bending, twisting, and translation) are determined upon excitation by an external load. In this study, a sensor fusion technique was introduced to enhance the accuracy of motion visualization. An angular velocity sensor and an accelerometer were mounted within each sensor box. The same sensor boxes were prepared, and boxes were placed at 12 positions in all. The performance of the system was checked using a mock-up reinforced concrete beam. In cyclic loading tests of the mock-up, variations in the natural vibration frequency and its mode shape were observed. It was shown that disturbance of the initial motion may be used to detect crack initiation, and that changes in the mode shape may be used to detect the location of the damaged area.

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Keywords: MEMS, wirelss multisite measurement, vibration, three-dimensional visualization, mode shape, mock-up of RC beam

1. Introduction

The quantitative evaluation of the damaged state in structural components is an important issue from the viewpoint of the maintenance strategy of infrastructure in Japan, especially concerning the safe use of more than seven hundred thousand bridges by the public. Some bridges on arterial roads and highways are constantly monitored using sensors embedded within components [1,2]. However, it is impossible to introduce regular monitoring with embedded sensors

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for bridges located in rural areas, due to the high cost. At present, visual inspection is conducted once every five years according to the routine inspection guideline set out by the Ministry of Land, Infrastructure and Transport in Japan. In addition to visual inspection, inspection based on the information of dynamic state is necessary for more accurate diagnosis. Thus, a device that consists of portable sensors and a control interface is needed for more efficient and practical inspections.

We developed a vibration measurement system that has wireless sensors placed at multiple points [3,4]. The system can be produced inexpensively because it is equipped with micro electrical mechanical system (MEMS) sensors. The vibration at multiple points can be simultaneously measured, allowing for observation of the three-dimensional (3D) shape of the vibrational modes in real time. Although many studies of wireless measurements using MEMS acceleration sensors have been reported in recent years [5,6], the novelty of the current research is the introduction of a sensor fusion technique [7] that enhances the accuracy of motion visualization. In this study, angular velocity sensors and accelerometers are used in the sensor fusion. Visualization makes it possible to not only obtain the movement of bridge components entirely but also to effectively locate the damaged areas.

As an application of our system, we investigated the dynamic behavior of a mock-up reinforced concrete (RC) bridge beam. In cyclic loading tests of the RC mock-up, we observed variation in the natural frequency and shape of the vibrational mode. Over the past few decades, research has been conducted in the area of structural damage detection by using the frequency shift that occurs when a load is applied [8]. Although the shift in natural frequency is an effective indicator that can be used for diagnostic purposes, it does not readily provide the location of the damage [9,10]. In this study, we determine the timing of crack initiation and the state of crack growth by observing the initial motion of the vibration and changes in the mode shape.

2. Measurement system for three-dimensional visualization of dynamic behavior

2.1. Hardware configuration

As shown in Fig. 1, the waveform collection system is composed of a wireless sensor node, a wireless router, and a laptop at the base station. The wireless sensor node has two MEMS sensors, which can measure triaxial acceleration (Kionix, KXR94-2050) and biaxial angular velocity (Murata, ENC-03R). It transmits voltage signals to the data transfer device through Bayonet Neill–Concelman (BNC) cables. The data transfer device is a WLS-9215 developed by National Instruments Corporation. The voltage signal is transformed into digital data using an analog-to-digital converter, and the digital data are sent to the laptop at the base station through a wireless LAN router. Therefore, all the digital data is stored at the laptop. In cases where we measure acceleration of the 3D axes at a sampling rate of 10 kHz, transfer speeds of about 0.48 Mbps (= 10 k × 16 bit × 3 axes) are needed. The nominal transfer speed of IEEE802.11g is 54 Mbps; therefore, approximately 112 nodes can be logically linked. For the experiment, we use a total of 12 sensor nodes. Half of the sensor nodes can measure both acceleration and angular velocity, and the rest can measure only acceleration. The wireless local area network transmits a header and footer with the transmission data packet; therefore, data loss never occurs and the data can be easily interpreted. The time synchronization of each sensor node is important and accurately determined using the pulse per second (PPS) signal sent from the global positioning system (GPS) sensor through the GPS signal receiver sensor (Navisys Technology, GM-316). The PPS signal error is less than 1 μs. By using the signal from the GPS to conduct the time synchronization, a sampling rate of approximately several thousand hertz can be achieved with accuracy.