APPLICATION OF SMART SENSORS FOR BRIDGE VIBRATION MEASUREMENT UNDER LOW TEMPERATURE ENVIRONMENT

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ABSTRACT

A vibration based Structural Health Monitoring (SHM) is expected to be a key technique to improve structural safety. In general application of SHM, an algorithm takes the year to year change in vibration characteristics and then diagnoses the condition of a structure. Its sensors must be located at a high density in order to determine little changes of the structural dynamic response. A conventional wired sensor system is not efficient in the SHM because such traditional sensor system takes installation time and costs.

A smart sensor which is an electronic device using MEMS (Micro Electro Mechanical Systems) has a potential to enable efficient vibration measurement because of its wireless communication function and on-board processing ability. The authors have developed a smart sensor system that meets requirements under low temperature environments where civil structures are exposed. The Imote2 smart sensor system is applied in such studies.

In this study, the authors performed a vibration measurement experiment on a curved PC box girder viaduct in winter season. 10 smart sensors are placed on the coping in the main span. The fundamental natural frequency of the viaduct and its mode shape are obtained from traffic-induced vibration. These vibration characteristics are equivalent to the measurement results that were taken when completed 12 years ago. As a result, it is considered that the viaduct has maintained structural integrity from the point of dynamic characteristics and smart sensor system can be applied to bridge vibration measurement as an efficient monitoring device.

Keywords: Smart sensor system, Structural Health Monitoring, Low-temperature environment

1. INTRODUCTION

Civil structures need huge maintenance cost because the number of structures which are in service more than 50 years have increased year by year in Japan. However, it has been pointed out that

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there is no consistency in the results in the visual inspection (Oshima et al. 2001). For this problem, Structural Health Monitoring (SHM) is considered as a reasonable solution for maintaining the service level of infrastructures by using real time monitoring of structural integrity. To monitor structural condition appropriately, it is required that a structure has adequate number of sensors with enough accuracy. Therefore, there is a motivation to develop less expensive sensor system for application to SHM.

Smart sensors which have low-cost MEMS sensor with a data processing function and a wireless communication function have been researched to allow efficient measurement in structural monitoring (Nagayama and Spencer 2007 ; Nagayama et al. 2009). Smart sensor is application of MEMS and it is complex of precision electronic devices. Moreover smart sensor has a wireless communication function and a data processing function to the terminal itself by it installing the combination of processor and memory and a wireless communication chip. As an essential technology for use in the vibration characteristics identification of the bridge, the MEMS sensor need to have time synchronization and packet loss measures in wireless communication. The Imote2 is one of prototype smart sensor system which meets demands for SHM application such as advanced wireless communication technology and high performance processor speed.

However, there are not sufficient experiences for bridge vibration measurement using smart sensor systems. In field measurements, weather protection and power supply for devices should be well considered to ensure its reliability. Especially there are several problems in cold environment, low temperature shortens battery life and insufficient input voltage causes wrong measured data. The authors have developed versatile devices for bridge vibration measurement using smart sensors. Its applicability has been examined by vibration measurement tests in a real structure. In this study, a measurement result in 3 span continuous PC box girder viaduct is reported and it is compared to the original vibration characteristics obtained 12 years ago.

2. SMART SENSOR SYSTEM FOR BRIDGE VIBRATION MEASURMENT

2.1. Imote2 Smart Sensor System

The smart sensor system used in this study is Imote2 from Crossbow shown in Figure 1. The Imote2 consists of 3 electronic circuit boards. A sensor board obtains acceleration and other physical phenomena. A processor board has ability to perform calculations with CPU and memory chip. Wireless communication function is provided by a radio chip and an antenna on the processor board. A battery board supplies input power to both sensor board and processor board. Several types of sensor boards are available for Imote2 system. The SHM-A and SHM-H sensor boards have been developed at the University of Illinois (ISHMP 2009a ; ISHMP 2009b). The SHM-A equips 3 MEMS accelerometers. Acceleration corresponding to the least significant bit (LSB) of the AD converter is about 0.14gal. The AD converter can select a cut-off frequency and sampling frequency according to predominant frequency of measured vibration. The SHM-H has sensitive

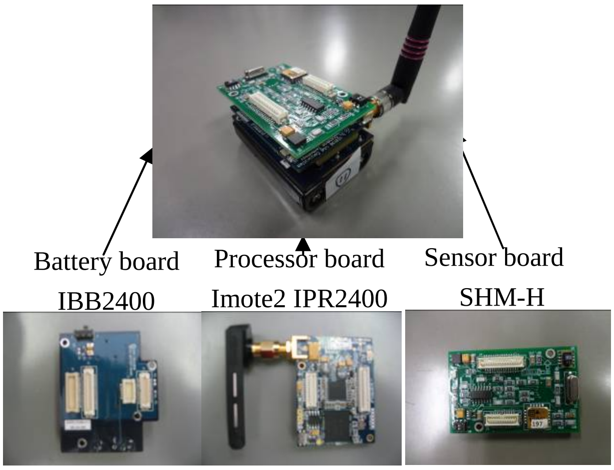


Figure 1: Imote2 smart sensor

Figure 2: Constant power supply system

accelerometer in z-axis. The same accelerometers of SHM-A are installed in x and y-axis. SHM-H can be switched measurement range -0.2 ~ 0.2G or 0.8 ~ 1.2G in the z-axis. Acceleration corresponding to the LSB of the AD converter is about 0.014gal for z-axis which is 10 times of x and y-axis.

Processor board executes a program for acquiring and processing data. The acquired data on each Imote2 sensor is sent to the central Imote2 connected a PC. The individual sensor is called “leaf node” and the central Imote2 is called “gateway node”. The processor board consists of PXA271 CPU, 256kB SRAM, 32MB SDRAM and 32MB FLASH memory. And its radio transceiver corresponds to an effective data rate of 250 kbps in the 2.4GHz band. The original Imote2 has a built in antenna and it is also exchangeable to an external antenna via integrated SMA connector. In this study, wireless communication distance is about 100m by using the external antenna. However actual distance is quite different by the existence of metal members and other obstacles.

The Imote2 processor board needs an operating system and application programs as same as general computer systems. In this study, the Tiny OS is chosen for the operating system and BHELMO (JIP Techno Science Corp.) is installed as application programs. BHELMO is a package of GUI-ized vibration measurement programs based on the ISHMP services toolsuite which is a middleware package developed in University of Illinois. The software performs multi-hop communication for transmitting and receiving data via the leaf nodes to each other. By performing multi-hop communication, it is possible to extend the communication distance to bypass the obstacle.

The original battery board operates by 3 AAA battery cells and provides power to the Imote2 system via connectors. A mini-B USB connector is also utilized for power supply to Imote2. The drive voltage range of Imote2 is 3.2 ~ 4.5V on the data sheet (Crossbow 2007). However if the voltage is less than 3.6V, an error may occur in measurement by an authors’ previous study (Miyamori et al. 2012). Therefore it is very important matter that a smart sensor system ensures the appropriate power supply. The AAA batteries in the original battery board are insufficient for multi node measurement on real bridges generally taking about a day. Moreover, the original Imote2 system is provided without any case by the manufacture. An appropriate housing should be applied to the sensors to prevent undesirable effect from such as rain, dust and extreme temperature. To satisfy above necessary condition, a constant power supply system with housing is developed for bridge vibration measurement under low-temperature environment in this study.

2.2. Constant power supply system

In order to use a smart sensor for a civil structure, protection apparatus with the waterproofness which can be used outdoors is needed. In addition, the original battery board of Imote2 operates by the 3 AAA type batteries. Since the capacitance is small and the operating voltage is also limited, it is necessary the battery replacement during an experiment. The validity of measured data needs to be checked in each sampling because lower voltage may also cause error. By supplying a constant voltage, stable measurement is achieved and efficiency is also improved. Therefore the constant voltage feed system as shown in Figure 2 is developed in this study (Watasaki et al. 2013). A small plastic kitchen storage box gives waterproof function. Thin closed-cell extruded polystyrene foam panels inside the box works as thermal insulator for extending battery life. The system uses 6 AA rechargeable Ni-MH cell batteries in a series connection and the battery box is connected to Imote2 via constant-voltage circuit using a 3-Terminal regulator. The constant-voltage circuit adjusts the supplied voltage from over the 8.4V to 4.5V. The capacitance of 6 AA batteries is enough for one day measurement in bridge site.

3. THE VIBRATION MEASUREMENT EXPERIMENT ON PC VIADUCT

3.1. Target viaduct and experimental methods

A vibration measurement test in real structure is performed to examine applicability of the developed constant power supply system for Imote2 smart sensors. A 120m 3 span continuous curved PC box viaduct, which was completed in 2001, is the target structure. The experiment has been done in the February 2013. The SHM-H high sensitivity sensor boards are applied to capture small amplitude vibration of a concrete structure.

10 sensors were placed on the center span of the viaduct. 5 sensors are on upstream side and the others are in downstream side as shown in Figure 3. The constant voltage supply system is applied to 8 sensors. For comparing the performance of the developed system, one sensor equips the original AAA batteries and the other sensor equips the power supply system with D cell batteries and a long distance antenna developed by JIP Techno Science Corp. The sensors were fixed with double-sided tape on the steel plate which was placed on the coping.

The traffic induced vibration was measured in accordance with the passage of large vehicles such as bus or trailer track. The sampling frequency is 280Hz and the number of data points in each sample is 16800 points. The 3-axis acceleration is recorded. During 4 hours experiment, 10 samples of

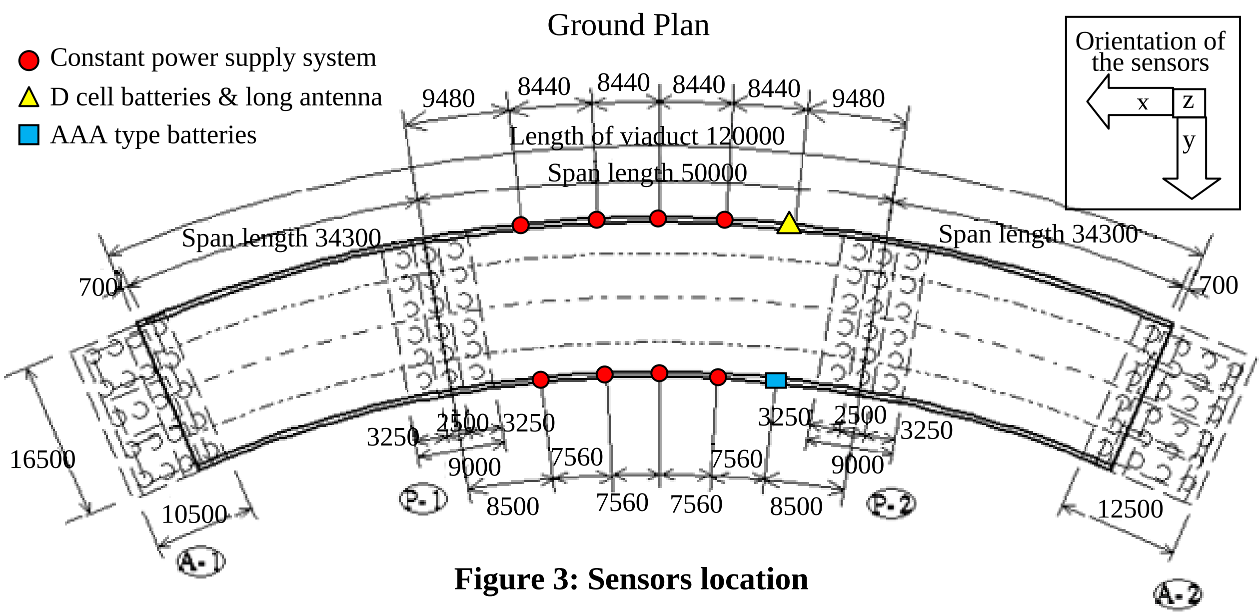


Figure 3: Sensors location

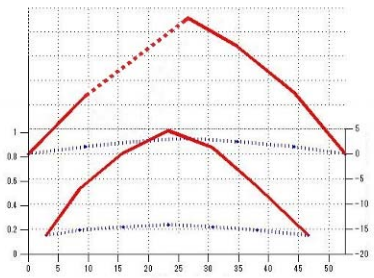
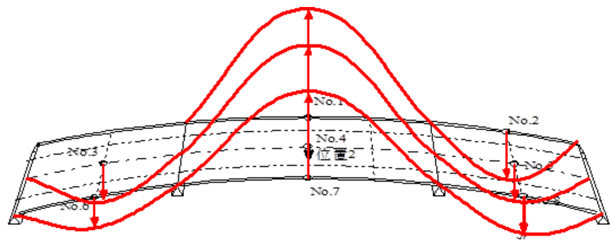
vibration data were corrected and the original AAA battery system needed 3 battery replacements because of voltage shortage. The proposed power supply system keep constant voltage level between 4.3 ~ 4.6V.

3.2. Structural vibration characteristics and comparison with past measurement

The fundamental natural frequency of the main span of the viaduct is determined by peak picking of the power spectrum of z-axis acceleration. The 1st mode natural frequency is 3.068Hz from average of 10 samples. The damping ratio is calculated from the damped free vibration after a vehicle passing through the span. The mode shape is obtained from the filtered wave amplitude in each sensor node. The result is summarized in Table 1. Since the data was not obtained in one sensor on the upstream side, a dotted line complements the mode shape. The mode shape shows symmetrical bending vibration and its amplitude is smaller on the downstream side because this is the curved viaduct.

Table 1 also shows comparison of vibration characteristics between this study and past measurement. The past measurement of this viaduct was conducted in November 2001 just after completed construction. In the past experiment, 9 wired strain gauge type accelerometers were distributed in the main span and 2 side spans. Free damped vibration was measured after a dump truck over the step. Data processing method was the same as the experiment in 2013. In the center span, natural frequencies and mode shapes shows substantially the same to the 2013 experiment result. It has considered that the bridge have not changed significantly from the point of view of vibration characteristics.

Table 1: Natural Frequency and Mode Shape

Experiment	February 2013	November 2001
Natural frequency	3.068Hz	3.063Hz
Damping ratio	0.014	0.013
Mode shape	 The main span only	 The main span and side spans

4. CONCLUSIONS AND FUTURE WORKS

In this study, smart sensors with the constant power supply system are applied to vibration monitoring in the actual bridge structure. The measurement result is compared to the result in 2001. It is considered that there is no significant change in the bridge itself from the point of view of vibration characteristics because the fundamental natural frequency and the mode shape have not changed from both results. It was also demonstrated that the constant power supply system to be useful in this experiment.

Smart sensors could perform measurement easier than wired sensor because of short installation time. The application of smart sensor in bridge structures is useful for SHM which dense and periodic measurement is required. As a further study, continuous measurements should be conducted on the viaduct.

5. ACKNOWLEDGMENTS

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