Development of a damage identification monitoring system for building structures

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Abstract

In Japan, deterioration of the building structures in 1970's becomes a social problem. They become lifelong duration due to be fixed and repaired. Therefore, it is important to check and manage the building structures on a daily basis. However, there are two problems of the checking. One is a shortage of specialists of the checking, the other is place regulation of infrastructure such as the bridges and highways. In this paper, we propose a damage identification monitoring system. It allows ordinary person to check the buildings structures with Fourier spectrum. We employ ARM & FPGA board to measure and analyze Fourier spectrum and also employ XBee ZB to construct wireless mesh network. In addition, we develop a low cost vibrometer using piezo-electric devices. The proposed system manages data of the building structures in all of our country, and finds damage of them. We are able to check Fourier spectrum and results of damage identification through Web application through a cloud server. In evaluations, the proposed system was able to detect a broken point of a test bridge. And we measured power consumption of the proposed system. Power consumption of it was low enough to drive it with only solar power and battery system.

Keywords: FPGA, piezoelectric element, health monitoring system, sensor network.

1. Introduction

Most building structures, such as office buildings, bridges, high ways, and so on, were built in 1970's and 1990's in Japan. Deterioration of the building structures in 1970's becomes a social problem. Conventionally, the building structures were demolished and rebuilt. However, affected by the recent Japanese economic slump, the building

structures were repaired and fix. Furthermore, we require the durability and earthquake-proof of the building structures for large-scale disasters and increase in car traffic. Consequently, the building structures become lifelong duration.

In order to put it into practice, it is important to check and manage the building structures on a daily basis. Ordinary, the building structures are checked by looking and hammering test of specialists. But, there are two problems of the checking. One is a shortage of the specialists, the other is place regulation of infrastructure such as the bridges and highways. We have to develop a damage identification monitoring system by which everyone can check the building structures without the specialists of checking and hammering test of the building structures.

Therefore, we are developing the damage identification monitoring system for the building structures. It allows us to find the place and degree of the damage by processing signals of vibration in the building structures. We develop a low cost vibrometer using piezo-electric devices which are put on the building structures. A previous work shows that it is possible for us to find the place of the damage on the building structures by the vibrometer using piezo-electric devices⁽¹⁾.

This paper will propose the low cost and low power damage identification monitoring system for the building structures. We will show a system organization using low cost FPGA board, PSoC, Zigbee, and A/D converter and evaluate it.

2. Related works

NTT-data developed real time remote monitoring system of bridges called BRIMOS⁽²⁾. It has displacement gauges, inclinometers, and accelerometers. It sends the three kinds of measurement values to server via optical fiber network.

These measuring instruments are very expensive. The measurements values and method of damage identification are different from the proposed system. A value which the proposed system measure is only a value of vibration of the building structures with piezo-electric devices. The proposed system measures the voltage of the piezo-electric devices, and analyzes Fourier spectrum and transfer function.

Monitoring systems of the building structures don't have to use high speed transfer media such as optical fiber to send the measurement values. Since they work at several times a day, it's enough to provide low speed and low cost media such as Xbee wireless communication device. Therefore, we employ low speed, cost, and electric power consumption transfer media.

Yicheng Tsai proposed another damage identification monitoring system^(3,4). His proposed system has sensor terminals. Each sensor terminal consists of a dsPIC and a MEMS triaxial acceleration sensor. It finds damages by analyzing frequency response of a building structure which is measured with the MEMS triaxial acceleration sensor.

There is a problem that the sensor terminal can only measure less sampling point due to a small amount of memory. The proposed system provides 4096 sampling point. It's able to analyze a primary natural frequency from these sampling points. The measurements values and method of damage identification are also different from the proposed system.

3. The Proposed System

There are four requirements on the proposed system.

Firstly, it is able to process large amount of data. In order to find the place and degree of the damage of the building structures, the proposed system is able to find a change of max peak frequency from spectrum analysis of vibration. We set many piezo-electric devices on the building structures and measure many sampling data (the number of the sampling data are 4096 point) to analyze the vibration spectrum.

Secondary, it works with low power consumption. In case of a difficult situation of electric power supply, we have to provide a compact solar and battery system. It is important for the proposed system to work with low electric power to supply electricity by the compact solar power and battery system.

Thirdly, the proposed system provides wireless sensor network automatically. It is hard to connect modules of the system with wire cables on the building structures which is

locate deep in the mountains due to spend a lot of money.

Finally, we are aiming at the low cost system. We are going to set the systems on around of the building structures of our country in the future. There are more than 2000 bridges only in Osaka prefecture.

In order to satisfy the first and second requirements, we employ ARM & FPGA board to measure and analyze vibration, and the third requirement, we also employ XBee ZB to construct wireless mesh network. These devices are not expensive (therefore, satisfy the final requirement).

3.1 Overall Structure of the Damage Identification Monitoring System

Figure 1 shows overall structure of the proposed system. It consists of measurement modules, a base module, and a cloud server. The measurement modules and the base module are set on the building structures such as a bridge described by Figure 1. They construct mesh network automatically. The measurement modules measure vibration several times a day at starting signals from the base module. They also transform a vibration signal to a Fourier spectrum, and send the Fourier spectrum to the base modules. The base module sends Fourier spectrums received from many measurement modules to the cloud server by Ethernet.

It manages data of the building structures in all of our country, and finds damage of them. We are able to check Fourier spectrum and results of damage identification through Web application.

3.2 Measurement Modules

Figure 2 shows Organization of the measurement module. It consists of eight piezo-electric devices, an external A/D converter board, a ZYBO FPGA board, and a synchronization module.

Fig. 1. Overall structure of the proposed system

Fig. 2. Organization of the Measurement Modules

3.2.1 External A/D Converter Board

The external A/D converter board consists of a charge amplifier and A/D converter chip. It converts amount of electric charge generated by a piezo-electric device to voltages. And it also converts analog value of the voltages to digital value.

Figure 3 shows a circuit of the charge amplifier. It consists of a bias circuit and an integrating circuit. An OP amp of the charge amplifier works with 0v-3.3v single power supply due to reduce the number of parts. In order to set 0 point of vibration on 1.65v (i.e. 3.3v/2), we employ voltage divider circuit with two 100kΩ resistors. When the piezo-electric device generates an electric charge, the integrating circuit accumulates the electric charge into a capacitor C_f and converts the electric charge to voltages. Lower cut off frequency of the circuit describes (1) below.

$$f_c = \frac{1}{2\pi C_f R_f} \quad (1)$$

Where R_f is 10MΩ and C_f is 0.01μF, Lower cut off frequency is about 1.59Hz. We assume that frequency range is from 2Hz to 10Hz by experimentation of a bridge vibration⁽¹⁾. We are able to measure vibration of the building structures with the system.

We employ MCP3208 as A/D convertor chip. Table 1 shows specification of MCP3208.

Fig. 3. Charge Amplifier Circuit

Table 1. MCP3208.

Resolution (bit)	12
Sampling Rate at 2.7V (kS/s)	50
Number of Channels	8
Communication Interface	SPI

3.2.2 ZYBO

ZYBO⁽⁴⁾ is an ARM and FPGA evaluation board of Xilinx. It has a xc7z010-1clg400 on the evaluation board (Zynq-7000 series). Zynq-7000 has two ARM Cortex-A9 processor and Artix-7 FPGA. Generally, FPGA is used for digital signal processing and numerical calculation, and ARM is used for Linux OS and communication such as Ethernet.

In this paper, FPGA controls A/D converter and analyzes Fourier spectrum of vibration with hardware. In order to analyze, we embed a measurement controller, a format converter, an Fast Fourier Transform IP (FFT IP), and a DMA Engine IP into FPGA.

Ubuntu which is one of the Linux distribution works on ARM processors. A python application working on Ubuntu controls the measurement modules and communicates the cloud server and the measurement modules by Ethernet.

3.2.2.1 Measurement Controller and Format Converter

The measurement controller controls an MP3208 A/D converter chip which is able to convert 8 analog values simultaneously. When the ARM processors begin to measure, they send a trigger signal to the measurement controller. It receives the trigger signal and samples the vibration data of the building structures in the selected sampling clock with the MCP 3208. The MCP3208 sends the sampling data to

Fig. 4. Data Format of FFT LogiCORE IP.

measurement controller via SPI. Sampling frequency of the data is 204.8Hz, and the number of the sampling data is 4096. The measurement controller sends the sampling data to the format converter.

The format converter converts the sampling data into a format decided by the FFT IP (See Figure 4). When it has finished converting all 8 sampling data, send them to the FFT IP.

3.2.2.2 Fast Fourier Transform IP

We employ Fast Fourier Transform LogiCORE (FFT Logi CORE) ⁽⁶⁾ produced by Xilinx inc as the FFT IP. It calculates discrete Fourier Transform described by (2) with hardwired logic.

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-j \frac{2\pi kn}{N}} \quad k = 0, \dots, N-1 \quad (2)$$

Figure 5 shows architecture of the FFT IP. It consists of switch, selector, data RAM, and butterfly computation logic. Butterfly logic employs Radix-2 algorithm (also known as the Cooley-Tukey algorithm). Radix 2 means that the number of samples must be an integral power of two. The decimation in time means that the algorithm performs a subdivision of the input sequence into its odd and even members

3.2.2.3 DMA Engine IP

The FFT IP writes the Fourier spectrum data to DDR memory via the DMA Engine IP. It interrupts ARM cores to inform the completion of the writing when it has finished writing the Fourier spectrum data.

3.3 Base Module

Figure 6 shows organization of the base module. It consists of an mbed and a synchronous module. The mbed

Fig. 5. Architecture of the FFT IP.

corrects a lot of Fourier spectrum data from many measurement modules. In order to reduce wire cost of a network between base and measurement modules, we employ Xbee ZB wireless communication device of the synchronous module. The corrected data was stored in a flash memory of the mbed temporarily. Once the base module has all the corrected data, it sends the corrected data to the cloud server.

3.4 Synchronous Module

The synchronous module performs the synchronization of time with accuracy and the wireless communication between the measurement modules (See left side of Figure 6). We employ a PSoC (CY8C29466-24PXI) produced by Cypress corporation as micro controller, and an XBee ZB produced by Digi International corporation as wireless communication module.

The synchronization method is MHRBS⁽¹⁰⁾. MHRBS is based on RBS⁽¹¹⁾. Since RBS is unsuited for time sync through repeater device of the network, MHRBS is improved so that it's able to synchronize through repeater device. We don't care about construction of the network and MHRBS

Fig. 6. Organization of Base Module.

synchronization by automatic setting on the synchronous module.

The base module and the measurement modules communicate with each other via the synchronous module. Each mbed (base modules) and Zybo (measurement module) connects the synchronous module via UART (wire connection). The synchronous module sends the Fourier spectrum data via XBee wireless device.

3.5 Cloud Server

We employ the general purpose logging system⁽¹²⁾ as the cloud server of the proposed system. It's able to upload and download measurement data via HTTP communication protocol. Since data base of our system is distributed Key-Vale store data base, retrieval time of it don't depend on an amount of the data.

4. Evaluations

4.1 Analysis of Fourier spectrum with Measurement Modules

In order to analyze the Fourier spectrum of vibration of the building structures preciously, we evaluate the proposed system with a test bridge. Figure 7(a) shows photo of the test bridge and Figure 7(b) shows places of piezo-electric devices. We make it out of aluminum. It has a total length of 2400mm and a total width of 300mm. The primary natural frequency is 3.61Hz. We set three conditions on a place of the main frame. The three conditions are intact, crack, and broken. We put eight piezo-electric devices on the test bridge. In the evaluations, the measurement modules connect Xbee with USB-serial converter module instead of the synchronous module.

We measure vibration and analyze the frequency of the test bridge on the two conditions (Intact and Broken). We make a comparison between the proposed system and measurement equipment on the market reported by reference (1).

5. Result of the Evaluations

5.1 Spectrum of The Test Bridge

Figure 8 shows the Fourier spectrum of the intact test bridge. Figure 9 also shows the Fourier spectrum of the broken test bridge. (a)-(d) of Figure 8 and Figure 9 correspond to number 1-4 of Figure 7(b) respectively.

(a) Overview

(b) Layout of piezoelectric elements

Fig. 7. Evaluation Equipment

All places of the intact test bridge showed a peak spectrum around 3.55Hz in Figure 8. On the other hand, number 1 and number 4 of Figure 9 showed the peak spectrum around 3.55Hz. But number 2 and number 3 which were put on around broken point didn't show any peak spectrum. The spectrums of number 5-8 of Figure 7(b) were omitted since both intact and broken test bridge showed the peak spectrum around 3.55Hz.

In these results, some piezo-electric devices put on the broken frame (number1-4) changed the peak spectrum. All piezo-electric devices put on the intact frame (number 5-8) didn't change the peak spectrum. Furthermore, only two piezo-electric devices put on the broken point (number2 and 3) didn't show the peak spectrum. Therefore, we achieved damage identification of the test bridge.

5.2 Power Consumption

Table 2 shows power consumption of the proposed system. We measured power consumption [W] for 5 minute, and repeated the measurement 15 times. Table 2 consists of minimum, maximum, and average power consumption for each 5 minute. Maximum was 3.145W, minimum was 2.785W, and average was 2.841W.

(a) Piezoelectric Element 1

(b) Piezoelectric Element 2

(c) Piezoelectric Element 3

(d) Piezoelectric Element 4

Fig. 8. Fourier Spectrum (Intact).

Figure 10 shows detailed power consumption data of No 9 in table 2. We omitted power consumption data after 80 second. Idle state indicates that the proposed system waits until it starts analysis. Measurement & Analysis indicates that a measurement module analyses Fourier spectrum and sends the results of the analysis data.

Power consumption of Measurement & Analysis was almost same consumption as that of Idle state. The power consumption of the system increased by 40mW during data

(a) Piezoelectric Element 1

(b) Piezoelectric Element 2

(c) Piezoelectric Element 3

(d) Piezoelectric Element 4

Fig. 9. Fourier Spectrum (Broke).

transfer due to working Xbee ZB wireless communication. On the other hand, it decreased by 70mW during spectrum analysis. It is assumed that the decrease of power consumption was caused by Bus clock reduction during DMA transfer.

In future, the proposed system will work with a solar power and battery system (i.e. energy harvesting). We will employ 4W solar power system. In order to set up it easily, it is desirable that size of the solar power and battery system is

Table 2. Table of Measurements of Power Consumption.

No.	min[W]	max[W]	average[W]
1	2.792	3.082	2.840
2	2.790	3.093	2.837
3	2.794	3.076	2.843
4	2.792	3.121	2.839
5	2.792	3.020	2.841
6	2.787	3.093	2.841
7	2.785	3.099	2.839
8	2.794	3.086	2.836
9	2.794	3.050	2.837
10	2.786	3.145	2.835
11	2.790	3.060	2.836
12	2.789	3.062	2.836
13	2.790	3.120	2.835
14	2.790	3.123	2.835
15	2.883	2.924	2.887

small. We have to improve the system to reduce power consumption by stopping clock of ZYBO during the stand-by period.

6. Conclusions and Future Works

In this paper, we proposed the damage identification monitoring system. It is able to measure vibration with piezo-electric devices, to analyze Fourier spectrum, and to upload the analysis data to the cloud server.

In evaluations, we analyzed Fourier spectrum of the test bridge on the proposed system, and measured power consumption of it. In these results, it detected the broken point on the test bridge (i.e. it worked normally), and power

Fig. 10. Power Consumption (No.9).

consumption of it was low enough to drive it with only solar power and battery system.

There are two future works. One is regulation of clock frequency of CPU and FPGA. It is important to reduce power consumption by clock regulation in order to embed smaller solar and battery system. The other is development the solar power and battery system which the proposed system embeds. On a sunny day, the solar supplies electric power for the proposed system and charge the battery. On a cloudy, rainy, or night day, the battery supplies electric power for it.

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