Ultra Low-Power Autonomous Wireless Structural Health Monitoring Node

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ABSTRACT

We developed low-power Autonomous Structural health monitoring (SHM) Node (ASN-1) using a DSP board, which eliminates a digital-to-analog-converter (DAC) for generation of an excitation signal and an analog-to-digital converter (ADC) for sensing the response [1]. ASN-1 employs a PZT-based impedance method, and it measures the phase (rather than magnitude) difference of the two impedances, baseline and the structure under test (SUT). In this paper, we present a new version of our SHM node ASN-2, which is developed using a TI MSP430 microcontroller evaluation board. ASN-2 is equipped with a radio and compensates the temperature dependency of a PZT patch. A cluster of ASN-2's forms a wireless network, and each node wakes up at a predetermined interval such as once in four hours, performs an SHM operation, reports the result to the host computer wirelessly, and sleeps back. The power consumption of our ASN-2 is 0.15 mW during the inactive mode and 18 mW during of the active mode. Each SHM operation takes about 13 seconds to consume 236 mJ. If our ASN-2 operates once in every four hours, it can run for about 2.5 years with two AAA-size batteries.

1 INTRODUCTION

In the past decade, structural health monitoring techniques have been extensively investigated and deployed for many applications such as civil infrastructures, aerospace and vehicles. An impedance based method employs a piezoelectric patch to excite the structure under test and to capture its response. Impedance-based SHM systems have several advantages such as simple hardware and good performance. However, the method is sensitive to temperature and requires a temperature compensation scheme [2].

To build a health monitoring system, hundreds of sensors may be distributed on a structure. It is desirable for those sensors to communicate wirelessly. Wireless sensors installed on a structure should operate long without recharging or replacing

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batteries. Low power consumption of these sensor nodes is critical for an SHM system. Further, low power sensors can operate desirably on the ambient energy.

Several researchers investigated to use off-the-shelf wireless sensor nodes for SHM applications. Tomonori et al. with University of Illinois at Urbana Champaign developed wireless sensors for SHM using Imote2 [3], and Sukun et al. at UC Berkley developed wireless SHM sensors using MicaZ [4]. Those general purpose wireless sensor nodes equipped with a tiny operating system are more versatile, but less efficient in power compared with dedicated SHM sensor nodes . In this paper, we present a dedicated low power wireless sensor node for SHM called Autonomous Structural health monitoring (SHM) Node (ASN-2), which employs a impedance-based method compensated in temperature.

2 PRELIMINARY

2.1 Digital SHM System

An impedance-based SHM system usually uses a digital-to-analog-converter (DAC) for generation of an excitation signal and an analog-to-digital converter (ADC) for sensing the response signal. The excitation signal actuates a piezoelectric patch, and the response captured by the ADC is processed by a processor to compute the impedance at the excitation frequency. Fast Fourier Transform (FFT) is typically used for commercial impedance analyzers to acquire accurate real and imaginary parts of the impedance. If the impedance information of the structure under test (SUT) is different from the baseline impedance by a certain predetermined amount, the system considers the SUT damaged.

Our previous SHM system ASN-1 eliminates a DAC and an ADC [1]. Unlike traditional SHM systems, it detects the phase difference (rather than magnitude) of the impedance between the SUT and the baseline. A DAC is eliminated since a rectangular pulse train is used as the excitation signal and can be generated from a processor itself. Also, a comparator rather than an ADC is used to measure the phase. Hence, the signal processing part is simplified as a XOR function and an accumulator. [1] ASN-1 is implemented with a TI digital signal processor (DSP) evaluation board. Even though ASN-1 is power efficient, the DSP board still consumes large power. Our successor SHM system, ASN-2, uses a microcontroller, which can run on two AAA-size batteries.

2.2 Temperature Compensation Algorithm

The impedance profile obtained using a piezoelectric patch is sensitive to the ambience temperature. Previous studies show that the amplitude of the real part of the impedance shrinks as the temperature increases, while peaks of the imaginary part shift toward lower frequency band [5]. Consequently, the accuracy of an impedance-based SHM degrades to cause false alarms or missed detections.

To compensate the temperature effect, we proposed an algorithm for the selection and estimation of baseline profiles [2]. Baseline profiles only at critical temperatures are selected and stored in advance, and they are used to reconstruct baseline profiles at other temperatures. A new baseline is constructed based on a linear interpolation between two neighbor profiles. Our algorithm reduces the total

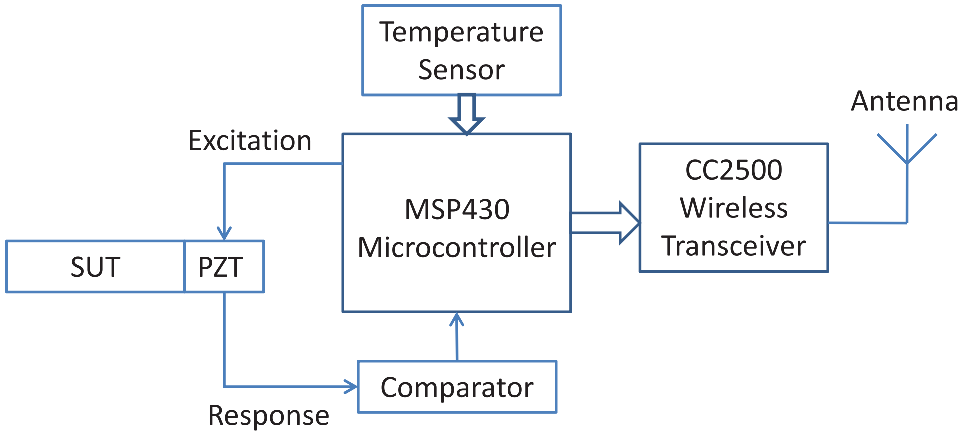

Figure 1: Architecture of our SHM sensor node

number of baseline profiles stored by more than 40%, which is important for SHM sensor nodes based on microcontrollers with small memory size.

3 PROPOSED DIGITAL SHM SYSTEM

3.1 Overview

Low power consumption is a key design requirement for our SHM sensor node ASN-2, and we decided to use a TI MSP430 microcontroller. A TI MSP430 microcontroller is low power and has a built-in temperature sensor. An evaluation board ez430-RF2500 has CC2500 radio operating at 2.4 GHz and offers a user friendly interface to ease development works. The architecture of our SHM sensor node based on TI MSP430 microcontrollers is shown in Figure 1.

The circuit shown in Figure 2 is the interface to excite the PZT patch and to sense the response signal. The circuit is identical to the one used for our previous version ASN-1 except one modification. A capacitor C_f is added in the feedback path of the bottom OP amp, which forms a lowpass filter to suppress high frequency harmonics. For details on the operation of the circuit, refer to [1].

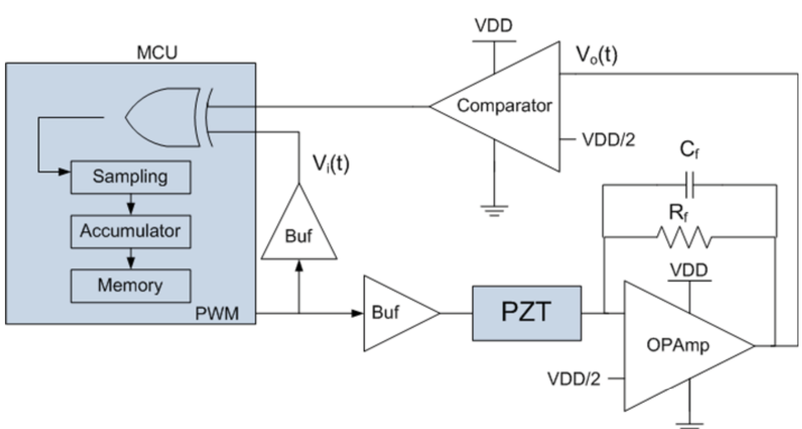

Figure 2: Interface circuit

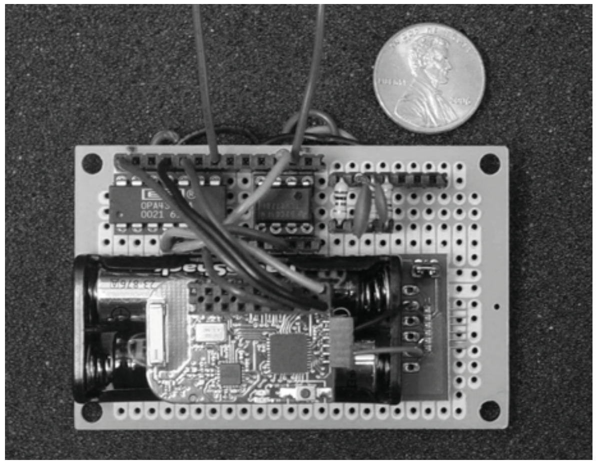

Figure 3: Prototype developed using a TI MSP430 evaluation board

A prototype for our wireless SHM sensor node ASN-2 is shown in Figure 3. The top part is the interface analog circuit, and the bottom part the evaluation board and the batteries. The size of the prototype is 4.5 cm×7 cm× 3 cm, and it runs on two AAA-size batteries.

3.2 System Operation and On-board Processing

Figure 4 shows the system operation of ASN-2. The microcontroller sweeps a user specified frequency range four times for each operation and averages the four

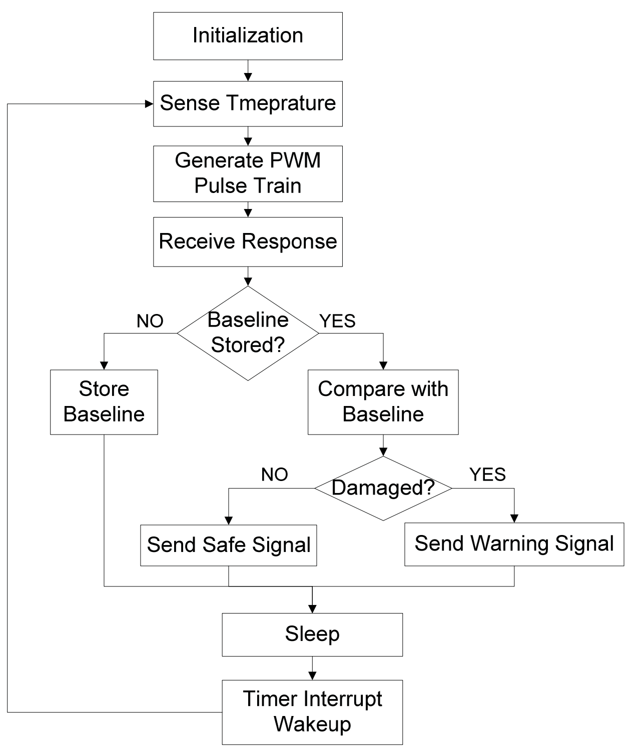

Figure 4: Flow chart of system operation

experiments to obtain baseline and SUT profiles. Each operation takes about 13 seconds including processing of the response data. Then, ASN-2 goes to the sleep mode for a predetermined time period controlled by an internal timer. During the sleep mode, most components such as the CPU, Op amps, and the ADC (used to sample the temperature sensor value for ASN-2) are turned off, and some other components such as the timer and the wireless transceiver are set to a lower clock frequency or the inactive mode. ASN-2 dissipates about 18 mW during the active operation and 0.15 mW during the sleep mode.

The data processing can be processed either at a local sensor node or at a remote host computer. A remote processing requires transmission of the impedance profile of the SUT to the host computer wirelessly. Since a radio consumes much more power than a microcontroller itself, it is better, in term of power saving, to process the data locally and sends its result (healthy or damaged) to the host computer. For example, an MSP430 microcontroller running under 1.2 MHz of the clock dissipates 6 mW in the active mode with the radio turned off. When the radio is turned on, the power consumption increases to 69 mW. To make our ASN-2 power efficient, we processe the data locally and reports its result to the host computer.

3.3 Wireless Communication

The evaluation board ez430-RF2500 for an MSP430 microcontroller has a built-in radio operating at the 2.4 GHz unlicensed band, which can be used to build a wireless sensor network. We configured a star network with multiple sensor nodes and a control center. A message on the application layer consists of three bytes, two bytes of the temperature value and one byte of the decision (healthy or damaged). The head information such as node ID, data length and synchronization signal is added at a lower layer. The transmission data rate is set to 250 kbps, which takes a fraction of one second to transmit one message including the overhead. Note that the radio is inactive for the rest of the time.

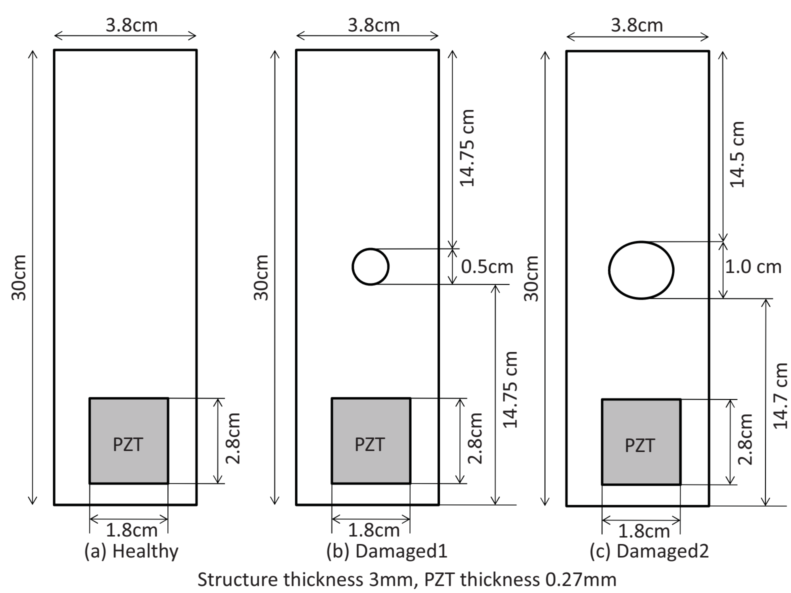

Figure 5: Structures under test

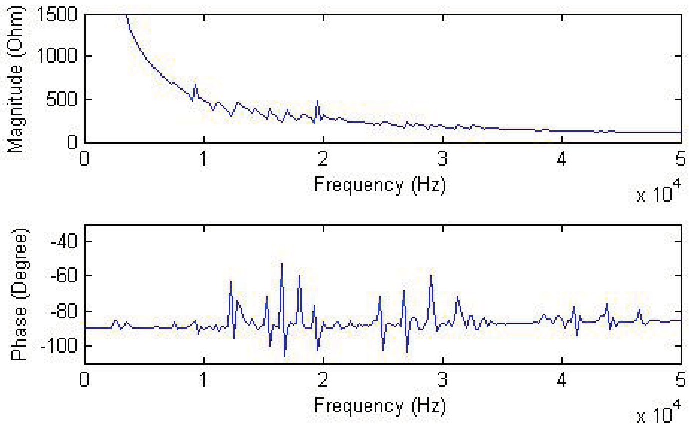

Figure 6: Impedance of the healthy structure under test

4 EXPERIMENTAL RESULTS

4.1 Test Structure and Environment

The structures under test are three aluminum beams with identical size and a PZT attached on one end of each structure, as shown in Figure 5. Two beams have drilled holes with different sizes at the center to simulate damage conditions. These test structures are hanged in free air with room temperature around 20°C.

We measured the impedance of these beams using an impedance analyzer and identified the band from 12 kHz to 35 kHz covering multiple resonant frequencies. Figure 6 shows the impedance of the healthy structure, which indicates that most resonant frequencies reside within 12 kHz to 35 kHz. Hence, the sweep frequency range of our ASN-2 is set to the same frequency band.

The damage metric is the absolute difference of the baseline phase and the SUT phase. The damage metrics of the two structures compared against the baseline phase are shown in Figure 7. The damage metric is defined as the normalized absolute sum of difference [2]. If the damage metric of a SUT is greater than a preset threshold value, the damage is detected.

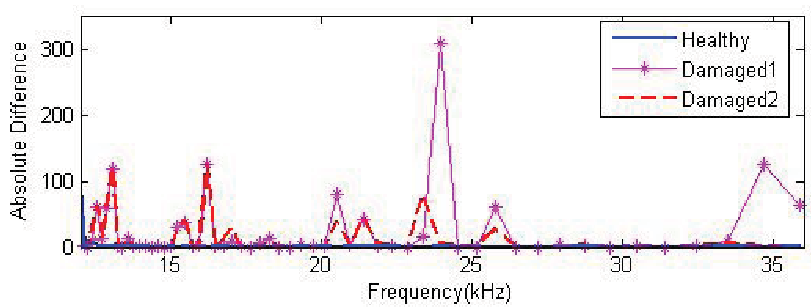

Figure 7: Absolute Difference between SUT and baseline

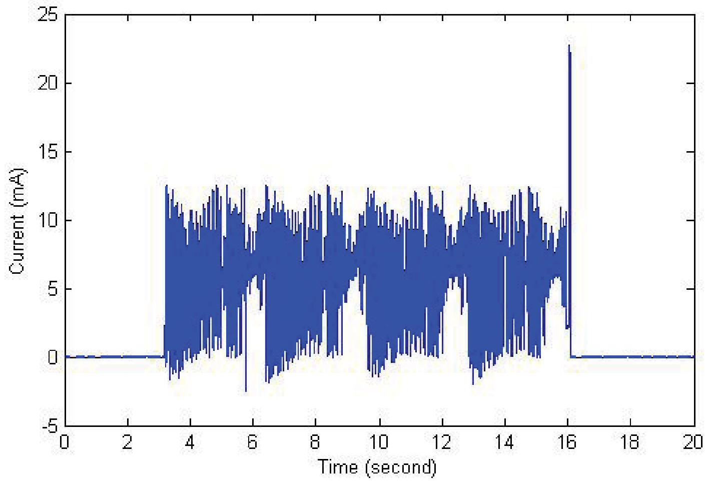

Figure 8: Measured current at active mode

4.2 Power Profile

Since the voltage supplied by two AAA-size batteries is mostly constant at 3V, we measured the power consumption by measuring the current. The measured current profile over one operation of ASN-2 system is shown in Figure 8. The current under the inactive mode is about 50 μA to result in 0.15 mW of power consumption. The current increases to 6 mA during the active mode with the radio off, which results in 18 mW of power consumption. The active mode lasts for about 13 seconds to consume 234 mJ of energy. When the radio is turned on at the end of the active mode, the current jumps abruptly to 23 mA to cause 70 mW of power consumption. However, the period lasts for about 0.03 second to result in 2.1 mJ of energy consumption.

Assuming the capacity of an AAA-size battery is 1200 mAh and our ASN-2 operates once in every four hours. ASN-2 can run for about 2.5 years. The average power consumption is 0.16 mW for the case, which can be powered by energy harvested from the ambient such as solar or vibration.

5 CONCLUSION

We presented a new low-power wireless SHM system ASN-2 developed using a TI MSP430 microcontroller evaluation board. The ASN-2 employs a PZT-based impedance method and compensates the temperature dependency of the PZT. A cluster of ASN-2’s forms a wireless network, and each node wakes up at a predetermined interval such as once in four hours, performs an SHM operation, reports the result to the host computer wirelessly, and sleeps back. The power consumption of our ASN-2 is 0.15 mW during the inactive mode and 18 mW during of the active mode. Each SHM operation takes about 13 seconds to consume 236 mJ. When our ASN-2 operates once in every four hours, it can run for about 2.5 years with two AAA-size batteries.

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