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Wireless Structural Health Monitoring (SHM) system for damage detection using ultrasonic guided waveform response

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ABSTRACT

This paper presents an improved version of a wireless device embedded with a smart PZT sensor to detect flaws and structural defects on selected investigated structure. Smart PZT sensors were used as an actuator and sensor, coupled with two XBee's and one signal generator IC chip. Programme execution on transmitting and receiving the ultrasonic guided wave via the PZT sensor had been written in MATLAB. The developed source code is basically to receive serial data from one Xbee to another remote Xbee attached to the investigated structural system. The refined waveform response is utilised for prognosis of the true structural status. The 4-mm simulated holed into one of the aluminium structural plate is benchmarked with its pristine condition in validating the effectiveness of the developed SHM wireless module. Results showed that the wave is more even in non-defected area and disrupted in affected area. Ultrasonic waves increase continuously for non-destructive evaluation and structural health monitoring in various structural applications because the guided wave can propagate long distances and reach difficult-to-access regions; for inspecting porous and some non-porous materials ultrasonic waves attenuate fast and are very useful. Recent advances in ultrasonic wave application model and results are discussed in this paper.

Keywords: microcontroller, piezoelectric sensor, sine wave signal, smart sensor, structural health monitoring, wireless sensor

INTRODUCTION

In the field of aeronautics, reliability is important and Non-destructive test (NDT) and Structural health monitoring (SHM) concepts are used to detect structural flaws. However, SHM is different from NDT whereby the former is used to monitor the integrity of mechanical structures in a continuous and independent way. Thus, SHM helps to reduce maintenance costs.

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Piezoelectric transducers or sensors have the capability to transform mechanical energy to electrical energy and vice versa. These sensors have been used in many applications.

The SHM involves integration of sensors, data transmission, smart materials, computational power, and handling out ability inside the structures (Chung et al., 2014). This is schematically presented in Figure 1.

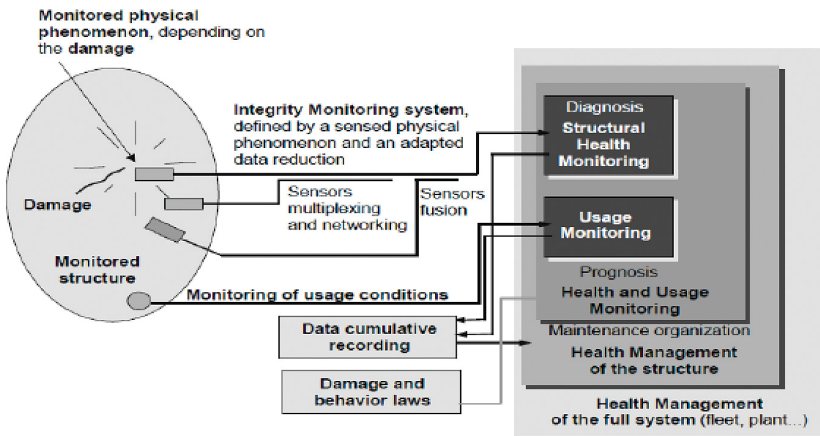

Figure 1. Organisation of SHM system (Chung et al., 2014)

Structural health monitoring has received much attention the last three decades. A brief literature review of this technology's development is presented below. Doebling et al., 1996, Inman (2003), Hoon et al. (2004) and Farrar et al. (2007) discuss extensively identification of damage and technical challenges inherent in the SHM adaptation which are common in all technology applications. Rytter proposes a categorisation system for SHM damage identification method (Mustapha et al., 2005) which had 4 levels originally and later expanded by Inman (2003) to include three more levels.

The other modal parameter technique is the mode shape method to detect damage in a structure. The MAC (Modal Assurance Criterion) is used to correlate modes, proposed by West (1984) for the first time, and is a method to locate and detect damage in a structure without using a prior FEM (Randall, 2004). The main weakness of this technique is the enormous number of sensors required to gather sufficient data.

Many SHM approaches have been used over the last decades. In many cases, there is no easy way for measuring the inputs or the external the structure. Wireless sensor can be utilised to locate, detect and assess structural damage produced by severe loading events and by progressive environmental deterioration and the economical realisation of SHM system. Cho et al. (2008) show the outcomes of cooperative international research on the smart wireless sensor. Heo and Jeon (2009) developed a monitoring smart system based on global computing method for infrastructure system. The system is designed in order to allow the usage of TCP/IP net procedure, connecting data measured by a sensing wireless unit found on Bluetooth technology. Chung (2014) investigated and developed MEMS type wireless sensor for real time seismic bridge motoring.

The wireless competence added to the established MEMS sensors offers the possibility prevent long multiple cables usage for bridge monitoring. This paper presents the use of PZT sensor and XBee module to connect remote structure and PC to detect faults in structural portions.

Sensors have many other usages and a huge potential for monitoring structures. Sensing modules consist of different types of sensors used to measure different parameters. Generally, systems can be identified by the following modules such as sensing, acquisition, wireless and output. Sensors sense changes to the environment signals before sending the signals to the acquisition module. This includes vibration analysis, damage detection and power consumption. The Acquisition module consists of controller, signal conditioning unit and analog to digital controller. In general, signal conditioning unit performs three major operations called filtering, amplifying, and isolation.

The next process is transferring data from sensing unit to server unit. A pair of Xbee's are used for this purpose, namely to detect damage. Received data can be sent to PC using XCUI software as interface for further analysis. The MATLAB is used to receive the signal wave forms. The diagram 2 below shows how the system operates .

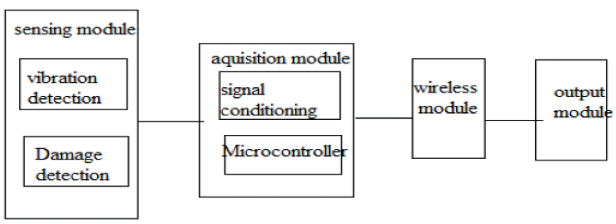

Figure 2. Modules involved in wireless system (West, 1986)

BASIC ARCHITECTURE OF THE DEVELOPED WIRELESS SHM SYSTEM

The proposed model of module detection system is shown in Figure 3. This module is mainly used to predict structural damage before it is discovered through general inspections. The overall system is combination of hardware components and software. The hardware is divided into two parts: transmitter section and receiver section. Transmitter section is developed using peripheral interface controller usually denoted by PIC and an Xbee unit coupled with a sensor. This PIC works exactly like in an acquisition module. Hardware consists of four modules as stated earlier: sensors detection, acquisition data, wireless communication and receiving data. The system reads vibration in the form pulse width. The higher the pulse width, the higher the vibrations. The PIC counts the pulse and transfers it to the wireless module section. This is seen in Figure 3.

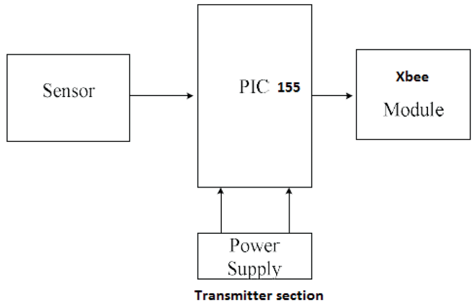

Figure 3. Detection system module (Hoon, 2004)

It is possible to use different types of accelerometer in SHM system and depends on the range of measurement. The proposed simple Interface diagram of Xbee is shown in Figure 4.

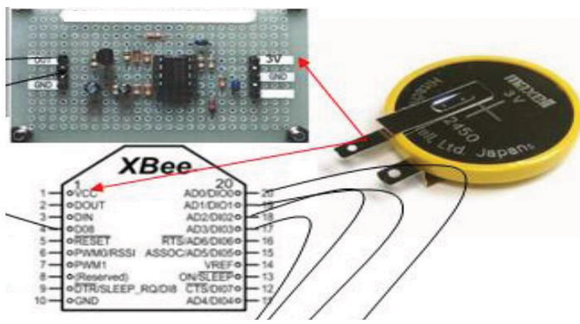

Figure 4. Interface diagram and connectivity of components

Figure 5 shows the block diagram of receiver section where the wireless Xbee module is connected to the PC and damages can be detected in the form of vibrations.

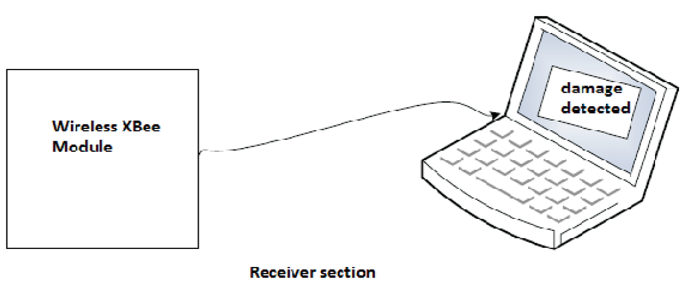

Figure 5. Receiver Section

HARDWARE

The device embeds ultrasonic Pieozo sensor and data acquisition electronics into the structure by using Xbee RF modules capabilities and radios for node communication and control. The PIC 155 has been chosen as transmitter and receiver sensor because it is categorised under soft piezo ceramic.

Defect detection, categorisation and localisation are prepared in three stages. Sensing (node stage), generation/acquisition, wireless communication stage, and base stage (Analysing). Sensing nodes are responsible for sine wave signal processing and collection and the second stage is to relay data to base station.

Sinewave Generator for piezo actuator excitation

Figure 6 shows the prototype of the sine wave board for piezo actuator. The standard amplifier is 741, with output 3V p-p and 1.5 offset. It can generate a frequency tunable between 100 Hz and 1.5 kHz. The power consumption of this circuit is less than 20 mW for 0.3% duty cycle.

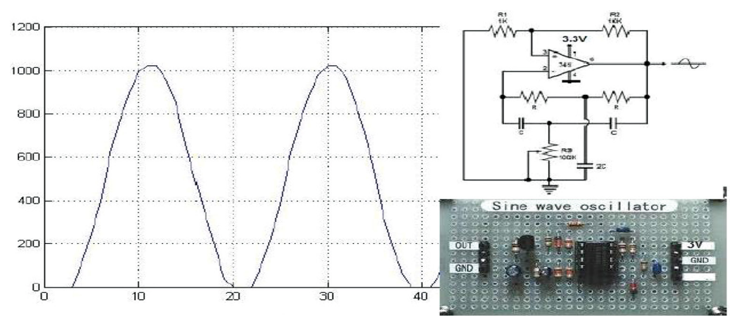

Figure 6. Sine wave generator

SYSTEM INTEGRATION

Wireless RF Modules Node Hardware

The Xbee is a wireless sensor network device which is low cost and low powered. The module operates within the ISM 2.4 GHz frequency band. Xbee radios have multiple I/O lines that can be used to collect digital or analog data and then transmit that to another Xbee for interpretation.

The analogue to digital converter (ADC) on Xbee radios are 10 bit, which will provide a resolution from 0 to 1023 (0x03FF hex). The selected XBee should not exceed 3.3 V on any pin to avoid damaging the radio module. The secondary microcontroller on this XBee is connected to the ADC pins instead of the RF processor as shown in Figure 7.

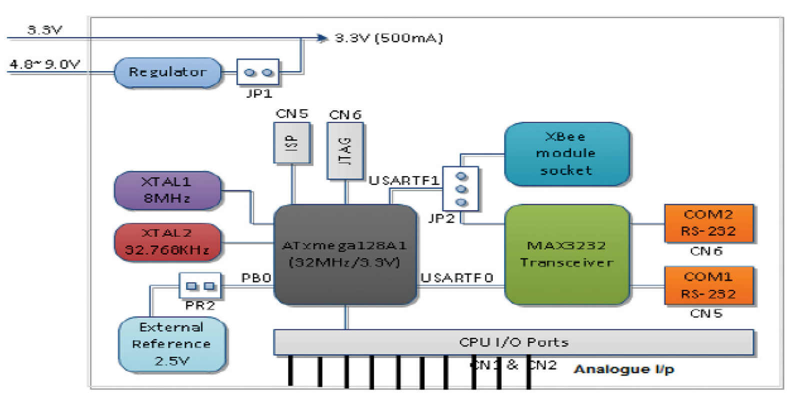

Figure 7. XBee diagram

SOFTWARE

X-CTU

The X-CTU is software used for configuring and testing XBee's data. It is like a frame work and configuration depends on the design. The software is interfaced with hardware and it is the lowest layer of software abstraction. Its role is to operate and control the unit's hardware to assist upper software layers in accomplishing their computational goals. The functionality envisioned indicates that the software could be complex and lengthy. The frame contains digital and analog mask indicating which I/O lines are configured as inputs.

EXPERIMENTAL PROCEDURES

The data acquisition method depends on several components such as selecting locations, sensors types, and the data processing that includes acquisition, storage, and data transmitting/receiving hardware. The economic consideration is quite important in choosing components and methods.

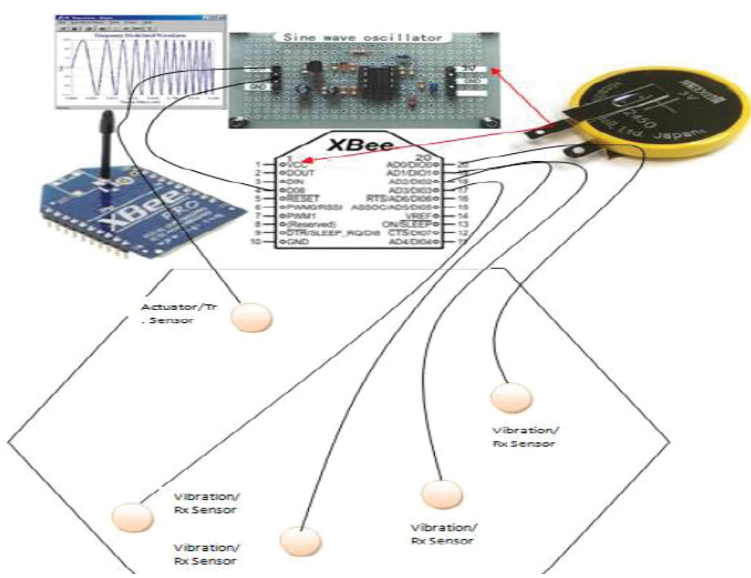

Figure 8. Single Xbee module

In this research, two PIC 155, two Xbee's and PZT sensors functioned as data acquisition components. Figure 8 shows a PCB circuit, model of single Xbee and interconnectivity of sensors in a single model space. The main objective of this experiment was to show wireless and remote communication with less power consumption and less complex compared with manual inspection. The next paragraph describes the connectivity of the basic components and basic setup of this experiment.

Two PZT sensors, PIC 155, are placed on the substrate and the distance between each sensor is 15 cm. One Xbee component is fixed on the substrate and coupled together with sensors and this Xbee is powered by a simple battery. The Xbee on substrate once powered is able to send data wirelessly and remotely to another Xbee pair which is connected to the computer through USB port. Data is then transferred to MAT LAB for further investigations. The XCTU software was installed to connect two Xbees and gather data from the substrate. This is shown in Figure 9.

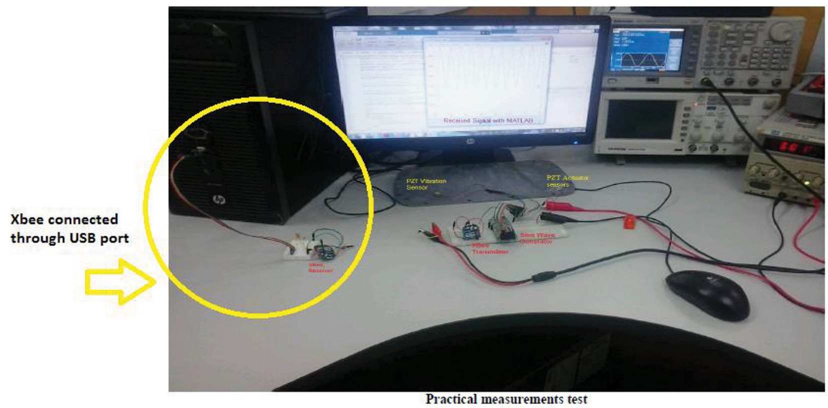

Figure 9. Connection wireless system and computer

RESULT ANALYSIS

The results of captured waveform are shown in Figure 10(a), 10(b) and 10(c). Figure 10 shows significant results of the investigated cases. There is no distortion or attenuation in Figure 10(a) and 10(b). Since the received data is similar to the PZT data, results prove that the same signals have been received with no defect or damage. This results obtained in signal amplitude value is 3V, which is equivalent to 1023 decimal code due the 10 bit ACD of the Xbee. Figure 10(c) shows significant variation in amplitude due because of the defective specimen. The signal was influenced by the damage and has distorted amplitude attenuation proportional with the position of the PZT sensor. It is found that the signal which travelled between the PZT actuator and the sensor has a value of 1.9$V_{p.p}$, whereby the sensors are supposed to be distributed to cover particular area on the body for detection at any point.

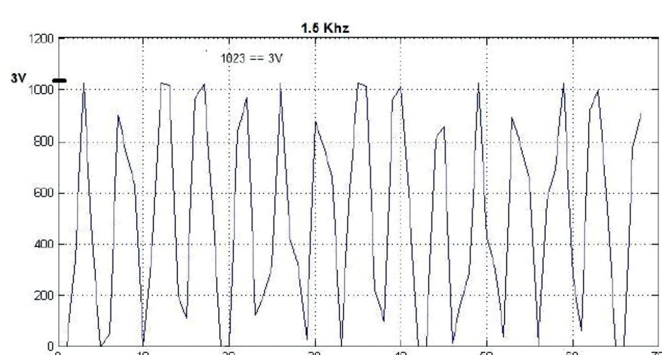

Figure 10(a). No defect plate, 1.6kHz

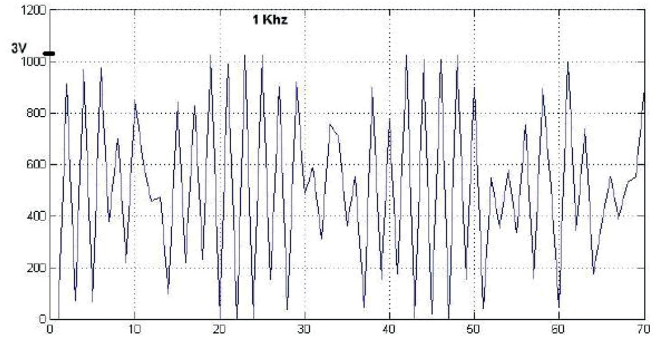

Figure 10(b). No defect plate, 1kHz

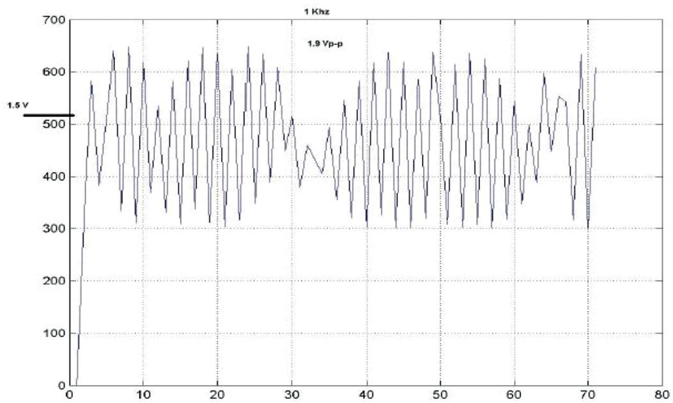

Figure 10(c). Defected plate, 1kHz

ADVANTAGES

Structural health monitoring system has a high potential to reduce cost dramatically in future. It helps us to minimise labour cost largely associated with manual inspections. In short, a wireless system reduces time cost which in turn increases profits. There is no necessity to replace components based on usage in all wireless module system. The main objective or focus of this research is to prevent or detect system damage before catastrophic failure occurs. Thus, the wireless system is promising compared with other conventional methods of detection failures. It does not lead to expensive repairs, and replacements or any periodical maintenance. This method eliminates sending humans into hazardous environments and help to extend the life of a structure.

DISADVANTAGES

In this study, a concept wireless monitoring system was developed from commercially available wireless sensing components. The monitoring system was applied to an aluminium frame structure with pre hole made in one corner. Despite the hardware limitations, the monitoring system successfully identified changes in the normal surface and affected surface.

The wireless sensor system requires steady power supply. The current power supply is limited because it is often difficult to obtain access to the system to replace the battery as well as difficulty in supplying continuous power to the system; rather, it depends purely on the characteristics of the structure where it's installed. However, in future, this could be rectified to enable large scale implementation.

CONCLUSION

This work shows the capabilities of the Xbee to achieve all required objectives of the SHM inspection with the use of low power. This device is less complex, has wireless serial communication and direct data processing and results. The resolution has been improved over the years. This is achieved by reducing conversion time when processing data. This device comes with minimal components and does not have additional microcontroller or Xbee to manage data. We investigated a particular application of wireless sensor networks. Based on the existing SHM system, the main challenges are identified first before summarising the corresponding technique. Future research should investigate further these challenges.

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