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Development of an extremely compact impedance-based wireless sensing device

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Abstract
This paper describes the development of the next generation of an extremely compact, wireless impedance sensor node for use in structural health monitoring (SHM) and piezoelectric active-sensor self-diagnostics. The sensor node uses a recently developed, low-cost integrated circuit that can measure and record the electrical impedance of a piezoelectric transducer. The sensor node also integrates several components, including a microcontroller for local computing, telemetry for wirelessly transmitting data, multiplexers for managing up to seven piezoelectric transducers per node, energy harvesting and storage mediums, and a wireless triggering circuit into one package to truly realize a comprehensive, self-contained wireless active-sensor node for various SHM applications. It is estimated that the developed sensor node requires less than 60 mW of total power for measurement, computation, and transmission. In addition, the sensor node is equipped with active-sensor self-diagnostic capabilities that can monitor the condition of piezoelectric transducers used in SHM applications. The performance of this miniaturized device is compared to our previous results and its broader capabilities are demonstrated.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Structural health monitoring (SHM) today is a very active field with worldwide interest, that seeks to ensure the reliability of the civilian and military infrastructure while protecting the safety of workers and citizens. Over the years, several different methods for performing SHM have emerged. The piezoelectric active-sensing approach is one of the most popular methods. The use of piezoelectric active-sensors provides many advantages: compactness, light weight, low power consumption, ease of integration into critical structural areas, ease of activation through electrical signals, higher operating frequencies, and low cost. The employment of a known and repeated input also facilitates subsequent signal processing of the measured output data.

Such active-sensors are very efficient at assessing the health of a localized area; however, for large-scale structures it may be necessary to incorporate hundreds or even thousands of sensors. The cost of implementing such a vast network of sensors using traditional wired systems can become very high; therefore, there has been a recent shift toward the use of wireless sensor nodes, which are well summarized by Spencer *et al* [1] and Lynch and Loh [2]. Advances in wireless communications and low-power electronics have enabled the development of power-efficient, compact sensor nodes for SHM and other engineering applications.

Piezoelectric active-sensing SHM techniques require a relatively large amount of electrical power to compete the operation, compared to passive-sensing systems. Because of this power requirement, only a few studies have addressed the development of wireless hardware systems which take full advantage of active-sensing technologies for SHM. Lynch [3] first explored expansion of the wireless structural monitoring paradigm by including the actuation capabilities in the design of a wireless active-sensing unit. The sensor node software uses an autoregressive with exogenous inputs time series model to identify structural damage. Liu *et al* [4] developed a wireless sensor node for high-frequency applications. The sensor node features a field programmable gate array for

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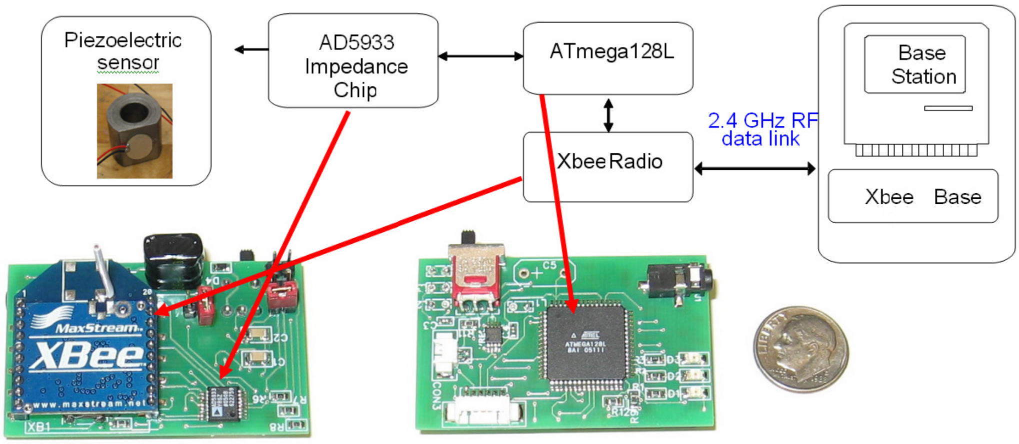


Figure 1. Wireless impedance device 1.5 which was developed and tested by members of our research team [13].

co-control, modular design, and ultrasonic sensing abilities. It is shown that the sensor node can successfully measure 100 kHz sinusoidal signals.

An SHM technique which utilizes the benefits of piezoelectric materials and shows great promise for structural health monitoring is the impedance-based health monitoring method [5–7]. The basic principle of the impedance method is to use high-frequency vibrations to monitor the local area of a structure for changes in structural impedance that would indicate damage or imminent damage. The impedance method also has applications in the field of sensor self-diagnostics in determining the operational status of piezoelectric active-sensors used in SHM [8, 9]. Another important aspect of the impedance method is that the method requires significantly lower power compared to other active-sensing technologies, which makes the method an ideal candidate for being implemented with a wireless active-sensing device. Grisso [10] developed a stand-alone prototype active-sensing unit, incorporating impedance data acquisition, local computation, wireless communication of the results, and a renewable power supply via piezoelectric-based energy harvesting. Zhao *et al* also introduced a new circuit implementation for electrical impedance monitoring coupled with the use of wireless telemetry [11].

Recently, a new advance in integrated circuit impedance measurement technology at Analog Devices, Inc., has opened the door for an efficient and low-cost solution for real-world and low-cost impedance measurements. This Analog Devices' AD5933 impedance measurement chip is equipped with an analog to digital converter (ADC), a digital to analog converter (DAC), FFT functionality, and a sampling frequency up to 200 kHz at the size of a coin. The AD5933 can be used to realize a self-contained, miniaturized impedance measuring solution. The use of this device will broaden its availability to the health monitoring community, as well as promote the miniaturization of the equipment needed to implement the impedance method. Therefore, in our previous work [12, 13], we used this AD5933 as a core component in developing a wireless impedance sensor node for SHM applications. This sensor node is different from the devices developed by others as we seek an integrated solution rather than discrete components for the impedance measurements. A schematic of the first wireless impedance device is shown in figure 1. However, some limitations were identified in these initial prototypes, including the ability to monitor only one single active-sensor, limited triggering capabilities, and the high power demands of the wireless telemetry component. Therefore, the second generation of wireless impedance device (WID2.0) was developed, and this will be described in this paper. The goal of this research is to develop an extremely compact, power-efficient impedance sensor node that can be used in SHM and sensor diagnostics. The development of a device that meets these requirements is critical in transitioning the current practice of SHM to field deployment.

2. Hardware capabilities and components

The wireless impedance device (WID2.0) was developed from the capabilities demonstrated in previous studies of the impedance-based SHM method. The WID2 was developed with many unique features that allow for diverse SHM operation. Some of the more important components that make up the WID2 are reviewed in this section. This newest generation of wireless impedance device is shown in figure 2, having overall board dimensions of 5.5 cm $\times$ 3.7 cm. The key components to be discussed are labeled in the figure.

2.1. AD5933 impedance chip

The main impedance component in the WID is the AD5933 chip from Analog Devices that allows for very low-power high-frequency impedance measurements to be taken. A picture of the AD5933 is shown in figure 2. The chip can be programed to take an impedance measurement from 1 to 100 kHz, with a variety of voltage levels and input gains to make best use of the ADC. The AD5933 can take as many as 512 points in a frequency sweep; for each point there will be an output stored in the output registers. The method which the AD5933 uses to measure the impedance of a piezoelectric patch (PZT) is similar to the technique discussed by Peairs *et al* [14]. Detailed

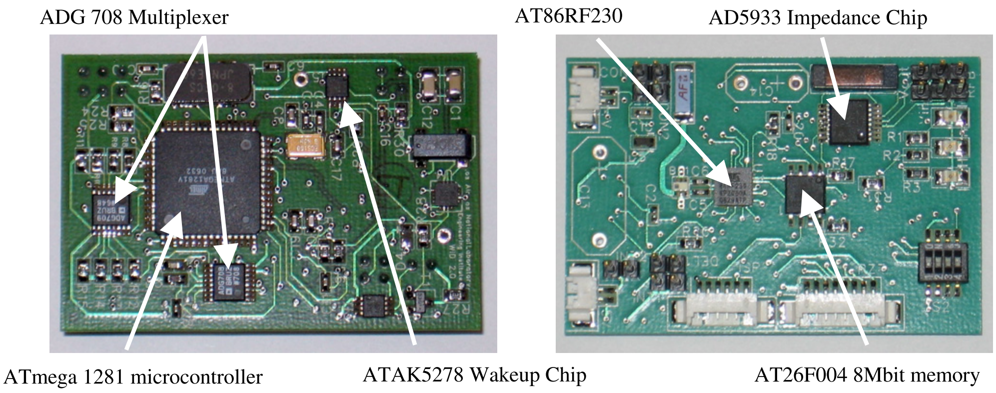


Figure 2. Second generation of the wireless impedance device (WID2.0).

information on programing this chip is outlined in our previous paper [13].

The impedance chip is also equipped with a thermocouple that can measure the temperature in the range −40 to 125 °C. This function provides additional flexibility that can monitor temperature variations under which the impedance sensors operate, and allows several temperature compensation algorithms to be easily embedded into the signal processing portion of the WID2.

2.2. Processor

The microcontroller that is used, an ATmega1281 (figure 2), is manufactured by Atmel and is part of their 8-bit AVR line. This microcontroller contains 128 kB of program memory allowing for complex and robust algorithms to be loaded on the chip. It also contains 8 kB of memory for computational requirements. The microcontroller is used to control each component of the WID and also perform local computing, for example a root mean standard deviation (RMSD) and/or cross-correlation analysis, which are typically used in impedance methods. This microprocessor was chosen because it requires a low voltage (2.7 V), has the proper interface to control the AD5933, and has the capability to be significantly expanded for future applications. This expansion includes added memory, added flash and control of additional components.

The ATmega1281 comes from a line of microprocessors that have available to them a large open source development community. Atmel is developing future versions with enhanced capabilities. These capabilities will include more memory and EEPROM, while maintaining the same form factor that would allow for pin compatibility. These features help with applications and expansion of capabilities in future versions of the WID.

2.3. Wireless telemetry

The wireless data transmission solution is also produced by Atmel, the AT86RF230 (figure 2). This telemetry is a 802.15.4 compliant radio, which uses a free Media Access Control (MAC) layer distributed by Atmel. The availability of the MAC layer facilitates coding to the wireless standard for robust data transmission. The AT86RF230 has very low energy requirements and low external component counts, making it particularly attractive for an SHM device.

2.4. Triggering options

The WID2.0 can be brought out of its sleep states in several ways, depending on the capabilities required. The WID includes a low-frequency (LF) wake-up chip that monitors an inductor for a magnetically coupled wake-up signal. This monitoring occurs at very low power (0.1 μA), but at a limited range of up to 3 m. This chip is shown in figure 2, and the inductor coil is located above the AD5933 impedance chip. This wake-up capability would be used for on-demand measurements triggered by a mobile base station capable of recording the measurements.

The second option is a real time clock (RTC) that can wake up the WID2.0 at intervals of 1 s to 1 year. The RTC chip is pictured in figure 2. This wake-up solution also operates with very low power consumption, on the order of a few microamps. With both of these solutions running it is conceivable that the WID2.0 could run in low-duty cycle operation for decades on a limited power supply.

2.5. Data storage

There are two main options for data storage on the WID2.0: internal EEPROM on the ATmega1281 and an optional DataFlash module. The data storage available is 8 and 500 kB, respectively. This is not a vast quantity of storage, but it is sufficient due to the types of measurement being made. The data that are measured are in the frequency domain, and therefore of much smaller size compared to the time series data of other methods. If the data are analyzed before storage, for example with an RMSD, and only the analyzed data are stored, the internal EEPROM and DataFlash modules would be able to contain 4000 and 500 000 data points of double precision floating point numbers.

2.6. Multiple sensors and autoranging capabilities

The previous version of the WID [13] had the ability to only measure a single sensor, and it also required manual selection of the bypass resistor for range selection. Both

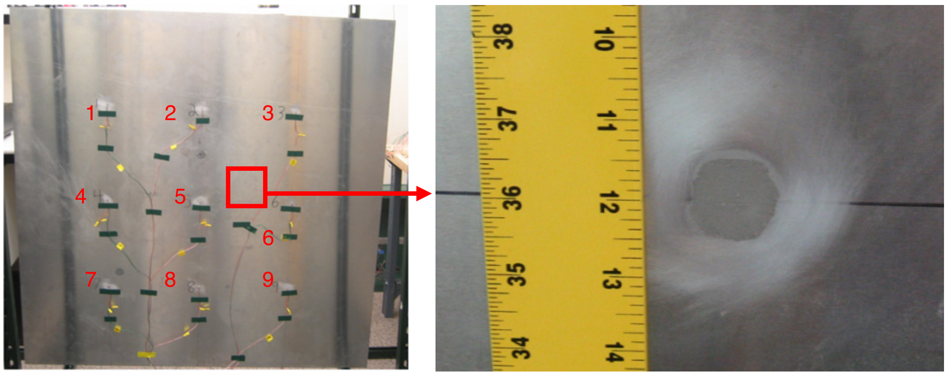


Figure 3. An aluminum plate with PZT transducers attached and corrosion induced into the structure.

of these shortcomings have been addressed with the current WID2.0 with the addition of two low-power and low-resistance multiplexers, as shown in figure 2. Each multiplexer has eight total inputs, allowing for four resistor ranges and seven sensors to be measured. One of the sensor ports is required for a calibration cycle, which reduces the available sensors from eight to seven.

2.7. Crystal oscillators

In order to facilitate low-power and accurate operation over a wide range of temperatures, three crystal oscillators are included in the design. The oscillators are for the ATmega1281, AT86RF230 and RTC, and they run at 8 MHz, 16 MHz and 32.768 kHz respectively.

2.8. Ports and switches

Four ports and a 4-bit switch were added for versatility and functionality. The four ports include two power input ports that allow different power systems to be used in low-power operation, one port for programing the microcontroller and one port to connect the seven piezoelectric transducers. A 4-bit dipswitch was added for the ability to change the operation mode of the WID2.0: one bit is used for the on/off power switch for the device, and the other three bits are used for operation selection through software coding of the port value.

Advantages of this new device include its low cost, low power, small size, greater accessibility, and wireless data telemetry. The price of the components required to fabricate one device is less than $200. It can be assumed that the cost would be reduced even more if the devices were manufactured in bulk.

3. WID2 performance verification

Once the WID2.0 had been designed and fabricated, experimental investigations were carried out in order to determine its performance as an SHM sensor node, and to see if the power consumption was low enough to make it a practical wireless sensor node. First, an SHM experiment was performed in corrosion monitoring of an aluminum plate and in bolted joint monitoring of a framed structure. Additionally, a sensor self-diagnostics test was performed in order to determine the capability of the WID2 in checking the functionality of piezoelectric active-sensors in operation. In these tests, impedance measurements made with an Agilent 4294 impedance analyzer were compared with measurements obtained from the WID2 for verification. For all of the testing performed, the WID was connected to two AA batteries and was programed with the required frequency ranges and data acquisition points. Once the measurement was taken, data were wirelessly sent to a STK500/501 development board with an ATAVRRZ502 Zigbee RF telemetry module that was used as a serial port interface. Several MATLAB scripts were written to import the data from the serial port and plot the data.

3.1. Corrosion monitoring

Corrosion is an extremely costly problem for industries and business sectors. Corrosion begins as moisture penetrates the protective barrier of a surface, starting an electrochemical process which over time leads to surface pitting. The combined action of mechanical stresses and corrosion induced pitting reduces structural integrity as the pits enlarge to form nucleation sites for surface cracks that eventually propagate into through-the-thickness cracks. In most cases, the total mass loss due to corrosion within the structure is small; however, significant reductions in mechanical strength and fatigue life can occur in the corroded material, leading to advanced crack growth rates or fast fracture. In 1998, Congress funded the Department of Transportation and the Federal Highway Administration (FHWA) to estimate the total cost of corrosion on the US economy and provide corrosion prevention guidelines. The final results of the survey estimated the extrapolated total direct corrosion cost to be $278 billion per year, which is 3.14% of the gross domestic product in the US [15]. Therefore, precise structural health monitoring of pre-crack surface corrosion is paramount in understanding and predicting the effects of corrosion on the fatigue life and integrity of a structure.

The WID2 has successfully been used to detect the pre-crack surface corrosion in an aluminum plate. The premise of this approach is that the sensor node can be permanently installed in a steel structure, including bridges or aircraft, to monitor the formation of corrosion and subsequent crack initiation. The test structure, shown in figure 3, is an aluminum plate (1200 mm × 1200 mm × 2 mm). Nine circular

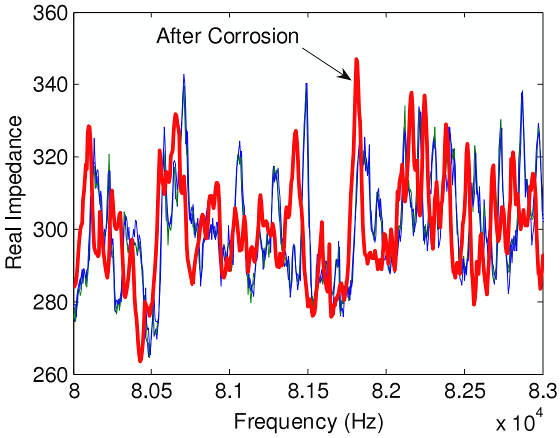


Figure 4. Real part of impedance from PZT 6 measured by the proposed sensor node.

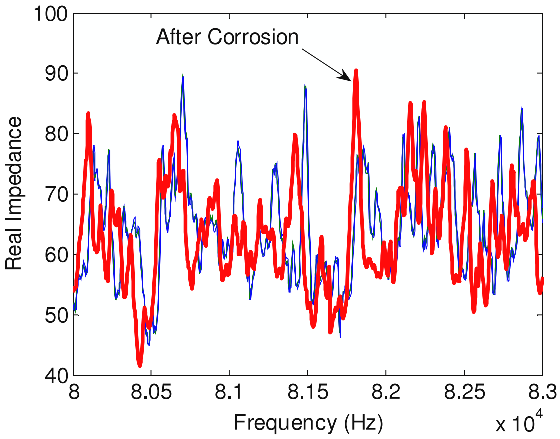


Figure 5. Real part of impedance from PZT 6 measured by a 4294A impedance analyzer.

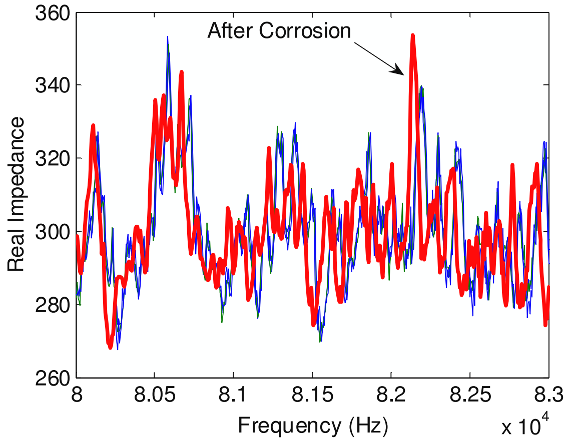


Figure 6. Real part of impedance from PZT 4 measured by the proposed sensor node.

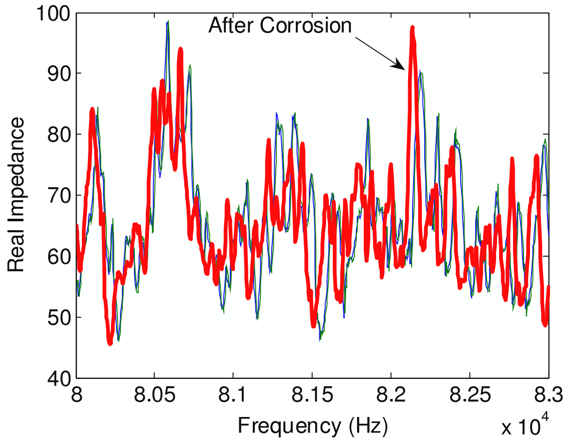


Figure 7. Real part of impedance from PZT 4 measured by a 4294A impedance analyzer.

piezoelectric patches are mounted using super-glue on one surface of the plate at equal distances. The locations and numbering schemes of these actuators/sensors are also shown in figure 3. The size of the circular PZT patch is 5.5 mm diameter with 0.2 mm thickness. A 3 cm diameter area of the plate's surface was corroded, close to PZT 6, resulting in the local reduction in thickness of the plate, shown in figure 3. Electrolytic corrosion was used to accelerate the corrosion process. Impedance measurements in the frequency range 80–83 kHz were made for each PZT patch using the WID2 to monitor the conditions of the structure. Additional measurements were made using an Agilent 4294A impedance analyzer for verification purposes.

Figure 4 shows the real part of the impedance measurement from PZT 6. Three baseline measurements are shown with a measurement taken after corrosion. One important feature of any SHM device is the repeatability of the measurement made. To test the repeatability of the WID2, three measurements were made (they are displayed in figure 4), which allowed for a comparison of the signals. These baseline measurements overlap one another, and are virtually identical. When the corrosion was introduced, there was a significant variation in the measured response, which is an indication of structural damage. These results indicate that the proposed sensor node provides an effective detection and tracking tool for corrosion induced structural damage. Figure 5 shows the measurement from an Agilent 4294A impedance analyzer. It can be seen that both devices show the same shape and follow the same trend before and after damage is introduced. It should be noted that the absolute magnitudes of the impedance values are different in the two measurements. This difference is caused by the fact that the AD5933 contains inherent electrical impedance inside the chip, while the sensing resister used to estimate the impedance value within the sensor node also contributes to the differences in magnitude. One can use an op-amp in a voltage follower configuration to reduce this offset, which is detailed in our previous study [13]. However, this approach was not taken in this study as the discrepancy does not reduce the sensitivity of the devices in detecting structural damage, as illustrated.

Figures 6 and 7 present the impedance measurements from PZT 4 using the proposed sensor node and the Agilent impedance analyzer, respectively. Because the sensor is distant from the corrosion, the response change (before and after corrosion) is not as distinct as in the case of PZT 6. However, both devices produce the same shape impedance response, demonstrating that the measurements of both methods contain the same information on the structure's own characteristics, which confirms that the proposed low-cost, lightweight sensor node can produce reliable impedance measurements suitable for SHM applications.

3.2. Bolted joint monitoring

It is estimated that 70% of all mechanical failures are related to fastener failure. One important mode of fastener failure is self-loosening of bolted joints. Self-loosening is especially problematic when the bolted joint is in an inaccessible location, a hostile environment, or a part of a machine whose shutdown would be costly. The structure that was tested was a bolted frame 31 cm high and 56 cm wide. The frame is constructed of three 6 mm $\times$ 50 mm aluminum beams bolted together at the ends with 10 mm bolts and angle irons. The whole structure is bolted to an aluminum base plate 61 cm $\times$ 15.2 cm $\times$ 1.2 cm. A photograph of the test structure is shown in figure 8.

To test the ability of the WID2.0 to make SHM measurements, the impedance measurements of four macro-fiber composite (MFC) transducers were taken. MFCs are a relatively new type of PZT transducer that exhibit superior ruggedness and conformability compared to traditional piezoceramic wafers. The MFC transducers used in this investigation have the dimension of 17 mm $\times$ 36 mm. The locations of the transducers are labeled in the figure. Sensors 1 and 4 were bonded to the outside of the vertical members of the frame and located 8 cm above the base plate. Sensors 2 and 3 were bonded to the top beam, starting 8 cm from each end. The impedance measurements were taken at a frequency range of 90–95 kHz. This frequency range was chosen as it contains a good dynamics interaction between MFCs and the structure with multiple peaks and valleys (resonances and anti-resonances).

Baseline measurements were taken at each of the patches with all of the bolts fully tightened (150 in lb); then the bolt nearest to sensor 3 was loosened (hand tightened) as a damaged condition and the measurements were repeated. The measurements were taken with both the WID2.0 and the Agilent impedance analyzer to allow for comparison.

The results are shown in figure 9. The figures show both baselines and damaged signals from the structure. It is easy to see qualitatively that the damaged signals are quite different, with the appearance of new peaks and shifts in the peaks at all frequency ranges examined. These changes are identified with exactly the same accuracy for the WID2 and the Agilent 4294A analyzer. Slight differences in the magnitude could be a result of differences in A/D conversion, the number of data points taken, and the internal impedance of the AD5933 chip. However, the measurement from the WID2 shows the structure's own characteristics, which again confirms the effectiveness of the device in SHM applications.

3.3. Sensor diagnostics

One critical aspect of piezoelectric active-sensing technologies is that large numbers of distributed sensors and actuators are usually needed to perform the required monitoring process. In addition, the structures in question are often subjected to various external loading and environmental condition changes that may adversely affect the functionality of SHM sensors and actuators. The piezoelectric active-sensor diagnostic procedure, in which the functionality of sensors/actuators is confirmed to be operational, is therefore a critical component to successfully complete the active-sensing SHM process. Because piezoceramic materials are brittle, sensor fracture and subsequent degradation of mechanical/electrical properties are the most common types of sensor/actuator failure. In addition, the integrity of bonding between a PZT patch and its host structure should be maintained and monitored as it modifies the strain and stress transfer mechanism. In our previous work, it was shown that the effects of bonding defects were remarkable, modifying the phase, amplitude, and shape of propagated Lamb waves and changing the measured impedance spectrum, which can easily lead to the false indication of a monitored structure [9]. In order to fully implement current active-sensing systems in SHM practice beyond the proof-of-concept demonstration, an efficient sensor-self-diagnostic procedure should be adopted in the SHM process.

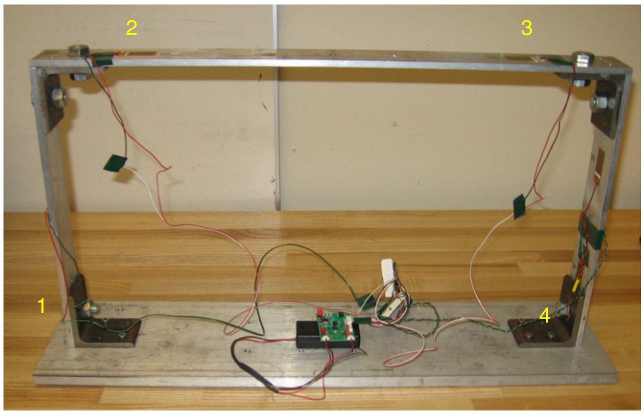
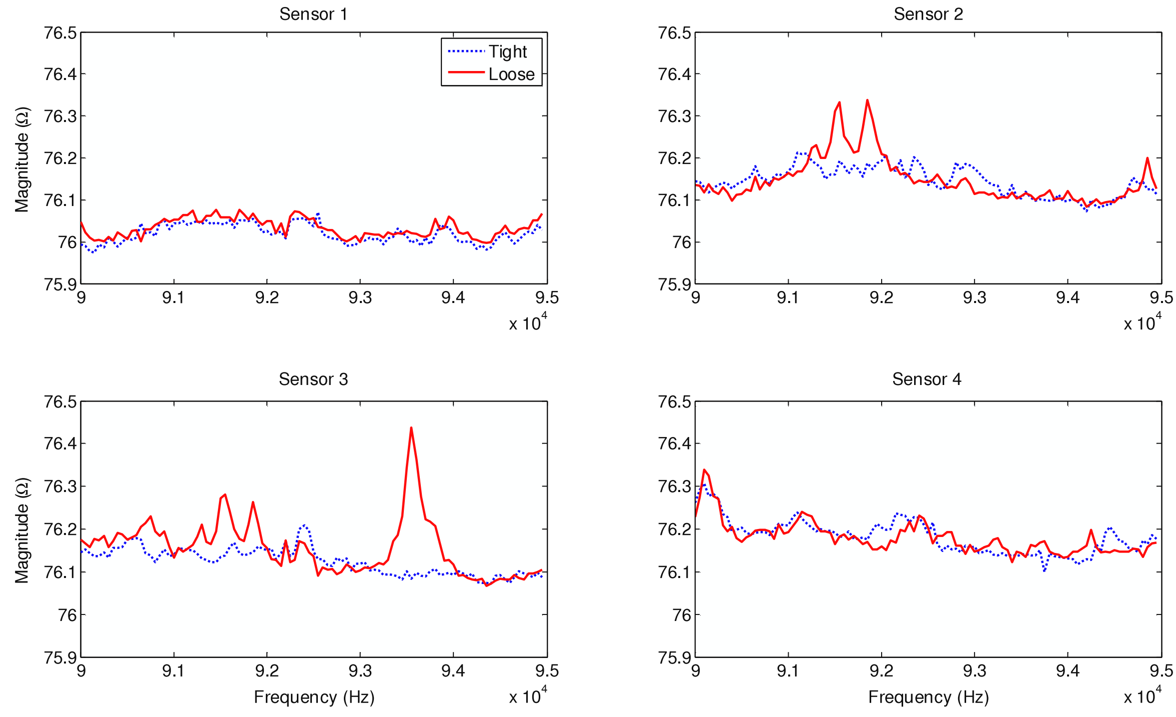


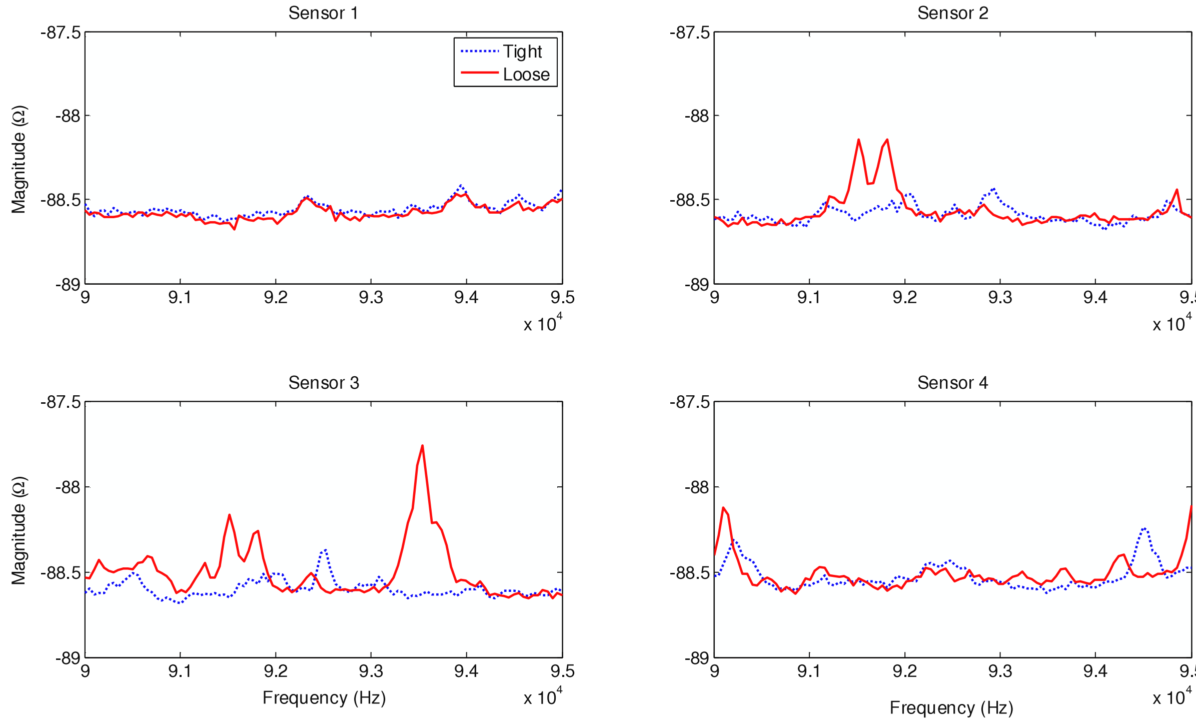
Figure 8. The portal frame structure tested.

A piezoelectric sensor diagnostic procedure based on electrical admittance measurements is therefore implemented in the WID2. The basis of the sensor diagnostic procedure is to track changes in the capacitive value of piezoelectric materials, which is manifested in the imaginary part of the measured electrical admittances [8, 9]. The changes resulting from the structural damage will cause complete changes in the real part of the admittance/impedance signatures, while causing variations along the imaginary part of the signatures (no change in the capacitive value). On the other hand, sensor failure will result in changes to both the real and imaginary parts of the admittance/impedance signatures, distinctively causing a decrease (sensor breakage) and an increase (debonding between PZT transducers and the host) in the capacitive value.

In order to determine the performance of the WID2 in sensor diagnosis, an experiment was performed. Three circular piezoelectric patches were mounted using super-glue on one surface of an aluminum plate. Each patch has a different bonding condition: perfect bonding, 25% area debonding, and 50% debonding. The size of the circular PZT patch



(a) Measurements from WID2



(b) Measurements from the Agilent Impedance Analyzer

Figure 9. Comparison between the WID2 and the Agilent impedance analyzer in bolted joint monitoring.

is 5.5 mm in diameter with 0.2 mm thickness. Admittance measurements in the frequency range 10–20 kHz were made to each PZT patch after installation, using the WID2 and an Agilent 4294A impedance analyzer. These results are shown in figures 10 and 11. With induced debonding, the slope is different from the perfect bonding condition, and as the debonding area increases, there is a corresponding increase in the slope. The theoretical base of this reduction is detailed

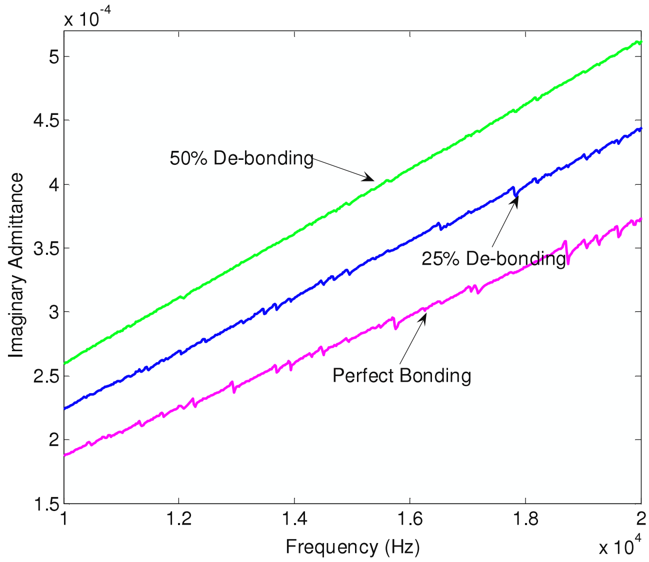


Figure 10. Sensor diagnostic results from the WID2.

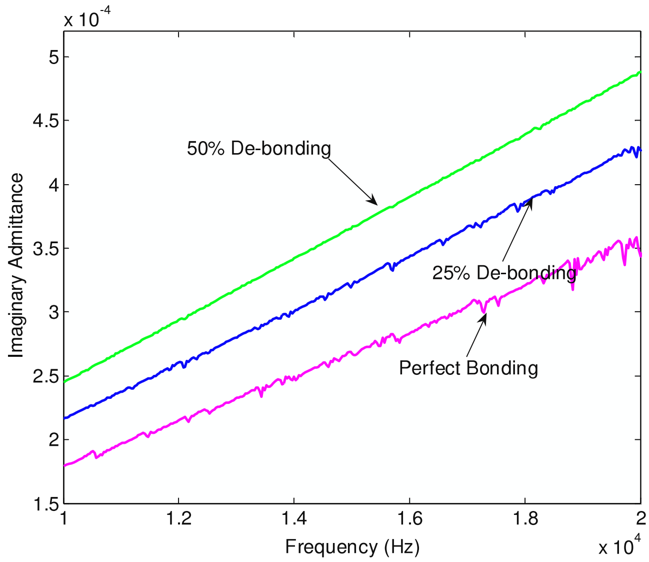


Figure 11. Sensor diagnostic results from the Agilent 4294A impedance analyzer.

in [8]. The measurement from the proposed sensor node is compared to those measured by an Agilent impedance analyzer, shown in figure 11. Although there is a slight offset, the impedance analyzer shows essentially the same pattern captured by the WID2, which demonstrates that the sensor node can be efficiently used as a sensor diagnostic device, as well as an SHM tool.

4. Power consumption of WID2

In order to produce the most versatile SHM device, consideration was given to making the WID have a small power requirement, which was achieved through the selection of power-efficient parts discussed in the previous section. To determine the actual in-service power consumption, several tests were performed on the WID2 during various operational conditions to identify the useful life of the device with different power sources. The power consumption measurements were taken during the previous measurements used to evaluate the impedance measurement capabilities of the WID. The addition of a multimeter allowed for the measurement of the current draw. The multimeter was placed in line on the WID's positive voltage terminal. A time reading was also taken to determine the length of each measurement phase.

Table 1. Current draw for the WID in various states.

State	Current (mA)
Measure	20
Transmit	22
Idle	0.65

The WID2 has very low power consumption, especially considering the active nature of its measurements. The current draw during various modes of operation was recorded and is shown in table 1. The WID2.0 operates at 2.8 V. The WID takes 6 s to measure four sensors with 100 points and four averages per point. With data reduction, only a few seconds would be required to transmit the data from the WID to the base station, or a few microseconds to store the data on the onboard locations. Initial testing indicates that the current draw could be reduced to approximately 0.01 mA with proper use of sleep modes. With these steps, it is conceivable that the WID2.0 could take, analyze, record and send one measurement per day for well in excess of 5 years on two conventional AA lithium batteries. At this extremely low power level, the WID could also be powered by a wide range of energy harvesting methods.

5. Conclusions

The WID2 was developed to meet a need in the structural health monitoring field for a small, power-efficient and flexible wireless impedance node. The size of the WID, at 5.2 cm × 3.7 cm, makes it a very small and convenient device to use in various situations, especially compared to typical impedance analyzers with required power and data lines.

At the current levels of power consumption, the WID2 is at the lower extreme of power consumption levels compared to the devices presented in previous studies. The power levels observed are even more impressive when considering that this system performs active-sensing measurements, unlike most of the devices in the literature, which are passive measurement systems. At these power levels, the WID2 could be powered by a wide range of energy harvesting methods.

There are several factors that contribute to the flexibility of the WID2. First, the ability to quickly and efficiently change code on the microcontroller, through the onboard ISP header, allows one to perform a wide variety of data manipulation with minimal effort. Second, the ability to accept power from diverse sources through the built-in power port and its low power consumption increase its versatility. The inclusion of a wireless telemetry solution allows the sensor node to be placed in remote and inaccessible locations, without the constraints of a wire-based system. Finally, the WID2 is capable of controlling multiple sensors per node (up to seven sensors) and is equipped with several triggering options, i.e. wireless triggering or timer triggering. All of the above factors contribute to make the WID2 a very attractive device for the SHM community.

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