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Autonomous hardware development for impedance-based structural health monitoring

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Abstract. The development of a digital signal processor based prototype is described in relation to continuing efforts for realizing a fully self-contained active sensor system utilizing impedance-based structural health monitoring. The impedance method utilizes a piezoelectric material bonded to the structure under observation to act as both an actuator and sensor. By monitoring the electrical impedance of the piezoelectric material, insights into the health of the structured can be inferred. The active sensing system detailed in this paper interrogates a structure utilizing a self-sensing actuator and a low cost impedance method. Here, all the data processing, storage, and analysis is performed at the sensor location. A wireless transmitter is used to communicate the current status of the structure. With this new low cost, field deployable impedance analyzer, reliance on traditional expensive, bulky, and power consuming impedance analyzers is no longer necessary. A complete power analysis of the prototype is performed to determine the validity of power harvesting being utilized for self-containment of the hardware. Experimental validation of the prototype on a representative structure is also performed and compared to traditional methods of damage detection.

Keywords: structural health monitoring; impedance method; damage detection; digital signal processor; wireless monitoring; wireless sensing unit.

1. Introduction

The use of wireless sensors and networks are becoming increasingly popular as a research topic for structural health monitoring (Spencer, *et al.* 2004, Lynch and Loh 2005). In a review of smart sensing technology for civil applications, smart sensors are defined as sensors which contain an onboard microprocessor, giving the system intelligence capabilities (Spencer, *et al.* 2004). However, with this general definition, many of the systems presented in the review simply acquire data from a structure and wirelessly pass this unprocessed information along for analysis at a later time. Besides civil infrastructure, many wireless sensors and sensor networks are also being developed for other structures such as aircraft and ships (Lynch and Loh 2005).

To alleviate the large power requirements necessary for wirelessly transmitting large amounts of data, research has been performed which incorporates local (at the sensor) processing capabilities with wireless sensors. One such example is described by Lynch, *et al.* who designed and fabricated a wireless active sensing unit from off-the-shelf components for monitoring civil structures (Lynch, *et al.* 2004). A computational core is combined with wireless transmission and sensing circuits to allow for

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remote actuation and sensing, processing of data with stored algorithms, and informing the end user to the condition of the structure. An auto-regressive with exogenous input (ARX) time-series model of the input-output data is used as the local processing method. A Berkeley-Mote platform is also used as a basis for a wireless structural health monitoring system with an embedded damage detection algorithm (Tanner, *et al*. 2003). Using the local processing capability of the system, the loosening of bolt preloads has been determined. The Berkeley-Mote platform described here in not well suited for high frequency structural health monitoring, such as the impedance method, based on its low input bandwidth of 1 kHz or less.

Impedance-based health monitoring techniques utilize small piezoelectric patches attached to a structure as self-sensing actuators to simultaneously excite the structure with high-frequency excitations and monitor changes in the patch electrical impedance signature (Park, *et al.* 2003). Since the piezoelectric is bonded directly to the structure of interest, it has been shown that the mechanical impedance of the structure is directly correlated with the electrical impedance of the patch (Liang, *et al.* 1994). Thus, by observing the electrical impedance of the piezoelectric, assessments can be made about the integrity of the mechanical structure.

Using the impedance method, damage has been successfully detected on a variety of structures from simple beams and plates to bridge truss structures, airplane composite patch repairs, and pipeline structures (Park, *et al.* 2003). Different damage mechanisms detected in these structures include cracking, bolt loosening, composite debonding and more. The hardware developed here is intended to detect any of these damage types, as well as the multitude of other impedance-based structural health monitoring applications not discussed here.

Traditionally, the impedance method requires the use of an impedance analyzer, which is used to measure and analyze impedance in electrical components and systems. Impedance analyzers generally provide precise electrical impedance (as well as capacitance, inductance, resistance, etc.) measurements over broad frequency ranges with extensive functionality and display options. Due to their high performance intended for electronics quality control, design, and other tasks, such analyzers are bulky, expensive, and not suited for permanent placement on a structure. With the current trend of structural health monitoring heading towards unobtrusive self-contained sensors, the first steps in meeting the low power requirements resulted in the MEMS-Augmented Structural Sensor (MASSpatch) (Grisso, *et al.* 2005).

Analog Devices has also recently introduced impedance measurement devices in chip format. The AD5933 has a 1 MHz sampling rate and also comes in an evaluation board format. A prototype similar to MASSpatch has been developed using the AD5933 evaluation board, an ATmega128L microprocessor, and Xbee radios for wireless communications (Mascarenas, *et al.* 2006). Using the microprocessor to control the evaluation board, bolt loosening was detected in a frame structure.

In contrast, MASSpatch is a single board computer system which interrogates a structure utilizing a self-sensing actuator and a low cost impedance method, and all the structural interrogation and data analysis is performed in near real time at the sensor location. Wireless transmissions alert the end user to any harmful changes in the structure. In the MASSpatch prototype, the computing core triggers an external function generator to provide a swept sine excitation signal. After recording the applied and response provided by a low cost circuit, the data is transformed to the frequency domain. By comparing any new impedance measurements in the frequency domain to a stored baseline, system changes can be discerned, and wireless telemetry alerts an end user to the presence of damage.

Unfortunately, there are some limitations with the MASSpatch prototype. The algorithm, written in C, to perform the impedance method was utilized as an executable in the DOS operating system. When using an operating system, much of the processing power is used to run the actual system, as well as the algorithm. Determining how much energy is used for computing the actual algorithm is difficult. Also, a digital-to-analog converter (DAC) was never fully incorporated into the system, and reliance on an external function generator was needed for structural excitation. A voltage controlled oscillator was constructed for the actuation of this prototype, but the period of the swept sine signal generated was too long. The development of the hardware discussed here began before this issue was resolved. For these reasons, a new processing device must be used in order to optimize the prototype. The current system is based on a digital signal processor (DSP) platform. The benefits of this new system are discussed, along with current research and the path forward to a complete stand alone structural health monitoring (SHM) system that requires minimum power.

2. Hardware development

Currently, nondestructive evaluation techniques are used to assess the condition of many structures while they are off-line. An autonomous impedance-based system would have the ability to directly detect damage by analyzing variations the electrical impedance of self-actuating sensors bonded to the structure. The developed prototype should deploy autonomous, wireless, self-powered sensors that harvest energy from ambient vibration and thermal gradients. In order to prevent single points of failure, each sensor is self-contained and operates independently from other sensors, but also has the ability to function in a network. The following work describes the initial steps at achieving such a wireless system.

2.1. Low cost impedance method

Due to the size and power limitations of using an impedance analyzer for permanent structural health monitoring purposes, a method has been developed to avoid reliance on such analyzers (Peairs, *et al*. 2004). A low cost impedance technique has been introduced as a first step in achieving a smaller, inexpensive impedance analyzer. This low cost method requires only a sensing circuit, consisting of a resistor, and a standard FFT analyzer. By placing the sensor in series with the piezoelectric, the circuit is simply a voltage divider. The output voltage across the sensing resistor is proportional to the current through the resistor. The current through the resistor, with small resistances, is close to the current through the piezoelectric as if the circuit were not there. Taking the ratio of the applied voltage and resulting current, the impedance can be determined.

Using a low cost impedance method, the impedance analyzer's weight, size, and power are taken out of the equation. However, some form of FFT analyzer must still be used, and data must be processed externally to determine whether changes in the structure have occurred. FFT analyzers can still potentially be large and expensive, so this project extends the concept of a low cost circuit by presuming that the functions of a FFT analyzer, as well as the required analysis, can all be performed on a single chip. With everything contained on a single chip, a sensor utilizing the impedance method for damage detection could be inexpensive and small enough for permanent deployment.

2.2. Hardware components

To implement the impedance-based structural health monitoring method in a field deployable setup,

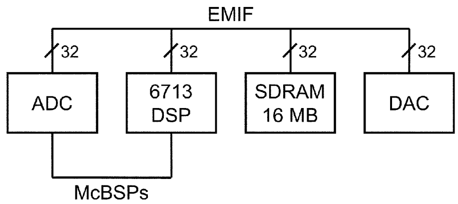

Fig. 1 A diagram of the prototype hardware configuration is shown

hardware is assembled as shown in Fig. 1. Using the low cost technique, accurate approximations of the structural impedance can be determined without complex and expensive external electronic analyzers. As shown in Figs. 1 and 2, all of the hardware needed to utilize the impedance method is condensed into a single stacked board configuration. This prototype is designed to function similarly to MASSpatch with key improvements in sampling frequency and integrated actuation. A description of each of the components to enable these upgrades follows.

This impedance-based prototype is based on a TMS320C6713 DSK evaluation DSP module from Texas Instruments (Texas Instruments 2005b). The DSP has an internal system clock speed of 225 MHz, 192 kB of internal memory, and external synchronous dynamic random access memory (SDRAM) of 16 MB. With a large amount of external memory, the memory space is partitioned into two major sections: samples for DAC output, and samples from the analog-to-digital converter (ADC). As shown in Fig. 1, the ADC, DAC, and SDRAM all share an external memory interface (EMIF). The DSP controls the ADC by means of a multi-channel buffered serial port (McBSP) acting in general purpose input output (GPIO) mode.

Two more evaluation boards from Texas Instruments are used as the ADC and DAC. The ADS8364 EVM ADC board has six channels of input and a 250 kHz sampling rate (Texas Instruments 2002). Conversion resolution for the ADC board is 16 bits. For the DAC, a TLV5619-5639 EVM board is used with a 5639 DAC (Texas Instruments 2001). The DAC evaluation board has two outputs and a maximum sampling rate of 1 MHz at 12 bit resolution. The physical orientation of the DSP kit, ADC,

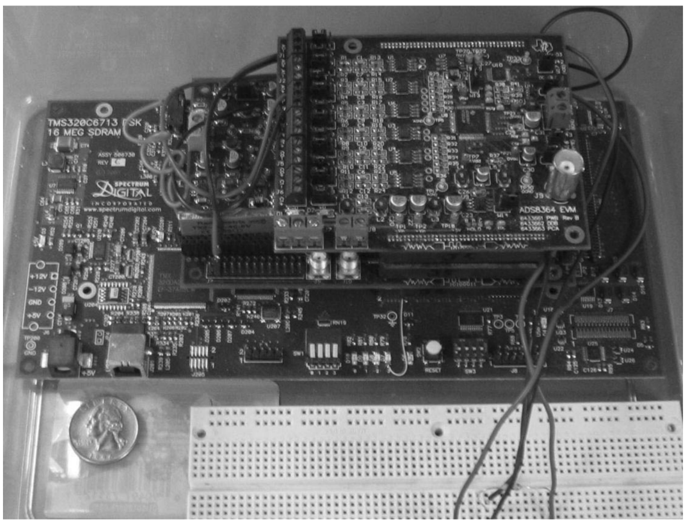

Fig. 2 The current prototype is shown with the DSP is on bottom followed by the DAC and ADC

Table 1 Specifications are displayed for the prototype

Processing/Programming		Sensing/Sampling		Wireless Transmission	
Processor	TMS320C6713 225 MHz Floating Point DSP	ADC Resolution	16 bit	Usable Range	over 1 km
Internal memory	192 Kb	Max Sampling Frequency	250 kHz per channel 750 KHz paired	Operating Frequencies	433.05-434.79 MHz
External memory	16 MB SDRAM	Sensor Types and Ranges	6 Analog at up to +10 to -10 V	Data Bit Rate	5 kbps

Actuation		Dimensions	
DAC resolution	12 bit	DSP Board	22 × 11.5 cm
Max sampling frequency	1 MHz	DAC Board	13.5 × 8.5 cm
Channels	2 up to 4 V	ADC Board	10 × 8.5 cm
		Height	4.5 cm

and DAC can be seen in Fig. 2.

The wireless transmitter and receiver are used to indicate the current state of damage for the structure of interest. The transmitter sends a quantified amount of damage, and the receiver displays this value on a host computer. The current prototype uses Radiometrix RX2M-458-5 and TX2M-458-5 wireless sensors as the receiver and transmitter (Radiometrix Ltd. 2005). The hardware component specifications and dimensions are summarized in Table 1.

2.3. Impedance-based health monitoring algorithm

As previously mentioned, when a piezoelectric material is bonded to a structure, the electrical impedance of the piezoelectric is directly related to the mechanical impedance of the structure. Therefore, by monitoring the electrical impedance of the piezoelectric, changes in the structure's mass, stiffness, or damping can be observed. Usually, an impedance analyzer is used to acquire data, and analysis is performed independently of data acquisition.

The operational flow of the current prototype allows structural health monitoring to be performed all with one piece of hardware. The DSP board controls the entire operation. An excitation signal is sent from the DAC board simultaneously to the ADC board and the structure of interest. The ADC reads the voltage signal from the DAC and the voltage across the sensing resistor (seen in the bottom of Fig. 2) of the low-cost impedance circuit concurrently. After ten excitation cycles, the signals are averaged, a FFT is performed, and one impedance measurement is generated. The first two measurements generated are baseline impedance curves. Once the baseline is stored, each measurement is compared with the baseline to determine whether there is damage in the structure by means of a damage metric. The algorithm allows for the specification of a threshold damage value. If the threshold damage value, as indicated by the damage metric, is exceeded, the wireless transmitter is activated. This signal is recognized by a wireless receiver across the room, and an LED is turned on to indicate damage. Once the damage metric drops below the threshold value, the transmitter, and thus the LED, is turned off to indicate no damage to the system.

Impedance signatures are, in general terms, simply frequency response functions (FRF). They have

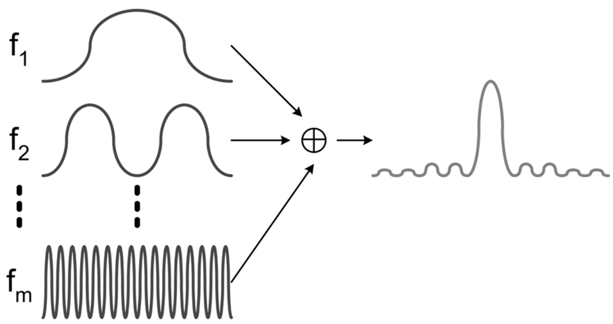

Fig. 3 A diagram showing the sinc function (on the right) and how the function is built

the general appearance of FRFs, as seen in Fig. 5. The main difference is that the input to the sensor is voltage, and the resulting current is the output. By monitoring the changes in the peaks of these FRFs, and simple damage algorithm can be used to quantify the amount of change in the peaks and thus the amount of damage in the structure. In this case, a variation of the root mean square deviation is used as the damage metric (Park, *et al.* 2003). The root mean square deviation is used as a way to express the difference between two curves as a single number. A higher numeric value indicates more disparity between the curves and, in this case, greater damage in the structure.

In order to excite the structure of interest, it was decided to use sine cardinal, or simply sinc, functions as the DAC output. The sinc function has the unique property in that its Fourier Transform is a box. Having a uniform value in the frequency domain allows for a band of frequency content in one pulse. The sinc function is based on a fundamental frequency and then frequencies which build upon the fundamental, as shown in Fig. 3. By slightly altering the fundamental frequency each time a pulse is sent out, the averaged spectrum is even smoother. The sinc function is described as (Schilling and Harris 2005).

$$\text{sinc} = \frac{\sin(x)}{x} \tag{1}$$

By using a sinc function instead of exciting the structure with discrete frequencies, more frequencies can be excited in the same amount of time. The auto spectrum of the output signal will also be a straight over all the frequencies excited. Other advantages of the sinc function include needing less memory space and less traffic in the external interface, as well as lower power consumption in the DSP, ADC, and DAC.

2.4. Power analysis

Currently, the prototype runs off of DC power supplies. In a permanent setting, the sensing system will operate off of battery power recharged by harvested ambient energy. To optimize the battery life and minimize the required maintenance schedule, both piezoelectric and thermal based power harvesting can be utilized to recharge batteries. Piezoelectric materials have the unique property of being able to transform mechanical strain into an electric charge. By using this property, piezoelectrics can harvest energy by using a systems own ambient motion, transform this mechanical kinetic energy into electrical potential, and store the electrical energy, power devices, or recharge a battery using power harvesting circuitry (Sodano, *et al.* 2003).

In order to prepare the hardware to be completely run off of a battery and power harvesting, a complete power analysis is done of the current system. In the prototype, the DSP board supplies power to the DAC board, which in turn supplies power to the wireless transmitter. Due to the connectivity of these systems, the power consumption of the DAC and transmitter cannot be exactly determined. However, they can be estimated. According to specifications, the maximum current the transmitter consumes is 100 mA at 5 V_{DC}, or 0.5 W (Radiometrix Ltd. 2005). The transmitter is being supplied with 3.3 V_{DC}, and is only sending out a low power signal, so 0.33 W (100 mA at 3.3 V_{DC}) is a high estimate. The DAC board is stated to consume 170 mA at 3.3 V_{DC} and 150 mA at 5 V_{DC}, or a range of 0.561 W to 0.825 W (Texas Instruments 2001). In this setup, the DAC board is being operated at 5 V_{DC}.

The DSP board is supplied with a 5 V_{DC} power supply, so the DSP, DAC, and wireless transmitter can be measured as a group. When the system is fully turned on, but the algorithm is not being performed, the DSP requires 470 mA at 5 V_{DC}, which is 2.35 W. While the whole impedance-based SHM operation is being performed, including wireless transmission, the current draw increases to 570 mA, giving a power of 2.85 W. So, wireless transmissions are shown not to be a significant drain on the power supply. All of these measurements are instantaneous power, but the current draw remained almost constant during a complete operational cycle.

The ADC has its own ±12 V_{DC} power supply. During operation, the ADC requires 60 mA, yielding 1.44 Watts of power. So, the total amount of power required to completely perform impedance-based SHM is 4.29 W. A summary of the power analysis can be seen in Table 2. Comparatively, the MASSpatch prototype used around 4.5 W of power (Grisso, *et al.* 2005). 4.29 W does not seem like a significant reduction considering the advances in hardware and excitation efficiency, however, remember that the MASSpatch prototype relied on an external function generator to provide excitations. MASSpatch did not include its own DAC, and the function generator used was plugged into a wall outlet and consumed a considerable amount of power.

Even with 4.29 W of power, the prototype is capable of being run solely off of battery power and piezoelectric power harvesting. For instance, if this system was being continuously run for ten or more minutes (a rather excessive time), ten 1.2 V, 200 mAh capacity batteries could supply more than enough energy to the system. In actuality, the system can power on, collect data, process the result, and broadcast the damage case in under a minute. A 1 Ah capacity means that a battery will last for 1 hour if it is subjected to a discharge current of 1 A. A 200 mAh battery can be recharged to 90% capacity in 1.2 hours with a random vibration signal at 0 to 500 Hz if a 6.35 × 2.375 inch piezoceramic (PZT) is used (Sodano, *et al.* 2003). As an example, an operating space shuttle should have plenty of ambient vibration, as well as thermal gradients, to fully recharge the batteries.

When placing an autonomous system in a permanent setting, it is important to ensure that enough energy is stored and available to complete the entire structural health monitoring procedure. That is, if the energy required by the system is greater than the energy collected from power harvesting and the

Table 2 The power consumption for all the hardware components

Power Analysis	
Wireless (estimate)	0.33 W (max)
DAC (estimate)	0.825 W (max)
DSP, DAC, Wireless Group	2.85 W during operation
ADC	1.44 W
TOTAL	4.29 W

power previously stored in the system, the duty cycle is too short for the required application. In many systems, it would not be unrealistic to assume that checking for damage once a day is more than adequate. If the system is being recharged in one to two hours on average, one day is an acceptable duty cycle.

3. Experimental validation

To validate this new hardware, the system's capabilities are demonstrated in the laboratory. A bolted joint, as seen in Fig. 4, is tested for the initial experiments. The bolted joint structure consists of two aluminum beams with 11.5 cm of overlap connected with four bolts. Both 4 mm thick beams are 61.5 cm long and 5 cm wide. Two rows of bolts are centered 4 and 7.5 cm from the ends of the beam and 1.5 cm in from the beam sides as shown in Fig. 4. A 2.7 by 2.1 by 0.0267 cm type 5H4E piezoceramic from Piezo Systems, Inc. is attached to this structure; the piezoelectric acts as a self-sensing actuator. Damage is induced in the bolted joint by tightening or loosing one or more of the bolts.

3.1. Impedance analyzer testing

Using traditional impedance techniques (a HP 4194A impedance analyzer), a standard for the bolted joint experiment is generated for comparison with the new system's results. Initial bolted joint testing shows that the impedance method readily detects damage induced by loose bolts. Only loosening one of the four bolts by a quarter turn significantly changes the impedance signature. The bolts were initially manually tightened as much as possible using wrenches. Loosening the bolt by a quarter turn does not change the tightness when hand checking the bolts; in other words, the bolts are still tight without using a wrench to turn the bolts. The actual tightness of the bolts was not the focus so much as providing a means of consistent comparison for damage cases. Fig. 5 shows impedance curves generated using an impedance analyzer.

As displayed in Fig. 5, the peaks of the impedance signature change as damage is introduced to the structure by loosening bolts. The more the structure is damaged, the more the peaks shift from the baseline. A frequency range of 10-30 kHz was selected for easy comparison to the prototype. In general, impedance measurements for structural health monitoring purposes are taken over a range of frequencies from 10 kHz to 400 kHz (Park, *et al.* 2003). This frequency range ensures the wavelength of excitation is smaller than the size of damage to be detected. Also, at these high frequencies, the method is generally insensitive to boundary condition changes, operational vibrations, or variations like mass loading. It is also important to note that the impedance method is a local detection method, not a global method; in other words, the peaks seen in the impedance curves of Fig. 5 are not structural natural frequencies but local modes. A variation of the Root Mean Square Deviation (RMSD) damage metric is utilized to analyze changes in these local modes and determine the amount of damage present.

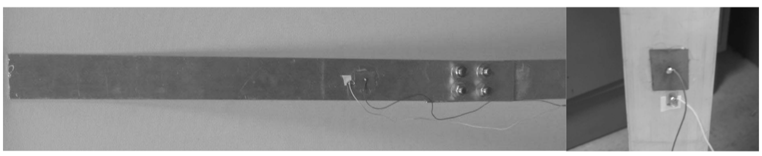

Fig. 4 Images of the bolted joint, and piezoelectric patch are shown

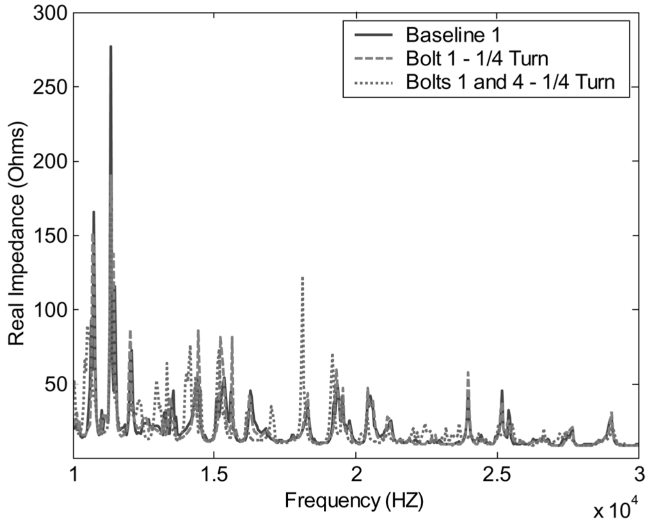

Fig. 5 The baseline and damaged impedance signatures for the bolted joint are shown

The RMSD method for finding the damage metric, M, can be described as

$$M = \sqrt{\sum_{i=1}^{n} \frac{[Re(Z_{i,1}) - Re(Z_{i,2})]^2}{[Re(Z_{i,1})]^2}} \quad (2)$$

where $Z_{i,1}$ is the baseline, or healthy, impedance of the PZT, and $Z_{i,2}$ is the impedance used for comparison with the baseline measurement at frequency interval i. Fig. 6 displays this damage metric in bar chart form.

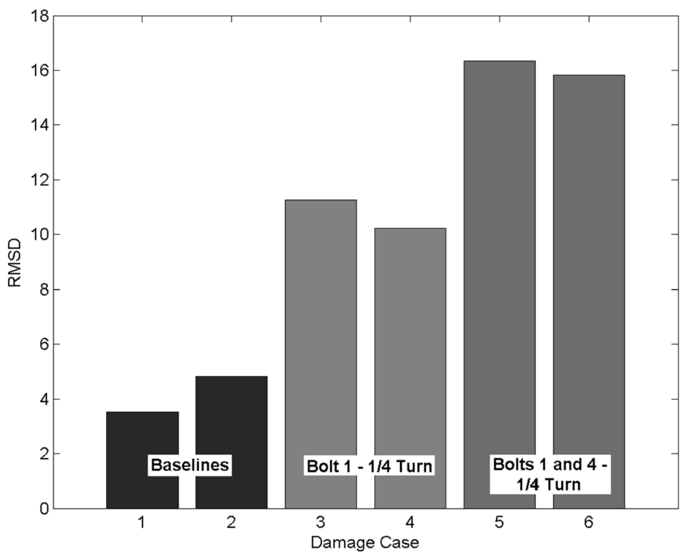

Fig. 6 The damage metric compares the baselines and damaged curves

For this experiment, three separate baselines were taken. One of these baselines will act as the undamaged case, or $Z_{i,1}$ curve, for each of the other values. In Fig. 6, the first two bars, labeled "Baselines" compare the second and third baselines (healthy measurements) with the first baseline. The bars are simply the M values generated by the RMSD equation. Ideally, with no variance in the system, the first two bars would be zero, meaning that all three baselines are identical. It should be noted that changes smaller than the noise in the system could potentially go unnoticed as damage. The next two bars, labeled "Bolt 1 – ¼ Turn", compare the two impedance signatures acquired with bolt one loosened to the first baseline measurement. Looking at Fig. 5, there is a significant difference between the baseline curve and the curve where bolt 1 is loosened a quarter turn. As expected, these differences show up as an increase in the RMSD value, which indicates damage to the end user. Similarly, the final two bars, labeled "Bolts 1 and 4 – ¼ Turn", compare measurements taken with both bolts one and four loosened to the first baseline. Again, the RMSD value increases indicating more damage to the structure.

3.2. Prototype testing

Using the same bolted joint, the prototype could be directly compared with standard impedance measurement methods. Code Composer Studio software allows for visualization of what the damage detection algorithm is doing in the DSP core (Texas Instruments 2005a). At each step in the algorithm, the real impedance measurement (as data is acquired) is displayed along with the baseline, the averaged real impedance measurement used to compare to the baseline, the original DAC sinc function output, and the ADC sampled output. The most important part of the display is the damage metric value, which is updated with each measurement to indicate how much damage is present in the structure. Impedance measurements are taken over the range of 10-32.1 kHz. Based on the sampling speed of the ADC, this frequency range is selected to allow for accurate sampling and digital representation of the acquired data which is within the typical impedance measurement range. Also, a high density of structural modes is seen in this range ensuring that there is a good dynamic interaction to allow for damage detection.

The spectrum of the output can also be displayed, as shown in Fig. 7. As expected from a sinc function, the auto spectrum is a flat line indicating that every frequency of interest is being excited. In Fig. 7, it should be noted that 512 frequency components are displayed, representing 0 to 64,200 Hz. In reality, only half of the spectrum is used, so 256 frequency lines represent 0 to 32,100 Hz.

Initially, measurements are taken with all of the bolts completely tightened. With no damage to the structure, the baseline and damaged impedance signature should be the same. As Fig. 8 shows, the

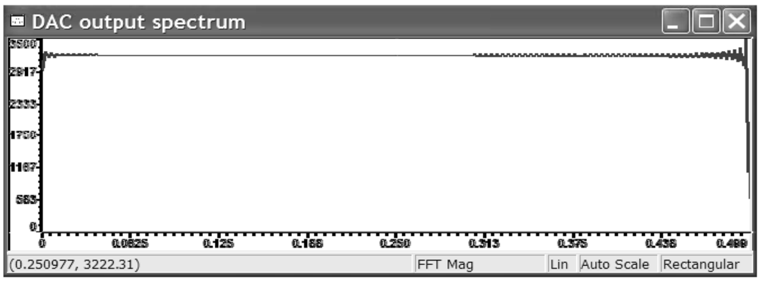

Fig. 7 The auto spectrum is displayed for the sinc function

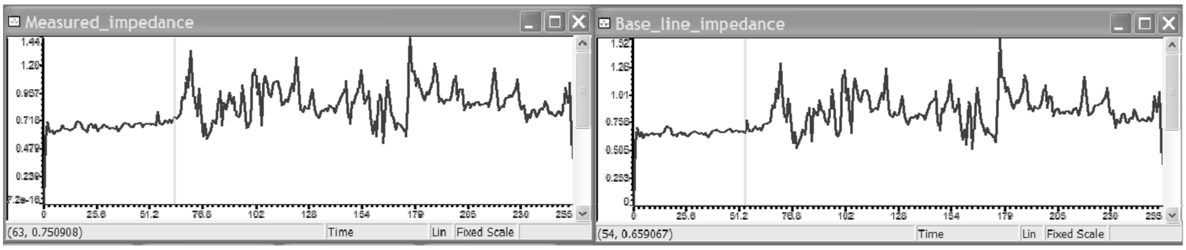

Fig. 8 The measurement with no damage to the structure is compared to the baseline

impedance curves for the new measurement and original baseline are almost identical. Fig. 8 is generated by Code Composer Studio, and allows for graphical displays of what is actually occurring at specific memory locations in the hardware. All of the computations are performed on the DSP, and the graphs just show the results. The damage metric value displayed is 0.02. It should be noted that the damage metric values generated in this experiment should not be directly compared to those given in Section 3.1. The prototype here and the impedance analyzer from the previous section measure and acquire impedance signatures with two different methods and the curve amplitudes are different. Thus, with different impedance curve values, the generated RMSD values will also be different. A more direct comparison between the two methods is the peak frequencies that the different systems measure, which will be discussed in the next section.

One interesting thing to note is that the impedance signatures from Fig. 8 and Fig. 5 are similar. Both show a good number of peaks in similar locations over the range of 10-32.1 kHz. Also, the frequency is displayed by a frequency index, *i*, from 0 to 256, where $i = 256$ corresponds to 32,100 Hz. The RMSD is then taken over the frequency indices of $i = 79$ to 256 (or 9,906-32,100 Hz), even though the whole frequency range from 0-32,100 Hz is displayed. Now, damage was induced on the bolted joint by loosening one of the bolts a quarter turn. This loosening is just enough turn the bolt while still keeping the bolt tightened by hand tight standards, but the prototype easily recognizes the difference as shown in the peak changes of the measured impedance seen in Fig. 9.

Comparing the two curves in Fig. 9, the damage metric increased to 0.13. This is a 550 percent change from the original damage metric. For this experiment, the damage metric threshold value was preset to 0.10. After the bolt was loosened, and the RMSD values was calculated, the wireless transmitter was activated, and the LED was turned on to indicate damage. Using a change in damage which could not be detected by hand, the damage metric easily indicates that the structure has changed. Next, a second bolt was also loosened by one quarter of a turn. Fig. 10 displays the difference for this damage case.

As seen in Fig. 10, with even more damage, the peaks of the measured impedance signature change

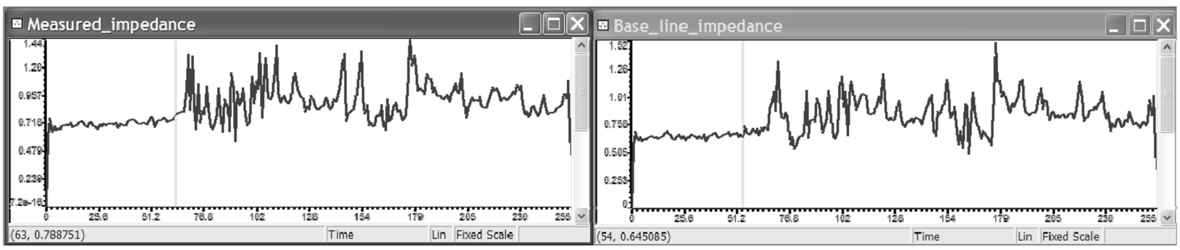

Fig. 9 The impedance signature for slightly loosening one bolt is compared to the baseline

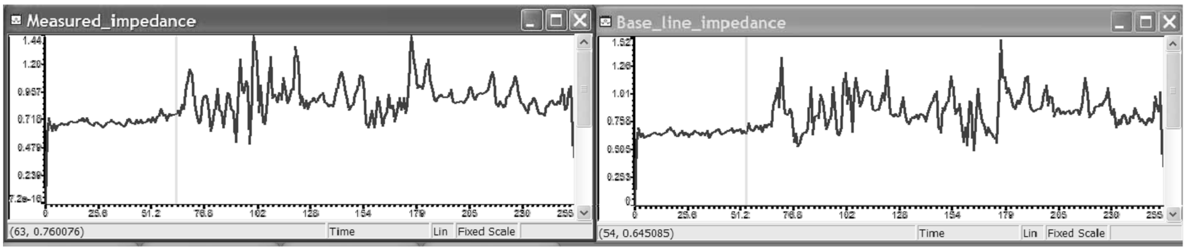

Fig. 10 The impedance signature for slightly loosening two bolts is compared to the baseline

even more. The damage metric also notices the change and calculates a new value of 0.21. The wireless transmitter and LED remained on, indicating the continued presence of damage. However, when both bolts were retightened to their original positions, the RMSD value decreased to near its original value, the transmitter stopped broadcasting, and the LED turned off to indicate no damage.

As previously mentioned, the threshold value for this experiment was set to a value of 0.10. This value was based on previous user knowledge of the system, which is an inherent flaw in using the non model based impedance method. Often, the impedance method is used as an indicator of structural damage presence and not necessarily to quantify the damage. Studies have been performed comparing the damage metric to the actual amount of damage in a system, including the torque in a bolted joint. Using a torque wrench to measure bolt tightness, different levels of damage, from a high load of 56.5 N·m down to hand tight in steps of 11.3 N·m, are clearly indicated using a damage metric (Allen, *et al.* 2004). The loosening at each step was observed by the damage metric before an operator would have noticed with a hand check. Here, the interest was not so much in matching the damage metric value to a specific amount of damage (calibrating the prototype to the bolted joint), but providing a repeatable experiment for validation of the new hardware. The results presented here are also comparable with an analysis performed with standard impedance measuring equipment.

3.3. Prototype and impedance analyzer comparison

As another method of validating the device, frequencies displayed by both the HP 4194A impedance analyzer (Fig. 5) and the new prototype (Fig. 8) are directly compared. Using the impedance analyzer, data was taken in the range of 10,000-32,100 Hz. Table 3 shows a comparison between select peaks shown in both Figs. 5 and 8.

Table 3 A frequency by frequency comparison of the new hardware

HP 4194A (Hz)	Prototype (Hz)	Difference (Hz)	Difference (%)
10,663	10,532.9	130.1	1.22
13,094	13,040.8	53.2	0.41
15,580	15,548.6	31.4	0.20
18,011.25	17,931	80.25	0.45
21,215.75	21,191.2	24.55	0.12
21,547.25	21,442	105.25	0.49
26,575	26,457.7	117.3	0.44
28,840.25	28,714.7	125.55	0.44
31,897	31,849.5	47.5	0.15

Obviously, this is only a small sampling of the frequency peaks between 10 and 32 kHz. Also, as is expected, each device is slightly more sensitive to some peaks than the other, so some peaks may be missed simply as a function of the frequency resolution. However, even when some peaks may appear to be well apart from one another, they are generally well within the frequency resolution of the machines being used. The impedance analyzer takes data from 10 to 32.1 kHz in 400 points, yielding a frequency resolution of 55.25 Hz. This prototype has a frequency resolution of 125.39 Hz. The percent difference is with respect to the HP 4194A impedance analyzer, which is assumed to be the true value for these experiments.

4. Conclusions

This paper presents the first fully self-contained system that performs impedance-based structural health monitoring. In previous research, a system was developed which performed most of the health monitoring steps, but needed the use of an external function generator for actuation. The current system effectively replaces an impedance analyzer and MATLAB. All of the structural excitation, data acquisition, and health monitoring analysis are performed in a matter of seconds. With traditional impedance techniques, after the data is acquired, all of the analysis must still be done using processing software to determine whether there is damage. Now, damage in a structure can be found almost immediately.

Also described is the first use of impedance excitation with targeted sinc functions. The use of sinc functions has the potential to save both excitation time and computational power. By slightly varying the fundamental frequency with each pulse, the structure will be excited at every frequency in the range of interest.

Future work of this device includes performing a complete excitation signal energy analysis to explore the benefits of actuation with sinc functions. Also, piezoelectric based and thermal power harvesting will be incorporated to allow the system to be fully self-sufficient. Eventually, with the knowledge gained from this prototype, an even smaller prototype can be custom designed with components specific to the project, all leading to the eventual goal of having a complete impedance-based SHM system contained on a single chip.

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