DEVELOPING AN AUTONOMOUS ON-ORBIT IMPEDANCE-BASED SHM SYSTEM FOR THERMAL PROTECTION SYSTEMS

Benjamin L. Grisso and Daniel J. Inman
Center for Intelligent Material Systems and Structures
Virginia Polytechnic Institute and State University

Abstract

Deployment of structural health monitoring systems for permanent damage detection is limited by the availability of sensor technology. The development of a DSP based prototype is the focus for initial efforts in realizing a fully self-contained active sensor system utilizing impedance-based structural health monitoring. The active sensing system interrogates a structure utilizing a self-sensing actuator and the low cost impedance method, and 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. Experimental validation of the prototype is performed on a representative structure and compared to traditional methods of damage detection.

Introduction

Thermal protection systems on spacecraft are crucial for the survival of the vehicle during Earth reentry. The complex nature of thermal protection systems and extreme reentry temperatures do not allow easy access for monitoring the condition of the spacecraft external surface. An active sensing system is proposed to interrogate the exterior of the surface and provide automated damage detection, diagnostics, and prognosis.

The use of wireless sensors and networks are becoming increasingly popular as a research topic for structural health monitoring.[1] However, many of these investigations are focused on the development of wireless monitoring systems for civil infrastructure. Spencer *et al.*, in a review of smart sensing technology for civil applications, defines smart sensors as sensors which contain an onboard microprocessor, giving the system intelligence capabilities.[1] 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.

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.[2] A computational core is combined with wireless transmission and sensing circuits to allow for remote actuation and sensing, processing of data with stored algorithms, and informing the end user to the condition of the structure. An ARX time-series model of the input-output data is used as the local processing method. Tanner *et al.* used a Berkeley-Mote platform as a wireless structural health monitoring system with an embedded damage detection algorithm.[3] Using the local processing capability of the system, the loosening of bolt preloads has been determined.

Impedance-based health monitoring techniques utilize small piezoceramic (PZT) 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.[4] Since the PZT 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 PZT.[5] Thus, by observing the electrical impedance of the PZT, assessments can be made about the integrity of the mechanical structure.

Traditionally, the impedance method requires the use of an impedance analyzer. Such analyzers are bulky and expensive, and are 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).[6] A single board computer system, MASSpatch is active sensing system which interrogates a structure utilizing a self-sensing actuator and the 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.

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. Distinguishing between the how much energy is used for 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. 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.

OMNI_THERM Hardware Development

On-orbit health monitoring and repair assessment of thermal protection systems (OMNI_THERM) is designed to provide online assessment of thermal protection systems. Currently, nondestructive evaluation techniques are used to assess the condition of protection systems while the structure is off-line. OMNI_THERM has the ability to directly detect damage by analyzing variations the electrical impedance of self-actuating sensors bonded to the structure. OMNI_THERM 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. The following work describes the initial steps at achieving such a wireless system.

Low Cost Impedance Method

Due to the limitations of using an impedance analyzer for permanent structural health monitoring purposes, a method has been developed to avoid reliance on such analyzers.[7] Peairs *et al.* introduce a low cost impedance technique as a first step in achieving a smaller, inexpensive impedance analyzer. The 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 PZT, 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 PZT as if the circuit were not there. Taking the ratio of the applied voltage and resulting current, the impedance can be determined.

With the low cost impedance method, the impedance analyzer is 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.

OMNI_THERM Components

To implement the impedance-based structural health monitoring method in a field deployable setup, hardware is assembled as shown in Figure 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 Figures 1 and 2, all of the hardware needed to utilize the impedance method is condensed into a single stacked board configuration. A description of each of the components follows.

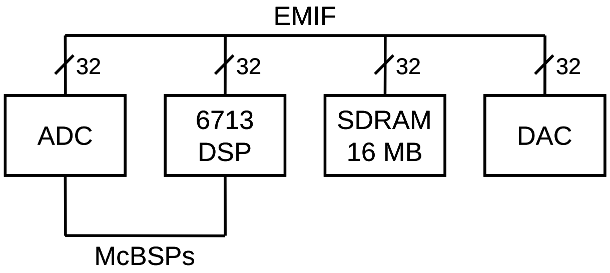

Figure 1. A diagram of the OMNI_THERM hardware configuration is shown.

The OMNI_THERM prototype is based on a TMS320C6713 DSK evaluation DSP module from Texas Instruments.[8] 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 Figure 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.[9] Conversion resolution for the ADC board is 16 bits. For the DAC, a TLV5619-5639 EVM board is used.[10] 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, and DAC can be seen in Figure 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.[11]

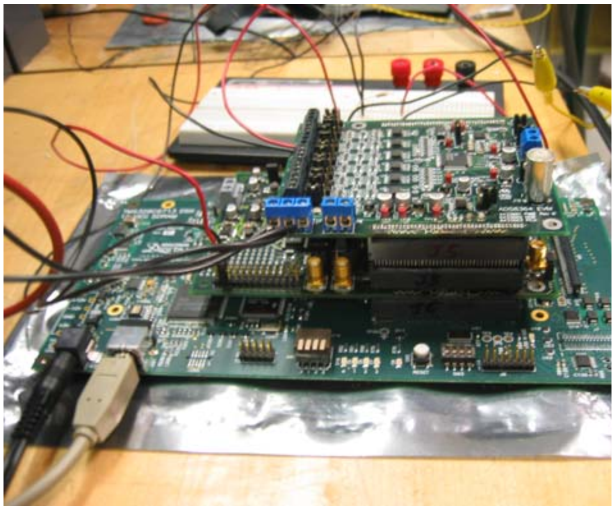

Figure 2. The OMNI_THERM prototype is shown. The DSP is on bottom followed by the DAC and ADC.

Impedance-based Health Monitoring Algorithm

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 whole 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 simultaneously reads the voltage across the sensing resistor (seen in the background of Figure 2) of the low-cost impedance circuit. After this is done ten times, the signals are averaged, a FFT is performed, and one impedance measurement is generated. The first two measurements generated are baseline impedance curves. After that, each measurement is compared with the baseline to determine whether there is damage in the structure by means of a damage metric.

Impedance signatures are, in general terms, simply frequency response functions (FRF). The have the general appearance of FRFs, as seen in Figure 3. 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.[12]

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. By slightly altering the fundamental frequency each time a pulse is sent out, the averaged spectrum is even smoother. 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.

OMNI_THERM Experimental Validation

To validate the OMNI_THERM prototype, the system's capabilities are demonstrated in the laboratory. A bolted joint is tested for the initial experiments. The bolted joint structure consists of two aluminum beams connected with four bolts. A piezoelectric patch 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.

Using traditional impedance techniques (a HP 4194A impedance analyzer), a standard for the bolted joint experiment is generated for comparison with OMNI_THERM results. Initial bolted joint testing shows that the impedance method readily detects damage induced by loose bolts. Slightly loosening only one of four bolts significantly changes the impedance. Figures 3 and 4 show impedance signatures and the resulting damage metric for a number of bolt cases.

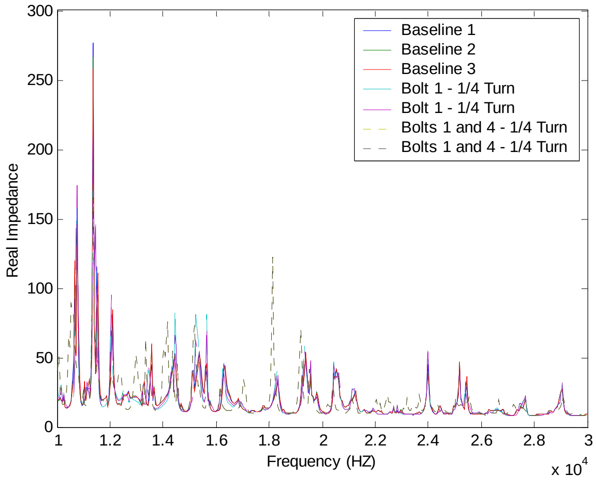

Figure 3. Bolted joint impedance signatures.

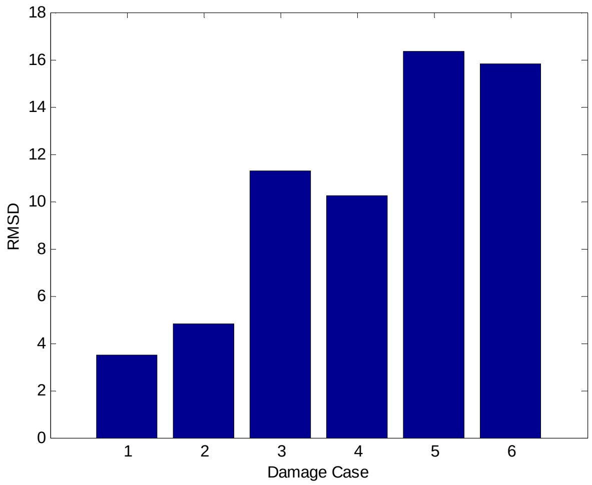

Figure 4. The impedance signature and calculated damage metrics are shown for a bolted joint.

As seen in Figure 3, as the amount of damage increases by the loosening of bolts, the peaks of the impedance curves shift. A frequency range of 10 – 30 kHz is used the acquisition of impedance signatures. The results of peak shifting can be visualized in the bar chart. The first two bars of Figure 4 compare the second and third baselines (healthy measurements) with the first baseline. The next two groups of bars compare the next two damage cases, the loosening of bolt one and the combination of bolts one and four.

Using the same bolted joint, the OMNI_THERM 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.[13] At each step in the algorithm, the real impedance measurement as data is acquired is displayed, as well as 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 spectrum of the output can also be displayed, and, as expected from a sinc function, the auto spectrum is a flat line indicating that every frequency of interest is being excited. 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.

Initially, measurements are taking with all of the bolts completely tightened. This means that the baseline and damaged impedance signature should be the same. As Figure 5 shows, the impedance curves for the new measurement and original baseline are almost identical. Figure 5 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.

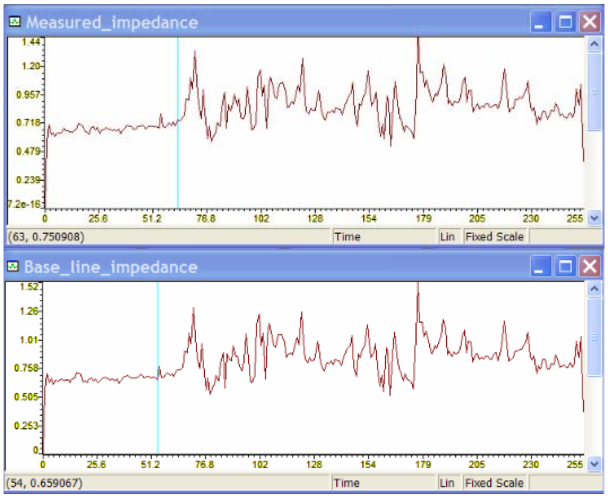

Figure 5. The measurement with no damage to the structure is compared with the baseline.

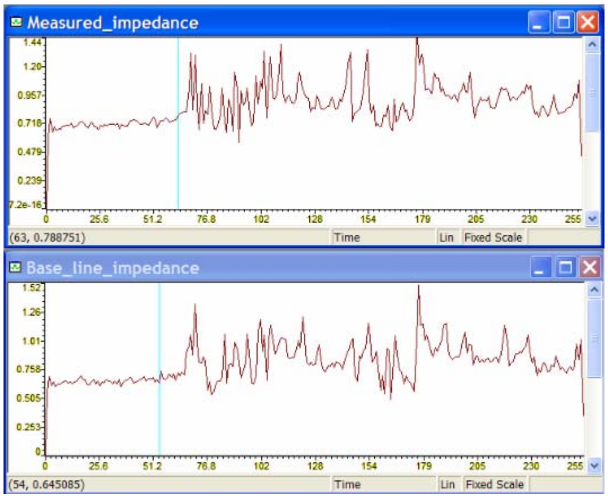

Figure 6. The impedance signature for slightly loosening one bolt is compared with the baseline.

One interesting thing to note is that the impedance signatures from Figure 3 and Figure 5 are very similar. Both show a good number of peaks in similar locations over the range of 10-30 kHz. Next, a small amount of damage was induced on the bolted joint by loosening one of the bolts a quarter turn. With just this small amount of damage, the prototype easily recognizes the difference as shown in the peak changes of the measured impedance seen in Figure 6. When the damage detection algorithm compared the two curves seen in Figure 6, the damage metric increased to 0.13. With only a small amount of induced damage, the damage metric easily indicates that the structure has changed by yielding an increase in damage metric of

550 percent. Next, a second bolt was also slightly loosened. With even more damage, the difference in appearance between the measured impedance and baseline is even greater. A new RMSD damage metric value of 0.21 is calculated and displayed on the computer, indicating that a higher level of damage is in the structure. Utilizing a bolted joint, OMNI_THERM has successfully detected varying amounts of damage. Even more promising is that the results are very comparable with an analysis performed with standard impedance measuring equipment, a HP 4194A impedance analyzer.

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 OMNI_THERM 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 the OMNI_THERM system includes performing a complete 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.

Acknowledgements

The authors would especially like to thank Hyung-Jin Lee, advised by Dr. Dong S. Ha, of the Virginia Tech Electrical and Computer Engineering Department for all his hard work and help on this project. Dr. Robert Owen of Extreme Diagnostics, Inc. and Dr. Gyuhae Park of Los Alamos National Laboratory also contributed to this research. The authors gratefully acknowledge funding for this research provided by NASA Langley Research Center and Extreme Diagnostics, Inc. (contract NNL05AB08P). This material is based upon work supported by the National Science Foundation under Grant No. 0426777. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

1. Spencer, Jr., B.F., M.E. Ruiz-Sandoval, and N. Kurata. 2004. “Smart Sensing Technology: Opportunities and Challenges,” *Journal of Structural Control and Health Monitoring*, Vol. 11, No. 4, pp. 349-368.

2. Lynch, J.P., A. Sundararajan, K.H. Law, H. Sohn, and C.R. Farrar. 2004. “Design of a Wireless Active Sensing Unit for Structural Health Monitoring,” Proceedings of SPIE’s 11th Annual International Symposium on Smart Structures and Materials, San Diego, CA. Vol. 5394, pp. 157-168, March 14-18, 2004.

3. Tanner, N.A., J.R. Wait, C.R. Farrar, and H. Sohn. 2003. “Structural Health Monitoring Using Modular Wireless Sensors,” *Journal of Intelligent Material Systems and Structures*, Vol. 14, No. 1, pp. 43-55.

4. Park, G., H. Sohn, C.R. Farrar, and D.J. Inman. 2003. “Overview of Piezoelectric Impedance-Based Health Monitoring and Path Forward,” *The Shock and Vibration Digest*, Vol. 35, Issue 6, pp. 451-463.

5. Liang, C., F.P. Sun, and C.A. Rogers. 1994. "An Impedance Method for Dynamic Analysis of Active Material System," *Journal of Vibration and Acoustics*, Vol. 116, pp. 121–128.

6. Grisso, B.L., L.A. Martin, and D.J. Inman. 2005. “A Wireless Active Sensing System for Impedance-based Structural Health Monitoring,” Proceedings of IMAC XXIII, Orlando, FL, January 31-February 3.

7. Peairs, D.M., G. Park, and D.J. Inman. 2004. “Improving Accessibility of the Impedance-based

Structural Health Monitoring Method," *Journal of Intelligent Material Systems and Structures*, Vol. 15, No. 2, pp. 129-140.

8. Texas Instruments. 2005. *TMS320C6713, TMS320C6713B Floating-Point Digital Signal Processors*, Texas Instruments Inc., Dallas, Texas.

9. Texas Instruments. 2002. *ADS8364EVM User's Guide*, Texas Instruments Inc., Dallas, Texas.

10. Texas Instruments. 2001. *TLV5619-5639 12-Bit Parallel DAC Evaluation Module User's Guide*, Texas Instruments Inc., Dallas, Texas.

11. Radiometrix Ltd. 2005. *UHF Narrow Band FM multi channel radio modules*, Radiometrix Inc., Harrow, Middlesex, England.

12. Grisso, B.L. 2004. "Considerations of the Impedance Method, Wave Propagation, and Wireless Systems for Structural Health Monitoring," MS Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, http://scholar.lib.vt.edu/theses/available/etd-09142004-151951/.

13. Texas Instruments. 2005. *Code Composer Studio Development Tools v3.1 Getting Started Guide*, Texas Instruments Inc., Dallas, Texas.