A multi-mode structural health monitoring system for wind turbine blades and components

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ABSTRACT*

The *Adverse Event Detection* (AED) system described in this paper supports nondestructive evaluation (NDE) systems and evaluates advanced composite structures such as wind turbine blades. AED is a joint effort by Extreme Diagnostics and Virginia Polytechnic Institute and State University (Virginia Tech). AED uses the impedance method to monitor bulk structural integrity, wave propagation methods to assess surfaces, and acoustic emission (AE) structural health monitoring (SHM) to detect adverse events such as impacts. The incorporation of AE methods significantly increases the sensor coverage area, which is crucial in health monitoring of large-scale structures like wind turbine blades. Our AED system provides on-line assessment of structural integrity during normal operations, as opposed to traditional nondestructive evaluation (NDE) methods that are commonly applied off-line—that is, systems must be shut down for inspection by conventional NDE. Our AED system not only provides timely information during operation, it can also reveal defects that only become apparent under operational stress—such defects can be overlooked by traditional off-line inspection methods. AED actively examines structures across several length and time scales in an autonomous fashion, thus greatly reducing the number of sensors required and lowering system complexity and cost. Our early AED prototype demonstrated impedance-based SHM in wind turbine blades. This project integrates three previously independent SHM approaches, and demonstrates damage detection on a composite structure. Our current AED prototype is a low-power, wireless, and embeddable sensor that detects incipient damage in near real-time and automatically provides early warning of structural damage. Our AED system is also suited to a variety of aerospace applications that include composite overwrapped pressure vessels. AED also supports Homeland Security, and furthers national preparedness by monitoring infrastructure integrity and disaster response by providing damage assessment.

1 INTRODUCTION

Increasingly demanding weight and performance needs in structures such as offshore wind turbine blades encourage widespread use of advanced composite materials. New systems are needed to detect incipient flaws in composites before damage becomes critical. Health analyzers that actively examine structures across several length and time scales in an autonomous fashion greatly reduce the number of sensors required and lower system complexity and cost; however, no practical system exists. The proposed AED system combines AE, impedance-based and wave propagation SHM across several length and time scales in the synergistic operation shown in the Figure 1 flow chart.

Complete health monitoring of large structures such as wind power turbine blades could require large numbers of sensors. If wiring is required to support each sensor, sensor deployment and system maintenance becomes both difficult and expensive. We propose a wireless, autonomous sensor system with on-board SHM control and analysis to address this problem. In order to achieve this goal, AED must be able to operate with very little power, so that long-term deployment can be supported with energy harvested from the environment. The current prototype combines an ultra-low power impedance-based SHM module and an advanced wave propagation module. Section 2 describes the impedance module, and Section 3 describes the wave propagation module.

2 DIGITAL IMPEDANCE-BASED SHM

Impedance-based SHM systems commonly use a digital-to-analog-converter (DAC) to generate a structural excitation signal and an analog-to-digital-converter (ADC) to sense the structural response. The excitation signal activates a piezoelectric patch, and the response is sent to a process to compute the electrical impedance at the excitation frequency. Since the piezoelectric patch is coupled to the structure of interest, the electrical impedance of the patch is directly related to the mechanical impedance of the structure—this in turn is related to structural damage. If the calculated impedance differs from a previously defined baseline by some predetermined amount, the structure is considered damaged.

Our digital approach eliminates a DAC and an ADC, and has been previously described (Kim et al., 2007). Unlike traditional SHM systems, this approach detects the phase difference (rather than magnitude) of the impedance between the structural response and the baseline. A DAC is eliminated since a rectangular pulse train is used as the excitation signal, and this can be generated from the processor itself. Also, a comparator rather than an ADC is used to measure the phase, so signal processing is simplified as a XOR function and an accumulator. The current AED prototype is based on a microcontroller, and can run off two AAA batteries.

2.1 Temperature Compensation Algorithm

Impedance profiles obtained from a piezoelectric patch are sensitive to ambient temperature. Specifically, the amplitude of the real part of the impedance shrinks with increasing temperature, while peaks of the imaginary part shift towards lower frequency bands (Park et al., 1999). Consequently, the accuracy of uncorrected impedance-based SHM can degrade in field environments. The AED prototype uses an algorithm based on the selection and estimation of baseline profiles to correct for temperature effects (Zhou et al., 2009a). Baseline profiles for critical temperatures are selected and stored in advance, and are used to reconstruct baseline profiles at other temperatures. New baselines are constructed based on linear interpolation between two neighbor profiles. This algorithm reduces the total number of baselines that need to be stored by over 40%, which is important for SHM sensors based on microcontrollers with small memory size.

2.2 System Hardware

Since low power consumption is a key design requirement, the AED prototype impedance module is based on a TI MSP430 microcontroller, which is low power and has a built in temperature sensor. The associated evaluation board includes a CC2500 radio operating at 2.4 GHZ and a user interface designed to ease system development efforts. Figure 2 shows the system architecture for this module.

Figure 3 shows the circuit interface that excites the PZT patch and senses the structural response. Figure 4 shows the actual hardware. The interface analog circuit is on top and the bottom part holds batteries and the TI evaluation board. The module measures 4.5x7x3 cm and runs on two AAA batteries.

2.3 System Operation and On-board processing

Figure 5 shows system operation. The microcontroller sweeps a user specified frequency range four times for each operation and averages four runs to obtain baseline and structure-under-test profiles. Each operation takes approximate 13 seconds, including response data processing. The module then goes into sleep mode for a predetermined time period. During sleep, components such as the CPU, Op amps, and the ADC used to sample temperature data are turned off, and components such as the timer and wireless transceiver are set to a lower clock speed or an inactive mode. Power dissipation runs around 18 mW during active operation and 0.15 mW during sleep mode (Zhon et al., 2009b, 2010).

Data can be processed at either a local sensor node for autonomous operation, or at a remote host computer. Remote processing requires transmitting impedance profiles. However, radio transmission consumes much more power than a microcontroller. For example, the MSP430 microcontroller running under 1.2 MHz dissipates 6 mW—if the radio is turned on power consumption increases to 69 mW. The AED prototype therefore processes data locally and transmits only when necessary.

2.4 Wireless communication

The MSP430 microcontroller evaluation board has a built in radio operating in the 2.4 GHZ band, which can be used to build a wireless sensor network. This has been implemented for the current prototype in a star network with multiple sensor nodes and a control center. A message on the application layer consists of three bytes, two bytes for the temperature value and one byte for a healthy or damaged SHM decision. The transmission data rate was set to 250 kbps, and took a fraction of a second to transmit one message, including overhead. The radio is otherwise inactive.

3 LOW-POWER WAVE PROPAGATION

A key parameter and component in our current system that uses considerable energy is the Analog-to-Digital conversion (ADC) traditionally required in previous implementations of the Lamb wave method. The ADC of a Lamb wave system is responsible for converting the received analog data into a format that can be processed by a processor. The power requirements for a high speed ADC as well as the processing requirements necessary to handle this amount of data greatly increase the total power requirements for a Lamb wave SHM system. Elimination of an ADC can therefore significantly reduce overall power dissipation of a Lamb wave system. We investigated this system parameter further and designed, built, and tested new electronics for an alternative low power methodology.

3.1 Low-Power Lamb Wave Implementation

The AED prototype for our comparator-based system is based on the TMS320F2812 DSP evaluation board. The ADC of a Lamb wave system captures the magnitude of the response signal at the sampling instance, and the magnitude value for an *n*-bit ADC is quantized to 2^n levels with a uniform distance between two adjacent levels. Our method is to quantize a value into three levels, values above a high threshold value are denoted as 1, values below a low threshold value are denoted as -1, and values in-between the two threshold values are denoted as 0.

We use two comparators: an upper comparator sets the high threshold value and a lower comparator the low threshold value. Figure 6 shows the basic layout. In the new design, the DSP holds the digital excitation waveforms in memory, and the TI THS5661 DAC converts them to an analog waveform. This output is then low-pass filtered and amplified to drive a PZT patch. The received signal is amplified and biased by an op-amp and then applied to the inputs of two comparators. The MAX942 comparator from Maxim was chosen because of the fast rise time on its outputs and its low power consumption. The upper and lower threshold values are controlled by onboard potentiometers.

The use of two comparators offers critical advantages over one comparator besides smaller quantization errors. The two comparators form a dead zone, which decreases the effect of low-amplitude noise. Further, it is possible to set up the thresholds in an asymmetric configuration, where the high threshold has a different magnitude than the lower threshold. This allows the system to differentiate two separate amplitudes of the received signal.

The output from the comparator circuitry is applied directly to GPIO (General Purpose Input Output) ports on the DSP, *completely bypassing the ADC* integrated in the DSP. An average of eight runs is then taken and compared to the calculated baseline waveform. The detection metric used in our previous prototype and shown in the equation below is also used for this new system.

To calculate the difference between separate runs, the following detection metric (DM) has been used. This detection metric calculates the total percent difference between the baseline waveform and the current waveform

$$DM = \frac{\sum_i \left| WT_{current}(i) - WT_{baseline}(i) \right|}{\sum_i \left| WT_{baseline}(i) \right|} \qquad (1)$$

The detection metric for an undamaged structure is ideally 0, and increases based on the amount of damage detected in a structure. $WT_{current}$ and $WT_{baseline}$ denote the DWT of the sensed and baseline waveforms, respectively. DWT represents the correlation between the excitation signal and the sensed signal.

The ADC integrated into the TI TMS320F2812 DSP used in our previous version consumed over 120 mW when operating at full speed. After identifying this component as a key parameter, we replaced this ADC with two comparators, whose combined power dissipation ranges from 2 mW typical to a maximum of 7.2 mW. In addition, this method simplifies the processing required by the DSP, which results in further power reductions. The result of this improvement is well over an order of magnitude savings in power consumption over our previous Lamb wave SHM implementation (Deyerle et al., 2010).

4 CONCLUSION

This paper describes two of the three AED modules under development. The next step in the AED project is the integration of the AE module with the first two modules.

ACKNOWLEDGMENT

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REFERENCES

J. Kim, B. L. Grisso, D. S. Ha, and D. J. Inman (2007). “An All-digital Low-power Structural Health Monitoring System”. IEEE Conference on Technologies for Homeland Security, 123–8, 2007.

S. Deyerle, D. S. Ha and D. J. Inman (2010). “A low-power system design for Lamb wave methods,” SPIE Smart Structures/NDE 2010, 7-11 March, San Diego CA, 2010.

G. Park, K. Kabeya, H. H. Cudney, and D. J. Inman (1999). “Impedance-based structural health monitoring for temperature varying applications,” JSME International Journal, 42, 249–58, 1999.

D. Zhou, J. K. Kim, D. S. Ha, J. D. Quesenberry, and

D. J. Inman (2009a). “A System Approach for Temperature Dependency of Impedance-Based Structural Health Monitoring”. Proceedings SPIE Smart Structures/NDE San Diego CA, 9-12 March, 2009.

D. Zhou, J. K. Kim, J.-L. Bilé, A. B. Shebi, D. S. Ha, and D. J. Inman (2009b). “Ultra Low-Power Autonomous Wireless Structural Health Monitoring”. Proceedings 7th International Workshop on Structural Health Monitoring, 2009.

D. Zhou, N. Kong, D. S. Ha and D. J. Inman (2010). “A self-powered wireless SHM sensor node,” SPIE Smart Structures/NDE 2010, 7-11 March, San Diego CA, 2010.

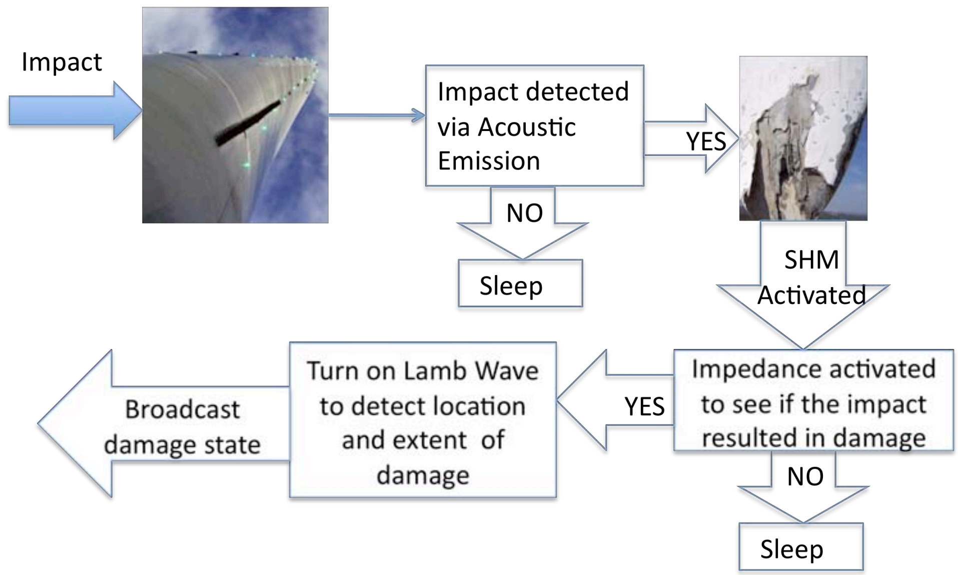

Figure 1. AED operational methodology flow chart

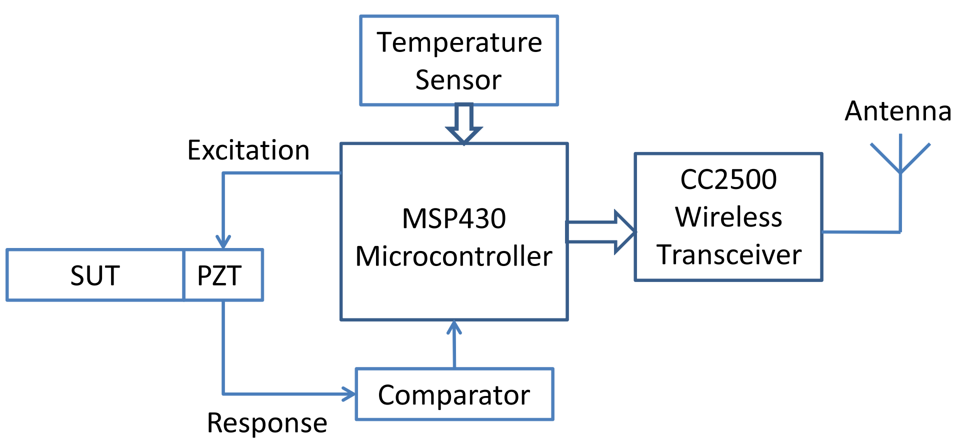

Figure 2. Architecture of impedance-based SHM module

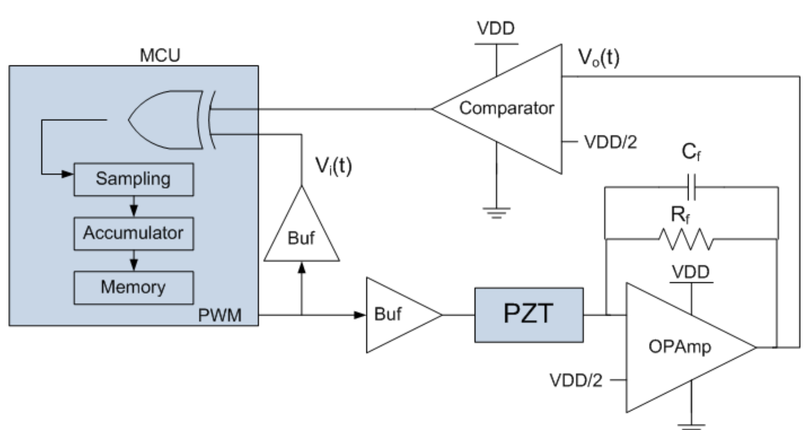

Figure 3. Interface circuit

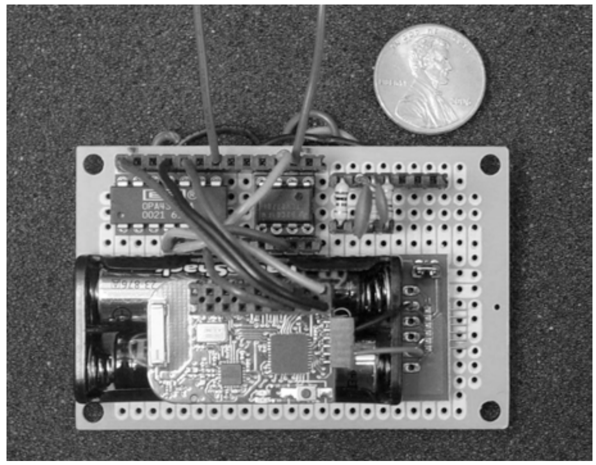

Figure 4. System hardware based on TI MSP430 evaluation board

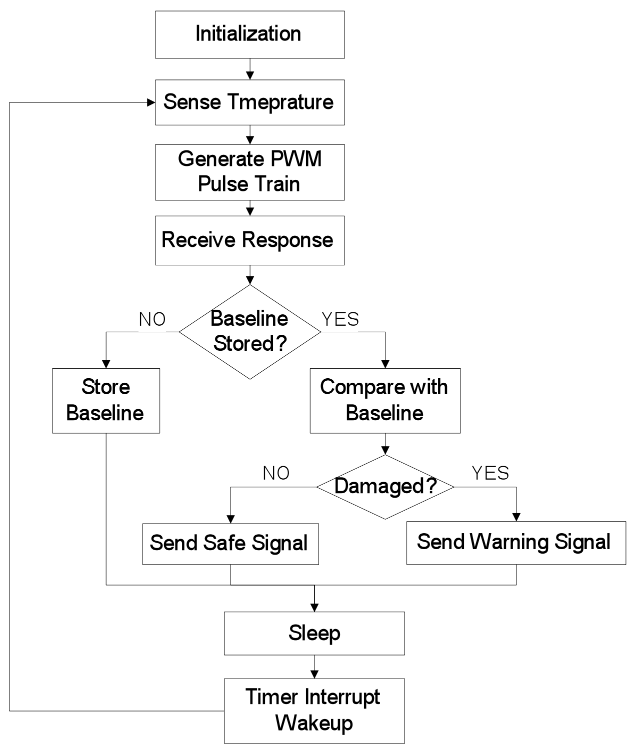

Figure 5. Flow chart of impedance module system operation

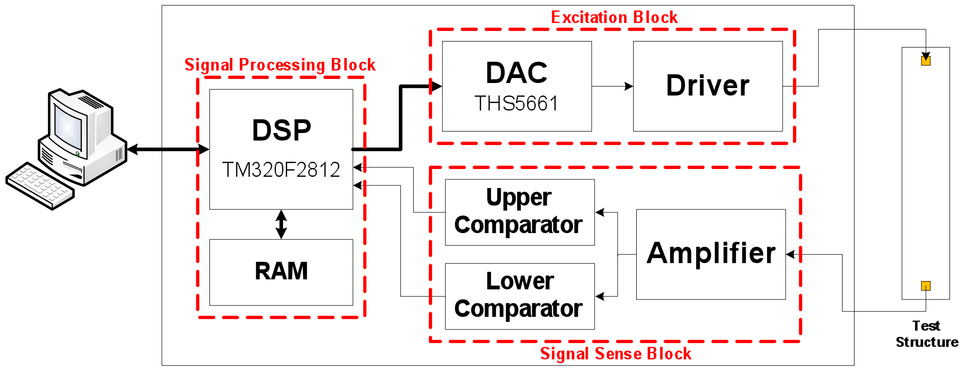

Figure 6. AED Lamb wave module layout, with traditional ADC component replaced by a set of comparators. This improvement reduces energy consumption by over an order of magnitude.