Autonomous Wireless Sensor Network for Structural Health Monitoring of Aerostructures

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Abstract In this work we demonstrate the feasibility of an embedded, cheap, miniaturized active sensor node for detection of damages on laminate composite or metallic structures by means of ultrasonic guided waves (GWs). The device is meant as the basic building block of an autonomous wireless sensor network (AWSN) able to monitor the integrity of the aerostructure and locate possible damages. Each node is permanently mounted on the surface and wirelessly powered by electromagnetic (EM) waves, which are also used for communication with the base station. The electronic circuit is interfaced with an innovative, patent-pending piezoelectric transducer (piezo) capable of generating and sensing directional ultrasonic GWs in the inspected structure. Elastic waves propagating through the structure and reflected back to the piezo are recorded and processed by each individual node thanks to embedded processing functionalities to detect and locate defects. The information is then sent back to the base station for further analysis and evaluation. The results highlight that a small, lightweight and low power system can be designed with off-the-shelf hardware. The proposed system provides good reliability and accuracy and brings many advantages over current systems.

1 Introduction

The monitoring and assessment of structural components integrity is of vital importance for aerospace vehicles and systems, land and marine transportation, civil infrastructures, oil and gas industry as well as other industrial and mechanical applications. In particular, the current design and maintenance procedure for

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composite or metallic aerostructures must consider the several types of loads and environmental stresses these structures undergo, as well as the fatigue and damages, which could result from the aforementioned causes. As long as the presence of cracks can be monitored and the propagation of the damage controlled, lighter weight aircraft can be designed to reduce direct operating cost. At the same time more frequent and accurate inspection has to be done in order to avoid any safety or reliability issue. Particularly dangerous are damages invisible to the human eye such as hidden delaminations in composite materials.

Several non-destructive approaches have been developed to support visual inspection with techniques based on ultrasonics or eddy current [1, 2]. Also, exploiting concepts from the structural health monitoring (SHM) field, the integration of a sensor platform in structural components can be performed to allow for easier and effortless inspection procedures. In fact SHM allows for the early detection of damages and the monitoring of its progression, leading to improvements in safety, reliability, and in maintenance and operating costs reduction above all.

Nevertheless, State-of-the-Art SHM systems feature piezo transducer interface electronics either based on general-purpose lab equipment or voluminous PCB assemblies. As such, when systems move from the lab into the field, where sensor nodes are deployed in multitude, the size, power and reliability of the control circuitry quickly becomes a bottleneck. This said the main motivation behind this work is the development of SHM devices with both high accuracy in damage detection and localization, and low hardware complexity and low power consumption for autonomous, reliable, in situ, real time operation.

Within this framework, the current work demonstrates that building a lightweight, small footprint circuit board with minimal hardware and energy harvesting and wireless communication capabilities is feasible. The key driver for this platform is an innovative sensor technology developed in collaboration with the Georgia Institute of Technology, Atlanta, namely the wavenumber spiral frequency-steerable acoustic transducer (FSAT) as discussed in [3].

Also, an impedance measurement device to ensure the transducer is properly coupled with the surface has been included in the sensor node's design. To rid the system of wires, energy harvesting capabilities are provided to each sensor node by means of a circuit capable of harvesting electromagnetic energy supplied by an RF power supply unit. Wireless power solutions based on RF energy harvesting overcome the limitations of alternatives (such as vibration harvesters) being reliant on ambient sources, because power can be replenished when desired.

2 System Implementation

The system is composed of three main sections: energy harvesting, self-diagnosis and actuation/detection circuitry. To prove the validity of the whole concept, the system has been split in almost independent parts so that it would have been easier to go through the development process in parallel. Tests have been conducted with three prototype off-the-shelf electronic boards to verify:

(a) The RF power transmission. A one-to-many charging system was implemented, basing on the “Lifetime Power Energy Harvesting Development Kit for Wireless Sensor” by Powercast as prototype circuit board. Each sensor board houses a microcontroller, which reads data from three different sensors and sends them to a remote PC via a 2.4 GHz radio module. The energy cost of wireless communication is in the range of J/bit. To perform these operations the sensor board drains 15 mA of average current at 3.3 V for 10 ms.
(b) The electro-magnetic impedance measuring circuit. An evaluation board AD5933 designed by Analog Devices was used to measure the impedance value of the piezo with a frequency sweep analysis. Graphical user interface software was provided to control the board and to download the impedance data.
(c) The sensing device. In order to test the damage detection capability and accuracy of the system we assembled the circuit responsible for the actuation of the piezo and tested it in different operation conditions. Both actuation and sensing has been addressed to ensure proper behavior for different modes of operation: active or passive, pulse-echo or pitch-catch.

3 Experimental Tests

3.1 Energy Harvesting

Multiple tests were performed to quantify the transmitted power versus distance. It is worth noting that, in many aerostructures made of composite materials, there are hollow stiffeners, which could be used to accommodate waveguides, as described in [4]. An obvious advantage of using guided over free space propagation for RF energy is that the first exhibits with much lower loss than the latter. For this reason, some tests were performed introducing the transmitter and the power receiver in a waveguide mockup: although not designed for this scenario, the hardware able to continuously collect up to 60 mW at a distance of 75 cm. The passive sensor node reported in [5] operates with a power consumption of 40 mW. As such, the implemented power transfer system allows for continuous monitoring of acoustic events while accumulating energy for the active inspections.

3.2 Electro-mechanical Impedance

The impedance value of different specimens of piezo transducers bonded to composite and aluminum plates was measured in the frequency range between 20 and 200 kHz. In this range the piezoelectric transducer can be modeled as a capacitance

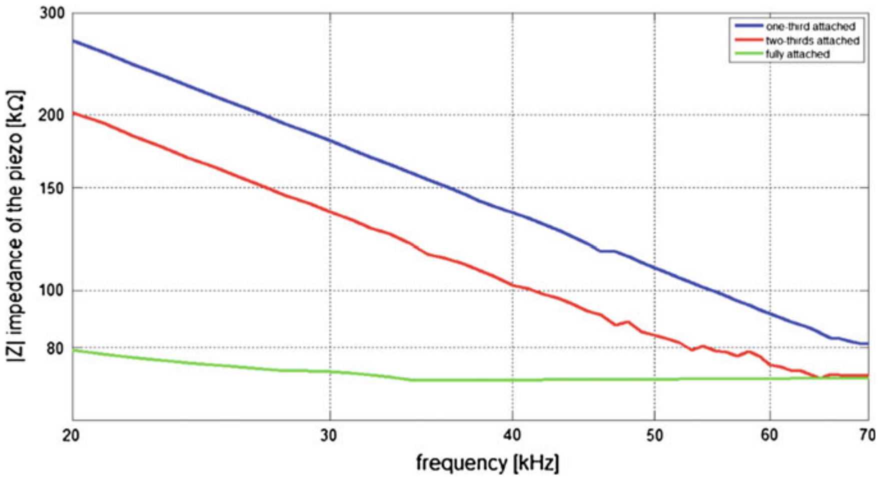

Fig. 1 Electro-mechanical impedance measurements: the different behavior between fully bonded (*bottom*) and partially disbanded sensors (*top*) allows for simple detection procedures

whose value can be easily extracted from measurements. Such a value changes when the acoustic coupling between the transducer and the surface becomes compromised due to disbonding. Multiple measurements were performed to assess this statement by varying the fraction of piezo surface attached to the composite plate.

The graph in Fig. 1 depicts the measured impedance for three of the aforementioned cases. Since the difference between the measurements for the detached piezos and that for the correctly bonded one are tens of kΩ, it is easy for the impedance measuring system to reveal an incorrect acoustic coupling.

3.3 *Frequency Steerable Sensor*

To test the performance of the FSAT the transducer was bonded at the center of an aluminum plate. Four other identical, omnidirectional piezos were glued at a radial distance of 25 cm and spaced 30° one from the other. The FSAT was used as the active element of the setup and it was connected to a waveform generator through a RF power amplifier. The four other transducers were used as sensors and connected to the oscilloscope. This setup is depicted in Fig. 2.

The FSAT was excited with a 10 cycle sinusoidal burst to achieve a sufficiently narrow frequency spectrum. Results show that the FSAT is capable to steer the ultrasonic wave according to the frequency of the sinusoidal burst.

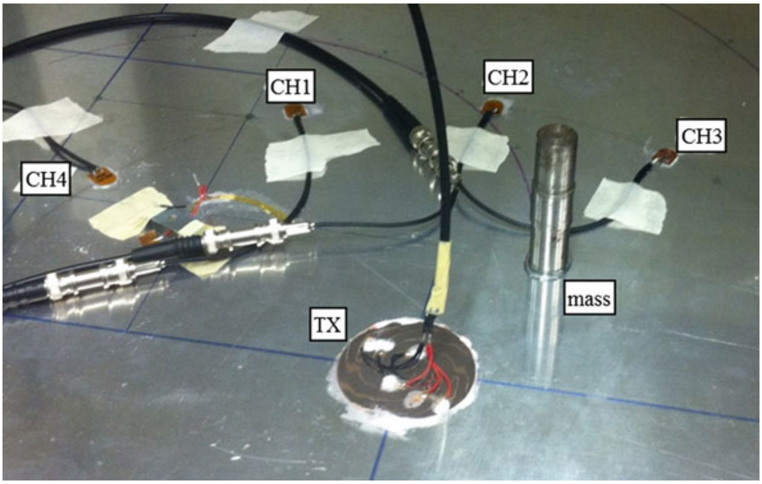

Fig. 2 Experimental setup for the assessment of the FSAT directionality and sensitivity to defects; the latter is simulated by means of a test mass stitched to the plate using ultrasound coupling gel

Finally, to simulate the presence of a damage, a cylindrical mass with a diameter of about 2.5 cm was placed between the FSAT and one piezo. The acoustic coupling between the mass and the aluminum structure was realized through an ultrasound transmission gel. When the mass was added to the setup, its presence produced the scattering of the ultrasonic waves and an attenuation of the intensity of the sensed signal. The presence of the simulated damage could be seen through the attenuation in the output signal of the first piezo sensor as depicted by the highlighted trace in Fig. 3.

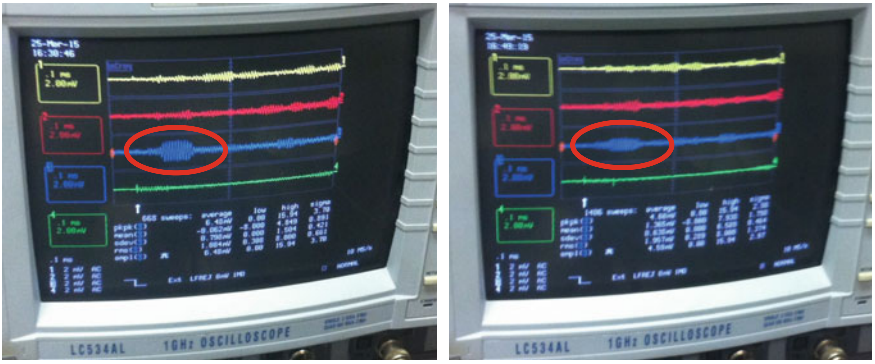

Fig. 3 Results of the signal acquisition phase: the FSAT was excited with a 10 cycles sinusoidal burst around 78 kHz. The presence of the mass is evident on the right hand side image where a noticeable decrease in signal amplitude is present

4 Conclusions

In this work, the feasibility of an embedded, cheap, miniaturized active sensor node for detection of damages on laminate composite or metallic structures by means of ultrasonic guided waves was demonstrated. Sensors could be made to be inherently dormant, requiring zero stand-by power. When a reading is desired, power can be transmitted until all of the stages of the inspection process are completed, namely the sensor's activation, the inspection and the sending back of the results. The continuous power transfer achieved in the waveguide case allows the sensor node to work in passive mode, i.e. sensing the ultrasonic waves already present in the surface and generated by impacts. When active mode operation is required for deep and extensive inspection, energy has to be stored in a super-capacitor like device so that it can reach the amount required for the actuation of the ultrasonic wave to take place. It is worth noticing that designing specifically dedicated directional antennas can further optimize the transmission efficiency and the overall results concerning energy harvesting. The results of the tests made highlight the concrete possibility of detecting the detachment of the piezo element from the surface by means of an impedance measuring system, which can be easily integrated on the node's circuit board. Such auto-diagnostic feature allows the sensor node to reveal a change with respect to the nominal operating conditions and ensures that the system can always offer high safety and reliability standards. The spatial filtering characteristics of the FSAT have been experimentally demonstrated and validated. This kind of sensor is perfectly suitable for actuating the ultrasonic waves, for arbitrarily steering them by changing the frequency of the actuating signal and for providing the information about the angular position of the reflected wave in the frequency content of the sensed signal. When compared with state-of-the-art guided waves inspections system based on phased arrays, the proposed solution features lower hardware complexity and lower power consumption by eliminating the digital beamforming delays, multiplexing, switching and spatial combination of multiple channels for image generation thanks to the exploitation of frequency-based steerability.

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