WIRELESS STRAIN GAGE FOR TESTING AND HEALTH MONITORING OF CARBON FIBER COMPOSITES

F. Gasco[1], P. Feraboli[1]*, J. Braun[2], J. Smith[3], P. Stickler[4], L. DeOto[5]
[1]Department of Aeronautics & Astronautics, University of Washington, Seattle, WA, USA,
[2]Department of Electrical Engineering, University of Washington, Seattle, WA, USA,
[3]Intel Research Labs., Seattle, WA, USA,
[4]Boeing Commercial Airplanes, Everett, WA, USA,
[5]Automobili Lamborghini S. p. A, Sant'Agata Bolognese, Italy
* Corresponding author (feraboli@aa.washington.edu)

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1 Introduction

Strain measurement is a critical component during aircraft certification. It is used to measure the strain at critical locations during tests at all levels of the building block, from the coupon level, through the element and subcomponent level, and up to the full-scale level. Unfortunately, for each strain gage used it is often necessary to utilize long, costly and cumbersome electrical wires that connect the gage to the data acquisition board. The possibility to utilize wireless devices to measure strain is therefore highly sought-after in the aerospace community. Several examples of wireless strain sensors can be found in the literature. The majority are based on analog technology which is appealing because it is more power efficient than digital electronics. However, analog devices are known to have poor repeatability due to the variability in measurements associated with environmental conditions (temperature, electromagnetic interference (EMI), etc.) and they are typically tied to extensive application-specific calibration, and therefore lack in flexibility of use. Recent developments in Micro-Electro-Mechanical Systems (MEMS) have enabled the advent of other battery-free wireless strain sensors. However, MEMS devices are usually very expensive, and in general they are not application-ready. In recent years, ultra-low-power microprocessors have enabled the design of digital wireless strain sensors that are commercially available. The sensors developed by Microstrain Inc. [1] provide analog-to-digital data acquisition and strain measurement is provided by conventional foil resistance strain gage, which is a proven technology. However, the devices are powered either by a Lithium battery, which has a long yet limited service life, or by a piezoelectric energy harvester. The sensor presented hereinafter is remotely powered and queried by a UHF electromagnetic signal and it communicates to the reader through backscattering of the same signal, like radio frequency identification (RFID) tags, thereby combining the advantage of having a digital data link with a battery-free powering system. The robustness of the measurement system as well as the absence of maintenance requirements makes this technology appealing also for heath monitoring applications of composite structures. The research discussed in the following sections is based on the WISP (Wireless Identification and Sensing Platform) device, patented by Intel [2], which is modified to interface with a foil resistance strain gage and tested for compatibility to carbon/epoxy composites, as detailed in [3].

2 Intel WISP device

The WISP printed circuit board (PCB) assembly is shown in Fig.1. WISP receives its power from a standard RFID reader which employs an 8 dBi circularly polarized patch antenna. The WISP rectifies the radio frequency (RF) signal (915 MHz) coming from the reader antenna in order to harvest the energy needed to power its on-board circuitry, and communicates with the reader antenna through backscatter uplink, which consists in modulating the RF signal reflected by the WISP antenna. This technique allows the WISP operating power to be as low as 1.08 mW. The WISP encodes its unique ID and additional data using an ultra-low-power programmable microcontroller. The microcontroller features a built-in 10-bit analog-to-digital converter (ADC) which allows interfacing the WISP with external sensors. The real-time data coming from multiple WISPs are decoded, processed and visualized through a personal computer connected to the RFID reader via local network protocols, Fig.2. The computer runs the reader software. In most operating conditions the power provided by the harvester is not sufficient to continuously power microcontroller, sensors and peripherals; therefore the power is accumulated in a storage capacitor over multiple reader queries. Once the turn-on voltage of 1.9 V is reached, the voltage supervisor activates the microcontroller which executes a sequence of pre-programmed operations (firmware). Typical operations include, but are not limited to, sensor powering and reading. Finally the digital encoded data signal is used to modulate the WISP antenna impedance through a frequency modulator, Fig.3. The frequency of data exchange between the WISP and the reader decreases with range as the RF power decreases with the inverse square of the distance between the WISP and the reader antenna, because more time is needed to harvest the required energy. The WISP provides ground reference (GND), excitation voltage (V_{CC}) and measure the output (V_{OUT}) of the external strain sensor discussed below.

3 WISPs/g for strain measurement of carbon fiber composites

In order to integrate a strain gage with the WISP, an analog interface comprised of a Wheatstone bridge and an amplifier has been developed for gage resistance measurement and signal amplification respectively. This signal conditioning circuit, which is hereinafter referred to as the Strain Gage PCB (SGPCB), is connected to and powered by the WISP. A uniaxial general purpose foil resistance strain gage (Omega SGD-13/1000-LY11) with 1000 Ω resistance, gage factor (GF) of 2.0 and active gage length of .5 in. (12.7 mm) is connected to the SGPCB, Fig.4. The overall system comprised of the WISP, SGPCB and strain gage is referred to as the WISPs/g. Given a strain gage type, one-time calibration is needed to tune the amplifier gain. The WISPs/g is calibrated for a maximum measurable strain of 10000 µstrain over the 1024 discrete digital levels of the ADC, which gives a measurement resolution of ± 5 µstrain. Before sensor operation the user is allowed to balance the strain and input the GF through a graphical user interface, in order to have the strain correctly computed by the reader software. Maximizing the signal to noise ratio (SNR), while keeping low power consumption, is a significant challenge because of the limited power budget available. The design of the signal conditioning circuit features ultra-low-power operational amplifiers and resistor values higher than conventional circuits either in the amplifier or in the bridge section (Fig.5). For the same reason a high resistance strain gage is selected. A detailed description of the SGPCB circuit is provided in [3]. Sufficiently high SNR is obtained at a sensor voltage V_{CC} of 1.8, thereby allowing the WISP turn-on voltage to be set at 1.9 V. The harvested RF energy can be used to power WISPs/g only when the power harvester is able to provide a rectified signal at a voltage equal or higher than the power-on voltage. If the voltage is lower the storage capacitor never reaches the required charge level, therefore the WISPs/g does not answer the reader query. Hence is the turn-on voltage that determines the maximum read distance of the WISPs/g and not the power required by the strain sensor, although a lower power requirement allows designing for a lower turn-on voltage and leads to higher strain read rate. At maximum read distance the RF input power seen by the WISP antenna is 110 µW (-9.5 dBm), as measured in [9]. It is well known that the RF power radiated by the reader antenna decreases in proximity of the composite surface in order to match the boundary conditions at the dielectric interface between the composite structure, which can have a significant electrical conductivity, and the air. However the read distance of the WISPs/g is not reliably predictable with closed form solutions or numerical methods due to the lack of electromagnetic properties for the composite material, the presence of electro-magnetic interference (EMI) due to RF reflection by the composite surface and the impedance mismatch between the power harvester and the reader antenna caused by the environmental conditions. Hence an experimental characterization of the read distance over a carbon/epoxy composite plate is conducted, Fig.6. The WISPs/g dipole antenna is mounted on fiberglass spacers to increase the distance from the composite surface. Increasing standoff thicknesses are tested. The operating temperature of the sensor is varied by heating the composite plate and controlled with thermocouples. The results are plotted in Fig.7 for a transmit power of 1 W (30 dBm). As expected the read distance increases with the standoff thickness. The WISPs/g, which is made with commercial electronics, does not experience performance degradation up to 175 ºF. The performance of a commercial RFID tag featuring integrated circuit (IC) and a patch antenna (Emerson & Cuming MetalTag) is also reported as performance reference achievable by a future, on-chip, WISPs/g. Given the same tag thickness the read distance of the commercial tag is four times greater thanks to the higher power efficiency of IC over discrete electronic components and a more applications oriented antenna design which exploits the conductive composite surface as a ground plane. Compatibility to higher temperatures can be achieved by employing specific electronic technology, like silicon on insulator (SOI).

4 Validation of the WISPs/g

4.1 Tension testing

The WISPs/g strain gage is bonded onto a carbon fiber composite specimen using conventional methods. The specimen is comprised of IM7/977-3 carbon fiber/epoxy unidirectional prepreg tape, having a stacking sequence of $[0/90]_{3s}$ for a thickness of 0.085 in. (2.2 mm). The specimen is a straightedge ASTM D3039 tension test specimen, Fig.8. Material properties provided by the supplier are ply thickness 0.0075 in. (0.19 mm), E_1 = 23.5 Msi (162 GPa), E_2 = 1.21 Msi (8.34 GPa), G_{12} = 0.72 Msi (5.0 GPa) and ν_{12} = 0.34. Two tension tests for each WISPs/g are performed, one with a step-function load and one with a ramp load. All tests are performed in the elastic region (strain measurement in the range 1000 to 4500 µstrain). Evaluation of the WISPs/g is performed against the measurements obtained by a single identical wired strain gage and a 1.0 in. (25.4 mm) gage-length extensometer. Four WISPs/g, denoted as #12, #257, #316, and #319, are tested using the same carbon fiber composite specimen and the same bonded strain gage. These are tested to check the variability of the response among the devices, in particular the accuracy and the noise of the strain measurements. The RF communication and power transfer from the reader antenna to the WISP are affected by EMI of the test frame machine and grips surrounding the test area. These metal components are longer than 6.3 in. (160 mm), which is the half-wavelength of the operating frequency of the RFID communication system. These electrically-long metal sections act as antennas and absorb some of the RF signal and also reflect some of the RF energy back into the air. Hence the distance between WISPs/g and reader antenna has to be dramatically reduced and the WISPs/g is raised 0.25 in. (6.35 mm) from the surface of the specimen using double-sided tape. It is found that for these tests, the RFID reader antenna needs to be kept within 2 ft (0.6 m) from the WISP. The test setup is shown in Fig.9. Typical results are shown in Fig. 10 A-B. The WISPs/g strain is in good agreement with the data collected with the extensometer and the wired strain gage, which means that the response of the WISPs/g is linear and the slope is consistent. The WISPs/g exhibits a slightly larger amount of high-frequency noise compared to the wired measurements. The primary source of noise is probably due to inconsistencies of the strain gauge amplifier power voltage V_{CC} caused by the duty cycling. Preliminary reduction of this noise is achieved by filtering V_{CC} by means of a capacitor placed on SGPCB across the power supply, and by introducing a time delay after WISPs/g turn-on in order to allow for sensor voltage stabilization before the measurement is taken. The time delay and a sensor voltage check to be performed prior to sensor reading are programmed in the WISPs/g firmware. However the noise observed is negligible in the context of the strain region typical of a quasi-static test, where data is average over a wide range of data points. Note that the time resolutions of each of the three methods of measurement are different. The wired strain gauge has the highest resolution, the extensometer's read rate is in the middle, and the WISPs/g has the slowest read rate. The time resolutions of the extensometer and the wired strain gage are fixed, while the WISPs/g time resolution, which is about 10 reads per second on average, is variable and is limited by its power budget.

4.2 Quasi-static indentation testing

In order to verify the ability of the WISPs/g to accurately measure complex strain states, a quasi-static indentation test of a flat composite panel is performed. The material and laminate stacking sequence are the same as the tension specimen. The test fixture has outer dimensions of 15 in. (381 mm) and an inner aperture (unsupported span) of 10 in.

(254 mm), Fig.11. The panel edges are supported between the upper and lower portions of the fixture, which in turn are clamped together by bolts. The panel is trimmed to 12 in. (304.8 mm), thus providing 1.0 in. (25.4 mm) of overhang on each side, which is clamped between the upper and lower portions of the fixture. The panel in-plane displacement at the edges is constrained only by friction, which is function of the bolt tightening torque. Previous research [4-6] has shown that such supports should be idealized as simply supported boundary conditions (b.c.). The fixture assembly is held in position through a bracket to the lower grip of the test machine, while the indentor is held in position by the upper grip of the test machine. A spherical indentor of 1.0 (25.4 mm) diameter is used to apply the load. The four WISPs/g devices are placed on the panel. Each WISPs/g strain gage is oriented at 45 degrees from the 0 direction of the panel, and oriented toward the center of the plate. All four gages are equidistant from the center of the panel long the diagonals, at a distance of 3.5 in. (90 mm), Fig.11 and Fig.12. Three different loading conditions are evaluated, Fig. 11 and Fig.13. Load case (a) is a centered load. Case (b) and (c) are offset loads. The load is increased using step loads under displacement control. At each increment of 0.05 in. (1.27 mm), the load is held into place while the four values of strain are recorded. A NASTRAN model is generated using the nonlinear solver SOL106 and CQUAD4 shell elements; element size is 0.25 in. (6.35 mm), Fig.13. For simplicity, nodes are numbered so that the nodes that fall in the same location of the strain gages, have the same number as the WISPs/g strain gages. The load is applied as concentrated (nodal) force at each of the three locations shown in Fig.13. The measurements obtained with all four WISPs/g devices are in good agreement with the FEM predictions given the complexity of the loading. Typical results for the load case (b) is shown in Fig.14. Maximum and minimum strains at locations#12 and #319 are plotted with the respective nodal predictions, together with the contour plot of strain in the 45º direction on the top ply.

5 Conclusions

Following the successful completion of this stage of the research, which proves that the RFID technology can be utilized for acquiring and transmitting strain-gage measurements, further work needs to be done to improve the packaging. The current WISPs/g platform is based on a bulky, heavy, and delicate PCB, which is suitable for research purposes since it can be easily modified in terms of hardware and firmware. Future developments will transfer the WISPs/g into an integrated circuit (IC) design. Such design can feature in a single-use (disposable), inexpensive package all WISPs/g components, Fig.15. The reduction in the read range due to the EMI and carbon fiber substrate compatibility is the main concern. Further work will be aimed at developing a custom antenna that can improve the RF communication. The sensor will include a dipole antenna with a high density polyethylene (PET) foam spacer, approximately 0.1 in. (2.54 mm) thick, for read range increase, Fig.15, or a patch antenna. Applications of this technology include strain measurement during structural static tests, as well as on-board real-time strain measurements for test flight or health monitoring.

Acknowledgments

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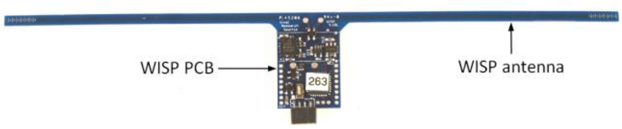

Fig.1. Intel WISP.

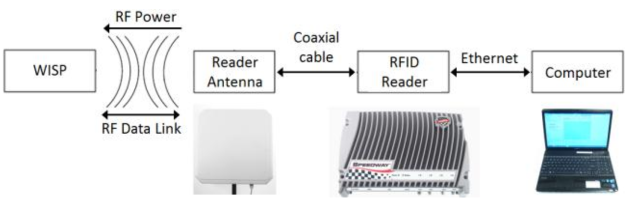

Fig.2. Querying and reading functional diagram.

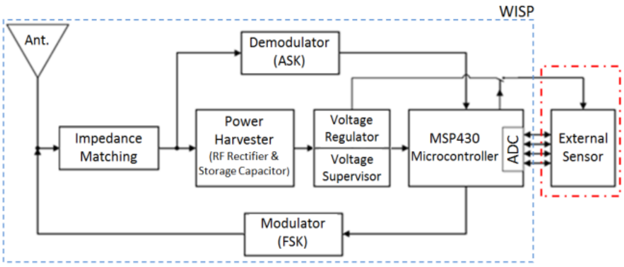

Fig.3. WISP functional block diagram [9].

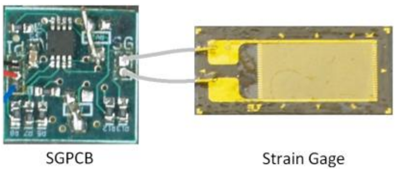

Fig.4. The SGPCB and strain gage.

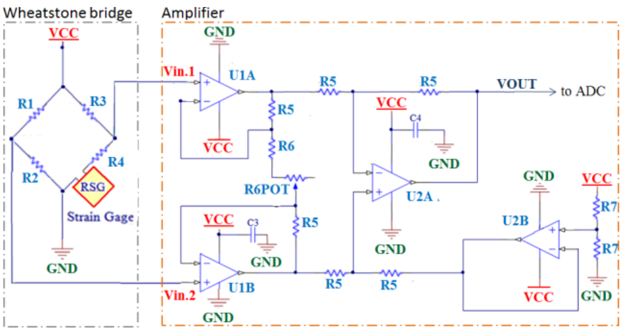

Fig.5. Schematic of the SGPCB.

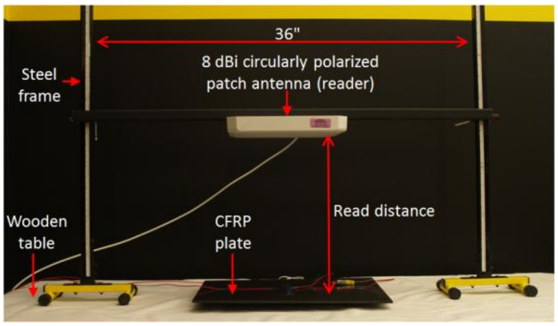

Fig.6. Read distance test setup.

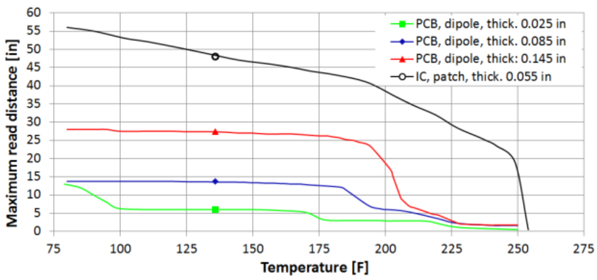

Fig.7. Read distance of WISPs/g (PCB, dipole antenna) and RFID tag (IC, patch antenna).

Fig.8. Tension test specimen with WISPs/g, showing from left to right the WISP, the SGPCB, and the strain gage.

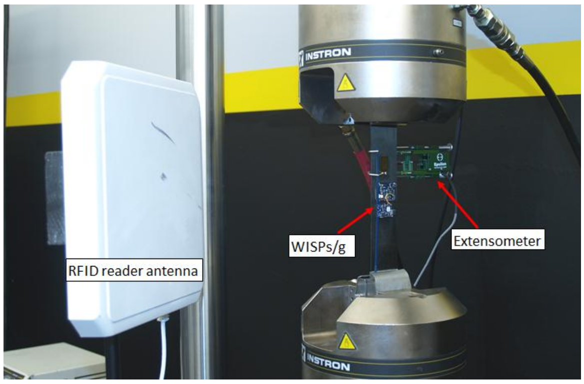

Fig.9. Tension test setup, showing the specimen in the test frame and the powering reader antenna.

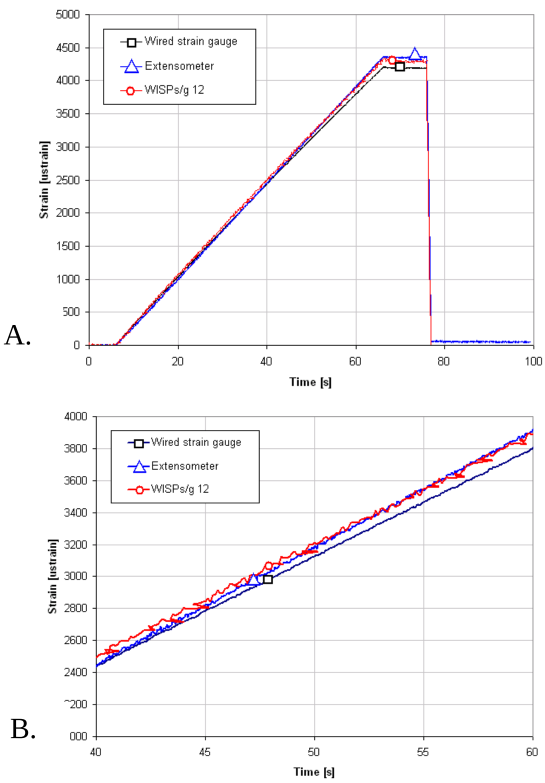

Fig.10. Ramp load tension test curves, as measured with the WISPs/g , wired strain gage and extensometer (A), and details of the curves showing noise (B).

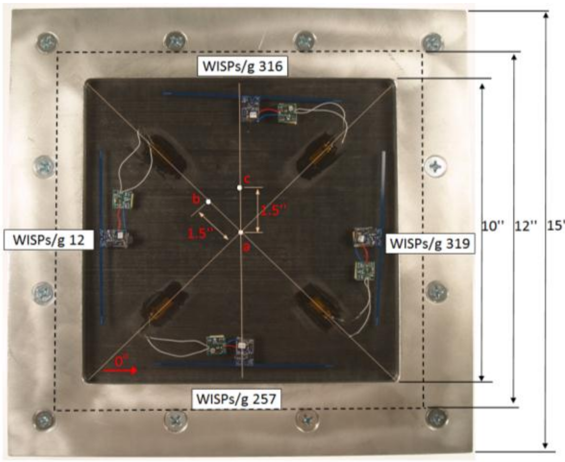

Fig.11. Quasi-static indentation fixture and panel dimensions, also showing the location and alignment of the four WISPs/g. Indentation test performed by moving the indentor to three locations: a) center load; b) and c) offset load.

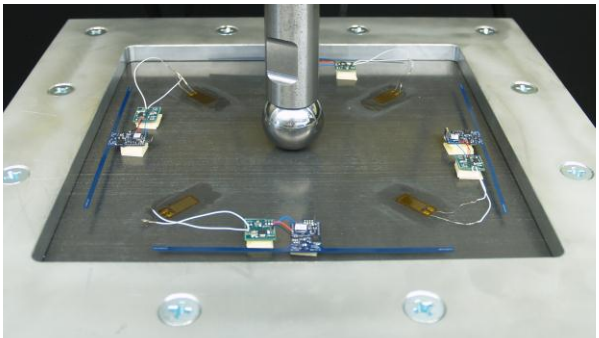

Fig.12. Quasi-static indentation test setup.

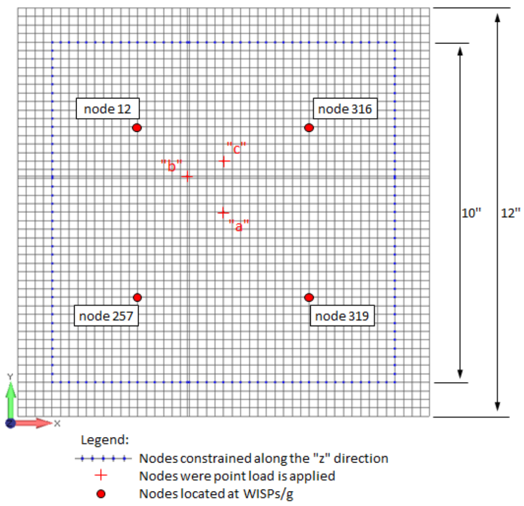

Fig.13. NASTRAN nonlinear finite element model of quasi-static indentation test,

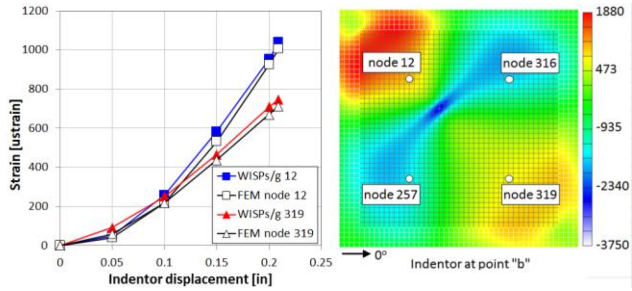

Fig.14. Left) Experimental and simulated strain curves for gages #12 and #319 as a function of indentor displacement for the load case (b). Right) Strain contour plot for the same load case.

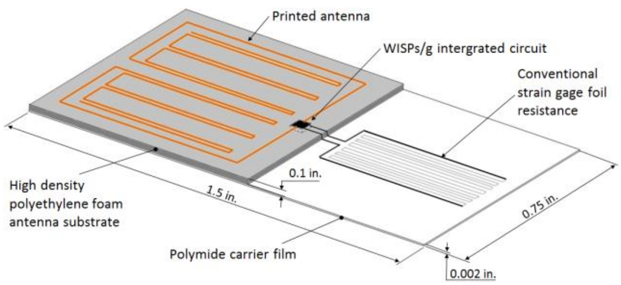

Fig.15. Future development of WISPs/g

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