DEVELOPMENT OF A WIRELESS SENSOR NETWORK FOR LIGHTNING STRIKE CURRENT FLOW DETECTION AND COMPOSITE STRUCTURAL HEALTH MONITORING

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ABSTRACT

The goal of this project was to investigate the feasibility and development of a wireless network of current sensors to characterize the electrical current flow of a lightning strike through composite structures. Carbon fiber reinforced plastics (CFRP) have found numerous applications in the aerospace industry and many others due to their extremely high stiffness to weight ratio. Due to the large volume fraction of carbon in the composite matrix CFRPs are efficient electrical conductors. However, the conductivity of most CRFPs is much less than the metal structures that they are replacing thereby increasing the structure’s vulnerability to lightning damage. The ability to analyze the nature of a lightning strike on a composite airframe in real-time could allow for advanced warning of risk to the airframe before a failure can occur. A Current Direction Sensor (CDS) was developed and found to accurately measure current magnitude and direction in two axes. To enable wireless communication, low power Zigbee Motes were initially used as a means of sensor data collection and transmission. Unfortunately, the low sample rate made the use of Zigbee protocol impractical for high frequency lightning waveform capture. To provide a faster sample rate the data was collected with a National Instruments USB Data Acquisition module. Utilizing standard 802.11 WiFi the sensors were successfully integrated into a wireless sensor network which measured current at each satellite location and transmitted it back to the base station. The system was capable of accurately measuring DC currents. In a simulated lightning test, the sensor output waveform was saturated and was unable to provide a faithful representation of the signal. Although the system was unable to capture an “real” lightning strike, the concept was proven to be successful and has generated enough interest from industry and academia to warrant further research.

INTRODUCTION

Many modern aircraft utilize composite structures due to an increased strength to weight ratio. The benefits of composites have come at the expense of reduced conductivity through the flight vehicle[1]. Conductivity through the structure is a critical aspect of the lightning safety of any structure. The higher the conductivity, the easier it is for the electrical current to pass through the aircraft, and the less damage it will induce. Conductive strips are used along the edges of surfaces in order to direct the flow of the current to static wicks at the extremities of the plane where the current should exit the aircraft. If the strips deteriorate or the current is too high to remain only on a common path of least resistance, the results can be disastrous. The last recorded plane crash due to lightning in the United States dates to 1967 in which lightning struck the airplane, exited the current strip on its wing, and arced into the fuel tank causing an explosion that ended in a fatal crash[2]. Even as recently as January 30, 2010, a lightning strike forced a US Airways flight to divert to an emergency landing[3]. While existing lightning protection technologies minimize damage due to most lightning strikes, as composite materials are increasingly used as load bearing structures, the impact of lightning and techniques to assess this impact on the continued safety of the aircraft become of greater importance.

Resistive heating is the primary mode of lightning induced failure of CFRPs. The power of an electrical circuit is governed by the equation:

\[ P = I^2 \times R \]

This simple but meaningful result states that given constant current, an increase of
resistance along a path causes an increase in the dissipated power along the same path. Therefore, if lighting enters an aircraft and the magnitude of its entry and exit current were found to be different, it can be stated that the power loss was due to energy dissipated into the aircraft. In aircraft with primarily metal structures, aluminum in most cases, the lighting induced heating is well below the threshold of altering the mechanical properties of the material. The damage threshold for CFRPs is much lower than that of metals and therefore the heat introduced into the composite from the lightning current is a significant concern[4].

Another major challenge that rises through the use of carbon fiber composites is their anisotropic properties. While Aluminum has approximately the same conductivity in all directions, a sample of carbon fiber has significant variations in conductivity as the direction of the current with respect to the orientation of the fibers changes.

![FIGURE 1](image)

**FIGURE 1** – Low Resistance Straight Path vs High Resistance 90 Degree Path, The star indicates the point of greatest damage potential.

**FIGURE 1** depicts the two fundamental options that current has when it is in transit through the composite matrix. When the current remains in the same tow, the resistance through the path is uniform and small thereby distributing and diminishing the damaging effects of resistive heating. If the electrical potential drives the current to change directions, the current is forced to short from one tow to another. The location of this short is indicated by the star in **FIGURE 1**. During the fabrication of CFRPs each tow is completely impregnated with resin. Each tow has a very thin layer of resin surrounding it that separates one tow from another. At the intersection of two tows, the resin acts as a resistor and the current flow causes concentrated heating between the fibers leading to a localized breakdown of the matrix.

Knowledge of how the current transited through the airframe can be combined with material testing results to determine the effect that a strike may have had on an aircraft. It is the position of this research that current direction in the composite matrix can be correlated to the potential for damage to occur[5]. The focus of this research was sensor development and to prove the concept of a distributed wireless sensor network.

**APPROACH**

A wireless sensor network was developed to facilitate multiple simultaneous current measurements. By combining the sampled data into a vector field, the magnitude and path of the current through the composite can be tracked.

Before work on the network began, the sensors themselves were verified for accuracy. The sensors were CSA-1V IC Hall Effect sensors mated to an evaluation board. Each sensor measures current in only one axis, therefore to measure direction in two dimensions, two sensors must be used.

![FIGURE 2](image)

**FIGURE 2** – Superposition of Two Current Sensors to Create Current Vector.

The sensors were calibrated by measuring a known current through a single wire supplied by a stable current source. After successful collection of single wire data, a test panel was built that contained two intersecting wires mounted to a
dielectric. Each wire was connected in series with a resistor. By changing the resistance in the wires, the bias of current flow, North-South or East-West, though the circuit could be varied.

The sensor was moved to various locations throughout the panel in an attempt to map the current field. As expected, current was found to be concentrated along the conductors. Measurements erroneously indicated small currents flowing through the dielectric; this was because the sensor directly measures magnetic field and calculates current.

To more closely replicate the current paths in a CFRP, a printed circuit board was designed with a grid of conductors on the surface. The conductors simulated the path that each tow supplied to the current. The circuit board model of the carbon fiber fabric allowed for many flow configurations to be tested. Current was injected at 0-180 and 0-90 orientations.

A Raster Current Measurement System was developed to collect current data from every intersection on the test panel. The test setup is shown in FIGURE 3.

![FIGURE 3 – Raster Current Measurement System, The inset shows a closeup of the grid and sensor head](image)

A computed numerically controlled milling machine was programmed so that the cutting head translated along the grid of conductors. At each intersection, the machine paused and allowed the measured value to be recorded. After the entire sample was scanned, the sensor was rotated 90 degrees and the sample was rescanned. Rotating the sensor is necessary to generate a 2-dimensional vector since each sensor can only measure along a single axis.

Matlab was used to process the data into vector fields and contour plots. The first data that was collected did not match the expected result because there was no correlation to the entry and exit points and the field. It was determined that the structure of the machine was altering the magnetic field to the extent that it overpowered the field generated by the current flow. To correct this, the sample was scanned without current flow, and the collected values were subtracted from the initial measured values.

![FIGURE 4 – Corrected 0-180 Current Injection Contour Plot](image)

The plot agreed with what was expected. Current followed a linear path and concentrated at the site of injection. The current dissipates into the panel before concentrating again at the exit site. Note how the input peak is higher than the output peak. A significant amount of power was lost in the panel. Since even an idealized panel at low current shows a non-trivial power loss, it is reasonable to assume that an actual CRFP would be subjected to significant heating.

To facilitate wireless data transmission, Crossbow MICAz Zigbee Motes were initially selected due to ease of integration and low-power consumption. Each mote was mated with a MDA300CA data acquisition card that allowed
The motes met the goal of a deployable wireless sensor network, but their data transmission rate was too low to measure a lightning strike waveform. Modifications could have been made to the software drivers of the motes to try and increase the sample rate, but that was deemed outside of the scope of this project.

To meet the goal of a faster sampling rate a 400kS/s National Instruments 6216 data acquisition module was used to sample the current sensors. The deployment configuration was very similar to that of the mote deployment; many sensors were connected to a single acquisition unit. A laptop was connected to the data acquisition unit and used to control, collect, and transmit data via a wireless connection. Deploying several laptops may appear to be overkill, but the drop in cost of Netbook form factor laptops made this solution a powerful and cost effective option. The distributed computing power will be very useful for future systems when on-board data compression and computation become of greater importance.

**RESULTS**

The cost of a simulated lighting test renders its frequent use impossible, therefore to verify system performance a means of generating microsecond current pulses was needed.

A power transistor was used to generate current pulses to test the system’s capability to faithfully reproduce short pulses. Pulses of 10, 50, and 100 microseconds were transmitted across the sensor. The measured signals were averaged to reduce noise and are displayed in the following figures.

**FIGURE 5 – MICAz Sensor Deployment, CSA-1V to MDA300CA to MICAz mote. D. Talaiver 2010**

**FIGURE 6 – Measured Signal of 100 µsec pulse, rectangle represents the input signal**

**FIGURE 7 – Measured Signal of 50 µsec pulse, rectangle represents the input signal**

**FIGURE 8 – Measured Signal of 10 µsec pulse, rectangle represents the input signal**
Due to cost and schedule, the system was only able to participate in one simulated lighting test. The test setup consisted of an aluminum enclosure designed to simulate the skin of an aircraft. The current sensor was placed inside of the enclosure, while the laptop was housed in an adjacent shielded housing. Protection of the laptop was a major concern in the lighting environment. Along with the direct effects of a high current pulse the lightning environment creates large potentially damaging magnetic fields.

The applied current pulse was in excess of 10 kiloamps. Unfortunately, the sensor was unable to measure such a large current because the sensor saturated. In addition, the sensor was unable to follow the rapid discharge of the current back to zero. Although the primary strike measurement had significant error, the simultaneous perpendicular measurement captured a transverse current oscillation in the panel.

The concept of a wireless sensor network was proven to be a feasible means to track current flow through an aircraft. The CDS was able to capture current direction, but the Hall-Effect sensors were unable to handle the large magnitudes of the lighting pulse. Although the CDS may be impractical for primary strike measurement there is still use for the sensor in low level current measurement. Also, in the future the system could be easily reconfigured to facilitate different types of health monitoring sensors such as temperature and vibration.

In the process of developing the CDS it was found that little is known about the mechanisms that break down a composite during high current exposure[4]. Correlations between current flow and damage must be found in order to develop an accurate damage assessment algorithm. The next phase of this research will change focus from hardware development to characterizing the electro-mechanical damage mechanism of CRFPs through experimental methods.

Although the system was only a partial success, it was able to collect enough acceptable data to warrant further development and has opened the door to a new and exciting area of research.
REFERENCES


