Computational Electromagnetic Modeling of SansEC™ Sensors

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Abstract: This paper describes the preliminary effort to apply computational design tools to aid in the development of an electromagnetic SansEC™ resonant sensor composite materials damage detection system. The computational methods and models employed on this research problem will evolve in complexity over time and will lead to the development of new computational methods and experimental sensor systems that demonstrate the capability to detect, diagnose, and monitor the damage of composite materials and structures on aerospace vehicles.

Keywords: Computational Electromagnetic Modeling, SansEC™ sensor,

1. Introduction

A SansEC™ planar spiral resonant sensor is an electrical inductor. Inductors are used in electronic design as storage components for magnetic field energy, unlike capacitors, which are used as storage components for electric field energy. In real inductors, there exists an inevitable associated resistance and capacitance that adds to the complexity of a resonant sensor's function. Placing the inductive sensor on a dielectric substrate material adds greater complexity to the sensor system through the additional dissipation of energy within the material from ohmic losses as well as supplementary storage of energy within the substrate material by means of additional capacitances. These parasitic components are important to the accurate physical design of planar resonant sensors and sensor systems but can be troublesome to properly account for computationally. More importantly, this phenomenon allows a SansEC™ resonant sensor placed on a material surface to determine physical characteristics and qualities about the material upon which it is placed. These relevant parasitics and the complexities of their effects are appropriately captured and studied by using well described sensor geometries and material properties in a computational electromagnetic model.

2. Problem Description

Electromagnetic modeling and simulation is a very useful design tool at any stage and for any scale of an electrical engineering research problem. For an emerging complex system requiring ongoing analysis and design, it is best to deploy computational electromagnetic model (CEM) tools early in the design process and in parallel to the introduction of the most fundamental hardware components. In this way one can evolve the use of appropriate computational methods, tools, and techniques in conjunction with the developing hardware. By using iteration and feedback to model physical hardware and then validate the CEM against that physical hardware by means of experimental measurements, a better and more economical hardware product can be realized. Simultaneously a more robust design tool is developed that will assuredly enhance the next stage of design complexity. As understanding and confidence in the computational model and the experimental hardware increases, the ability to integrate sub-elements into larger system elements occurs. In this manner we undertake the first steps in designing and understanding a SansEC™ resonant sensor both as a computational model and a physical hardware component that will ultimately become a full demonstration array of sensors capable of detecting, diagnosing, and monitoring the damage and flight worthiness of composite materials and structures integrated into an aerospace vehicle.

3. Approach

Eight planar SansEC™ resonant spiral sensors were fabricated to provide test articles for measuring sensor characteristics and performance on a network analyzer. These experimental measurements were used to verify and validate equivalently modeled sensors simulated in a computational electromagnetic code. The sensors varied in size from 2 to 9 inch squares as depicted in Figure 1. The fabricated sensors were made from copper metal foils that had a thickness of 1.25 mils. Each sensor consisted of a copper metal trace that formed a continuous square spiral that started at the center and ended at an outer corner. The copper traces were 93.75 mils wide with a gap between the spiral traces of 31.25 mils. The copper metal foil trace of each individual sensor was encapsulated within a low dielectric thin sheet of plastic.

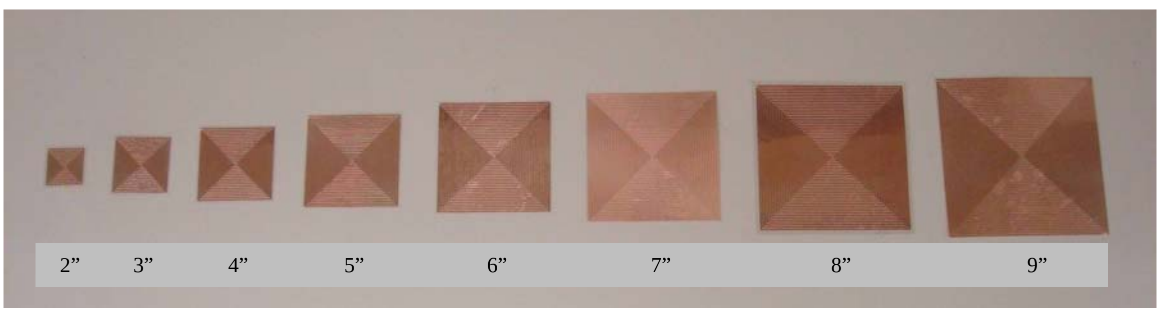
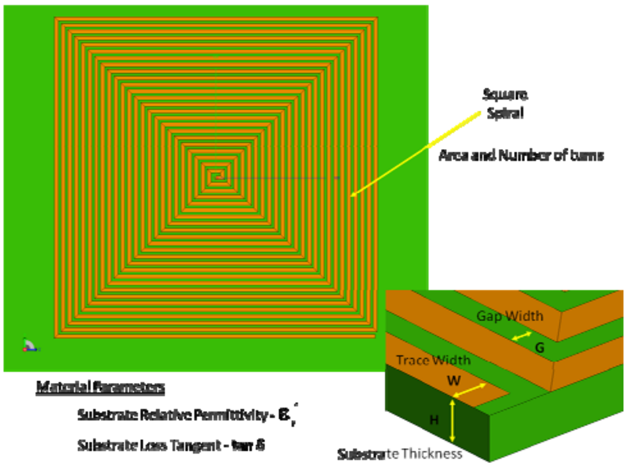


Figure 1: A Series of Square Spiral Resonant SansEC™ Sensors

To simulate a planar SansEC™ resonant sensor upon a composite airframe as a fundamental sensing element, the various spiral resonant sensors were centered upon a 14 inch square of a ¼ inch thick structural fiberglass composite sheet. The geometry and material properties of this simple arrangement were modeled in FEKO which is a comprehensive electromagnetic analysis software suite. The sensor on the surface of the composite along with a square loop antenna positioned above was modeled as a three dimensional object. A combination of FEKO and MATLAB were used to build parametric features into the model. The sensor/material model was constructed such that physical dimensions of the sensor system were variable. As shown in Figure 2, the copper trace width W could easily be set to new design values. The copper materials were also modeled as a perfect electrical conductor (PEC), but this too could be changed. The edge to edge separation distance, or trace gap G, between the conductive legs of the spiral could be adjusted. The composite dielectric substrate thickness H could be changed. The electrical material properties of the substrate were modifiable thus making it possible to simulate other composite materials or fatigue stresses and damage within the material by altering the relative value of the electric permittivity ε, and/or the electric loss tangent $\tan\delta$. The length of the trace of a square spiral resonant sensor is further parameterized by the area A. This determines the sensor size which directly relates to the design operation frequency and the amount of composite material surface that the sensor covers. Also the number of turns *N* that comprise the inductive loops of the sensor is parameterized. The square loop antenna used to excite the sensor and read back the response was model with a stand-off parameter *S*, so that the height of the antenna above the sensor/material structure could be adjusted.



Parameter	Description
W	Trace width
G	Trace gap width
H	Substrate thickness
ε	Relative permittivity
tan δ	Electric loss tangent
A	Area of spiral
N	Number of turns
S	Antenna stand-off distance

Figure 2: Square Spiral Resonant Sensor Model with several Parameterized Features

The FEKO computational electromagnetic modeling software supports the Method of Moments (MoM) to perform a full wave solution to Maxwell's integral equations in the frequency domain. Special extensions were configured to the MoM formulation to enable the modeling of complex dielectric media associated with the simulated and real aerospace composite materials. Planar Green's functions were considered for some substrates.

In addition to supporting the full parametric creation of the models, FEKO was used to mesh the geometry, and to specify other solutions, settings, and calculation requirements in the graphical environment. The geometries were meshed as frequency dependent triangles, segments, and connection points. The geometrical data numerical results were processed by the software as the one-port S-parameter S_{11} (return loss) which allowed comparison to the experimental network analyzer measurements which were similarly configured. The matrix elements were stored in memory and the calculation of the elements using the Method of Moments provided a vector solution to the linear set of Maxwell's equations. The matrix was decomposed, and a backwards substitution provided a determination of the surface currents, impedances, and power amplitudes as a function of frequency.

The binary output files were read in FEKO and then the results were displayed in the form of S_{11} S-parameter plots. These return loss data offered the best comparison of computational modeling results to the experimental measurements. Three dimensional views of the sensor and substrate geometries were also available to display surface currents and electric or magnetic fields. The meshed geometry and optimization results were viewable. The 3-D views allowed researchers to gain a functional perspective on the interaction of the sensor with the simulated composite substrate. These examinations aid in the next generation design or modification of a sensor's geometry for improved sensing capabilities. Studies of field penetrations into a particular substrate will be of great future benefit in optimizing sensor/composite systems.

Once computation was completed and the data plotted, the results were validated and verified against experimentally measured results. An Agilent E8364C 10 MHz to 50 GHz Performance Network Analyzer (PNA) system was used to measure the *S* parameter S11 of each of the eight test sensors. After calibration, port 1 of the network analyzer was connected to a four inch square loop antenna which illuminated the sensor-under-test with a broadband frequency swept electromagnetic field up to 1000 MHz as in Figure 3. The transmitted energy from the loop antenna was incident upon the sensor-under-test which excited resonant modes in the sensor. The sensor passively re-radiated its response signature back to the network analyzer through the same loop antenna. The resonant response of the sensor was related to the geometry and structure of the sensor/material system.

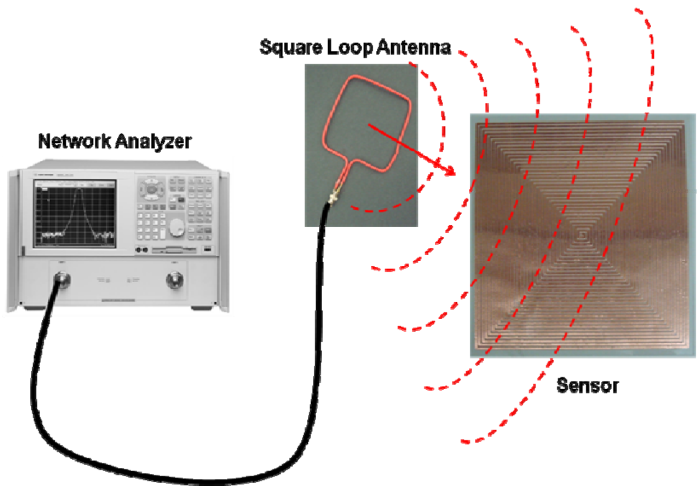


Figure 3: Experiment Measurement System and Setup

4. **Results and Discussion**

The electric field generated due to a planar resonant spiral inductor's magnetic flux is confined within the substrate of a dielectric material. At higher frequencies, the electric field becomes large enough that it capacitively couples through the material substrate. This is the self-resonance frequency (SRF) of the spiral inductor combined with the material substrate. This effect associated with the spiral inductor induces the substrate currents. The substrate currents are mainly composed of two parts: displacement currents from spiral traces to the substrate through capacitance, and eddy currents in the substrate. The displacement currents are a product of the time varying electric field through capacitance, and increase with higher frequencies. The eddy currents are a product of the spiral inductor time-varying magnetic field penetrating the material substrate. The induced currents in the material substrate flow in opposite direction to the current flow of the spiral inductor, producing a counter effect on the performance of the integrated spiral inductor/material system. The detection of the differences in frequency and amplitude of the induced currents within a material substrate offers a means of detecting damage or changes to the state and condition of the material substrate. The experimentally measured resonant frequency values of various square resonant sensors in free space and on the same composite substrate are compared with the FEKO method-of-moment computations. Figures 4 and 5 below illustrate data for the measured and computed response in free space of the three inch square resonant sensor. The x-axes represent the frequency (MHz) and the y-axes represent the S_{11} magnitude (dB). Both figures represent data from 1 Hz to 300 MHz.

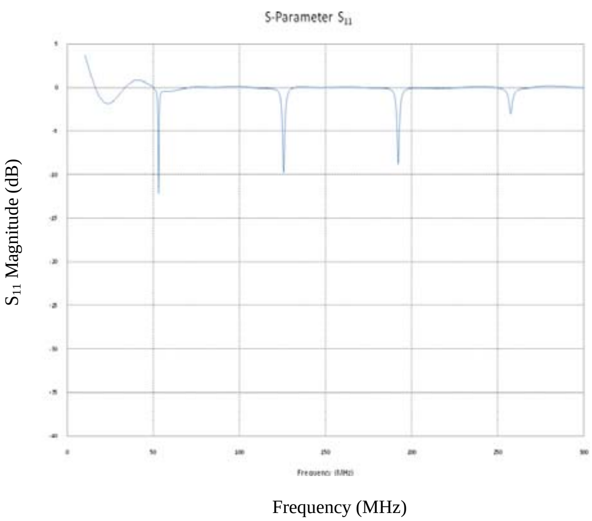


Figure 4: PNA Measured

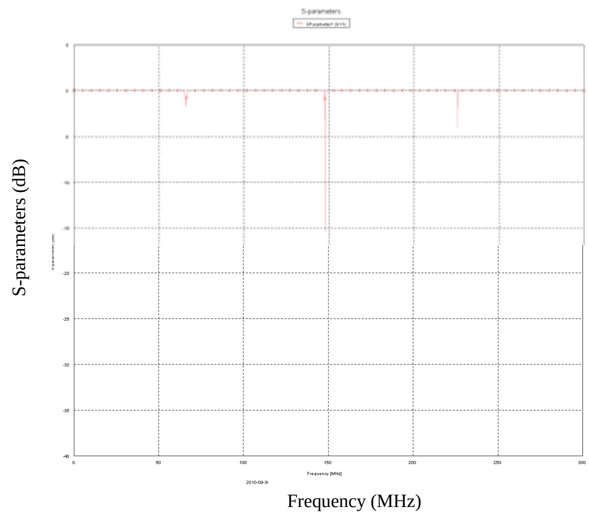


Figure 5: FEKO Computed

5. Conclusions

The self-resonant frequencies of spiral inductors were shown from measured *S* parameters and method-of-moments computation. The network and computer analysis reasonably agree for all eight cases of this preliminary study. More work still needs to be done in FEKO to compensate for an observed frequency offset. However, CEM shows open circuit resonant sensors can be used to indicate a change in the impedance characteristics in materials placed in close proximity to the sensor. A resonate sensor placed on a composite panel can indicate a change in resonance within a composite material matrix and thus indicate potential damage.

Future work will mature in measurement and modeling complexity from the simple proof-of-concept sensor/material panel demonstrations described within this paper. Ultimately the ability to demonstrate a robust electromagnetic model of resonant sensors embedded in and on more realistic aircraft composite structures and to simulate damage to those structures is desired.

6. Acknowledgements

The authors gratefully acknowledge Rohit Sammeta of EM Software and Systems (EMSS) and Dr. C.J. Reddy of Applied EM for guidance in setting up a fully parameterized CEM model. Support from the NASA's Aviation Safety Program's Atmospheric Environmental Safety Technologies Project team members: John Mielnik of Lockheed Martin who was key in the development of the physical sensors used in this NASA research activity and Sandra Koppen, Truong Nguyen, and Jay Ely of the NASA Langley Research Center High Intensity Radiated Fields (HIRF) Laboratory for beneficial discussions and support. Special thanks to Dr. Stanley Woodard of the NASA Langley Research Technology Directorate. Dr. Woodard is the inventor of SansEC™ and several SansEC™ technologies and applications. Also a special acknowledgement to Dr. Woodard's post doctorate researcher Dr. Chauntong Wang of the National Institute of Aerospace (NIA) for additional SansEC™ measurements in the NASA Structural Dynamics Research Laboratory.