COVER SHEET

Title: *Multi-Physics Modeling and Simulation of a Slotted Patch Antenna for Wireless Strain Sensing*

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ABSTRACT

This research studies multi-physics simulation of a slotted patch antenna sensor. In our previous work, a folded patch antenna was designed for passive wireless strain and crack sensing. When experiencing deformation, the antenna shape changes, causing shift in electromagnetic resonance frequency of the antenna. The wireless interrogation system utilizes the principle of electromagnetic backscattering and adopts off-the-shelf 900MHz radiofrequency identification (RFID) technology. In this research, a slotted patch antenna sensor is designed, while maintaining antenna resonance frequency to be around 900MHz. The slotted antenna detours surface current using slotted patterns, so that the electrical length is kept similar as previous folded patch antenna sensor yet sensor footprint is reduced.

To accurately describe both mechanical and electromagnetic behaviors of the antenna sensor, a multi-physics coupled simulation approach is pursued. A multi-physics finite element model uses the same geometry and meshing for both mechanical and electromagnetic simulations. Because electromagnetism has little influence on the mechanical behavior of the sensor, displacement field and electrical field can be solved separately using segregated steps. Known as sequential coupling, the solution method involves two or more analyses, each solving for a different physical field. The mechanics-electromagnetics coupled simulation is implemented

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using a commercial software package, COMSOL. Strain sensing performance predicted by the multi-physics simulation is presented.

INTRODUCTION

Strain is one of the key performance indicators for the safety condition of many structural components. Current strain sensing technologies include metal foil strain gages, fiber-optic strain sensor, vibrating-wire strain gages, *etc* [1]. While these technologies offer relatively accurate measurement, most sensing systems either require running lengthy cables in the structure, or require expensive data acquisition equipment. As a result, current technologies suffer from high instrumentation and monitoring cost and are not practical for large-scale/large-area deployment in the field.

To eliminate cabled connections in a strain sensing system, researchers have investigated electromagnetic antennas for strain sensing. The basic concept is that when a small piece of antenna (usually planar) is under deformation, its electromagnetic resonance frequency changes accordingly. Such change can be interrogated by a wireless reader and used as a strain indicator. Researchers have studied different types of antenna sensors. For example, a patch antenna has been designed for wireless strain sensing [2], where a phototransistor is adopted for modulating the RF signal backscattered from the antenna sensor. However, besides requiring line of sight, the light-switching mechanism is not practical for outdoor application, where light intensity is usually so strong that the phototransistor is constantly activated and thus, loses ability of switching. Most recently, a circular patch antenna has been proposed for omnidirectional strain sensing by wirelessly measuring scattering parameter [3]. Since no signal modulation is used by the sensor, the wirelessly received sensor signal is mixed with background reflection, and the sensor has very limited interrogation distance.

To distinguish backscattered sensor signal from unwanted background reflection, researchers have investigated RFID modulation with an antenna sensor. A small-size meander-line antenna with RFID modulation has been designed for wireless strain sensing on non-metallic structures [4], although the demonstrated measurable strain resolutions are unlikely enough for most SHM applications. Recently, the authors developed an RFID-based folded patch antenna as a passive wireless strain sensor [5]. The system utilizes the principle of electromagnetic backscattering and adopts a low-cost off-the-shelf RFID chip to reduce the design and manufacturing cost. A slotted patch RFID antenna sensor is later proposed to reduce the sensor footprint by introducing slotted antenna patterns [6]. The sensor design is performed using a commercial software package, Ansoft HFSS. To simulate the strain effect on the electromagnetic performance of the antenna sensor, dimensions of the sensor is simply scaled according to the applied strain and Poisson's effect. Although the electromagnetic simulation through simple scaling provides reasonable results, the simulation accuracy is limited. The strain distribution in the antenna sensor is generally not uniform and cannot be precisely represented by simple scaling. To achieve accurate strain effect simulation results, mechanics-electromagnetics coupled simulation is needed.

In this research, a new slotted patch antenna design is proposed for strain sensing. The slotted patch antenna is simulated using a commercial software package, COMSOL, which supports mechanics-electromagnetics coupled simulation.

Mechanical behavior of the antenna sensor is first simulated by applying load to the base structure, i.e. an aluminum plate where the sensor is mounted on. As a result, accurate deformation of the entire antenna sensor can be captured. Electromagnetic behavior of the deformed antenna is then simulated, preserving the exact deformed meshing from mechanical simulation. The simulations are performed at different strain levels, in order to study how antenna resonance frequency shifts with strain. The rest of the paper is organized as follows. First, the strain sensing mechanism and design of the slotted patch antenna sensor are presented. The multi-physics model built using COMSOL is then described, followed by strain sensing simulation results. Finally, a summary and discussion of this work are provided.

STRAIN SENSING USING A NEW SLOTTED PATCH ANTENNA SENSOR

The RFID sensing system contains an RFID reader and antenna sensors, where each antenna sensor includes a small antenna and an RFID chip. The chip provides backscattered signal modulation and anti-collision functions [7]. The sensor wirelessly collects operation power from the interrogation electromagnetic signal emitted by a reader. The sensor then sends modulated backscattered signal to the reader for interpretation of shifted resonance frequency under strain.

Figure 1 shows the drawing of a newly designed slotted patch antenna sensor. The top layer of the sensor is a patterned copper cladding (as conducting component of the antenna) and the bottom layer is another copper cladding serving as the ground plane. Sandwiched between the two copper claddings, both 0.017 mm thick, is the dielectric polymer substrate. The two copper layers are connected through vias to realize the "folding", which reduces the sensor size by half compared with a patch antenna without folding. Two slots are also introduced on the top copper cladding to detour current paths and further reduce sensor dimensions. The adopted substrate material is Rogers RT/duroid®5880, a glass microfiber reinforced poly-tetra-fluoro-ethylene (PTFE) composite with a dielectric constant ε_r of 2.20 and a thickness of 31 mils (0.79 mm). The RFID chip is soldered on top copper cladding. The adopted chip is the SL3ICS1002 model from NXP Semiconductors. The chip operates in the ultra-high frequency (UHF) band (840MHz-960MHz), which allows international usage.

Impedance matching technique is adopted for the antenna sensor design. Proper impedance matching between the antenna and the RFID chip gives efficient power transmission and increases interrogation range (maximum distance at which a reader can read signal from the sensor). The scattering parameter, S_{11}, quantifies this

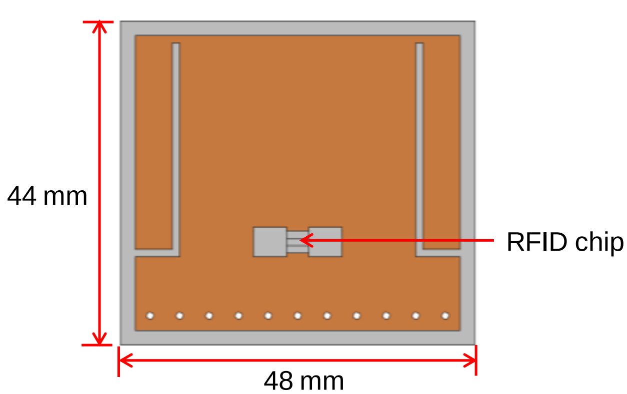


Figure 1. Design drawing of the slotted patch antenna sensor (top view)

transmission efficiency [8]. Calculated as follows, S_{11} equals to the ratio of the power reflected by the antenna over the power infused by the RFID chip. A smaller value of S_{11} indicates higher transmission efficiency.

$$S_{11}(f) = \left| \frac{Z_a - Z_c^*}{Z_a + Z_c} \right| \tag{1}$$

where "*" represents the conjugate of a complex number and Z_a denotes the impedance of the antenna. A smaller value of S_{11} indicates higher power transmission efficiency. The antenna pattern is tuned to match the impedance of the RFID chip by adjusting the dimension and location of the slots, as well as the location of the RFID chip. The impedance of the chip, Z_c, is 13.3-j122 Ω ("j" is the imaginary unit). During the sensor design phase, impedance of the antenna is adjusted to match the conjugate of RFID chip impedance. As a result, a smallest amount of power needs to be transmitted from the reader in order to activate the RFID chip. Figure 1 shows the final design of the antenna sensor that achieves optimum matching.

The antenna at the sensor side has certain electromagnetic resonance frequency. Eq. (2) estimates the resonance frequency of a slotted patch antenna [9]:

$$f_0 \approx \frac{c}{8(L+L')\sqrt{\varepsilon_{\mathrm{reff}}}} . \tag{2}$$

where c is the speed of the light, L is the physical length of the top copper cladding on the antenna, $\varepsilon_{\mathrm{reff}}$ is the effective dielectric constant of the antenna substrate, and L' is the additional electrical length corresponding to $\varepsilon_{\mathrm{reff}}$ and the antenna thickness-to-width ratio. Because the thickness-to-width ratio (equal to 0.016 in this design) is close to zero, the effective dielectric constant $\varepsilon_{\mathrm{reff}}$ has approximately the same value as the dielectric constant ε_{r}, according to following equation [9] :

$$\varepsilon_{\mathrm{reff}} = \frac{\varepsilon_{\mathrm{r}}+1}{2} + \frac{\varepsilon_{\mathrm{r}}-1}{2}\left(1+12\frac{h}{W}\right)^{-1/2} \approx \varepsilon_{\mathrm{r}} \tag{3}$$

where h and W are thickness and width of the substrate, respectively.

Once an antenna sensor is bonded on the surface of a base structure, the sensor deforms together with the structure. As a result, the antenna length changes with structural strain. When strain ε occurs in the longitudinal direction (antenna length direction), the resonance frequency is shifted to:

$$f = \frac{c}{8(1+\varepsilon)(L+L')\sqrt{\varepsilon_{\mathrm{r}}}} = \frac{f_0}{1+\varepsilon} \approx f_0\,(1-\varepsilon) \tag{4}$$

The equation shows that if strain ε is small, the resonance frequency shifting is approximately linear to strain. This linear relationship indicates that strain can be derived by measuring shift in the antenna resonance frequency. This serves as the fundamental strain sensing mechanism of the wireless antenna sensor.

In previous study, the strain effect on antenna resonance frequency is simulated by simply scaling all sensor dimensions according to applied strain and Poisson's effect [6]. Although the scaling approach can estimate strain effect on antenna resonance frequency, the simulation accuracy is limited, especially when the antenna pattern is more complex than a simple patch. First, the simple scaling assumes same longitudinal strain in the base structure, the substrate, and the top copper cladding. However, due to shear lag across the sensor thickness, the actual strain developed in the substrate and top copper cladding can be much different from the strain experienced by the base structures. Second, the simple scaling assumes uniform strain on the top copper cladding, but the actual strain distribution on top copper cladding is non-uniform and varies significantly with antenna pattern. To accurately compute shifted resonance frequency under strain, exact deformed shapes of both the substrate and top copper cladding are needed. A mechanics-electromagnetics coupled sensor modeling is investigated to this end.

MECHANICS-ELECTROMAGNETICS COUPLED SIMULATION

The antenna sensor is modeled using the COMSOL Multiphysics™ software package. Figure 2 shows the COMSOL simulation model. The antenna sensor is attached at the center of an aluminum plate. The RFID chip is simulated as a lumped port with the same electrical impedance ($Z_c = 13.3\text{-}j122\ \Omega$). The bonding between the antenna sensor and the aluminum plate is assumed to be ideal, i.e. no relative displacement occurred at the interface. Similarly, bonding between the copper cladding and the substrate material is assumed to be ideal. The antenna sensor and the aluminum plate are placed at the center of an air sphere. At the outer surface of the air sphere, boundary condition is set as a perfectly matched layer (PML). The PML boundary condition allows electromagnetic wave emitted by the antenna sensor to pass through with minimal reflections, which mimics the dissipation of electromagnetic wave into infinite free space. The two copper layers, top antenna cladding and the bottom ground plane, are meshed using shell elements with a thickness of 0.017mm. Key mechanical and electromagnetic properties of the materials are summarized in Table I. Copper and aluminum materials are taken as perfect electric conductor (PEC) in the electromagnetic simulation.

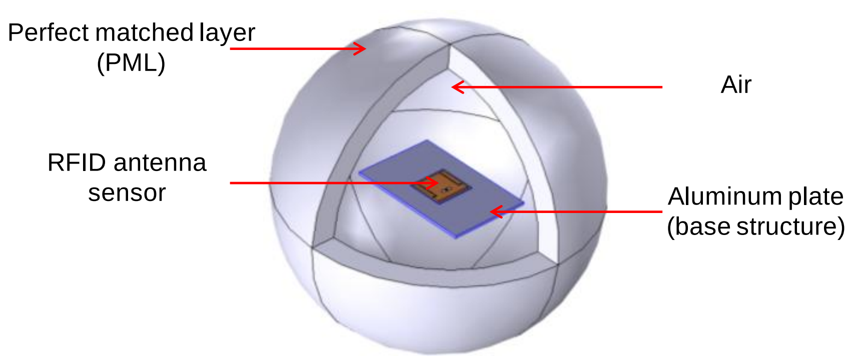


Figure 2. Multi-physics simulation model using COMSOL

TABLE I. KEY PROPERTIES OF THE MATERIALS USING COMSOL SIMULATION MODEL

	Substrate	Copper cladding	Aluminum
Material type	Rogers RT/duroid® 5880	Copper	6061 Aluminum alloy
Relative permittivity (ε_r)	2.2	1	1
Conductivity (S/m)	0.5×10^{-9}	PEC	PEC
Poisson's ratio	0.4	0.35	0.33
Young's modulus (GPa)	1.07	110	69
Dimensions (mm^3)	48×44×0.79	44×40×0.017 (Top) 48×44×0.017 (Bottom)	150×100×3.175

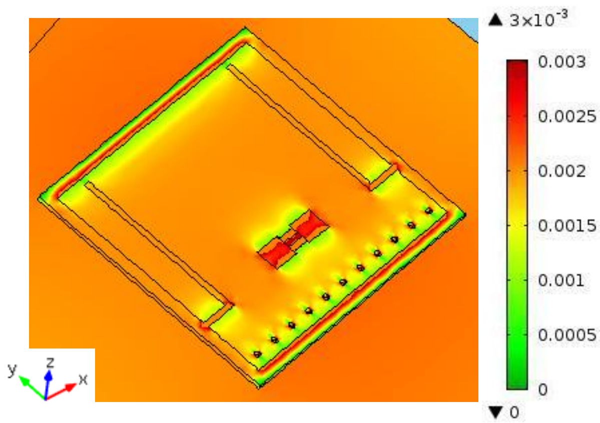
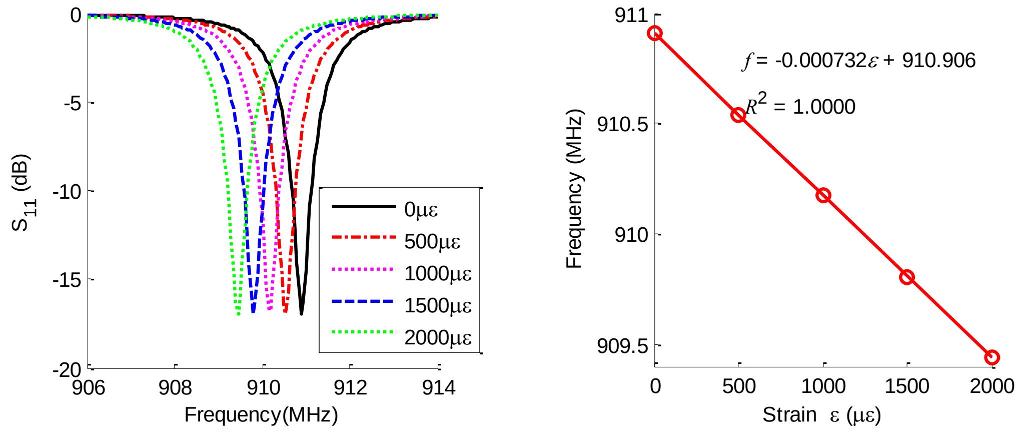


Figure 3. Strain distribution ε_y of the aluminum plate and the antenna sensor

In the mechanical simulation, only the aluminum plate and the antenna sensor (including the substrate and two copper layers) are involved, while the air sphere is neglected. Uniformly distributed tensile loads are applied at two ends of the aluminum plate. The loads are adjusted so that five different strain levels (from 0 to 2,000με at an increment step of 500με) are generated in the aluminum plate. After the mechanical simulation at each strain level, the deformed meshing is directly used for electromagnetic simulation to determine the resonance frequency of the antenna sensor under strain. During the electromagnetic simulation, a frequency domain solver is used to calculate scattering parameter S_{11}. The simulated frequency range is 900~915 MHz with a frequency step of 0.05MHz. The resonance frequency is finally determined by picking the lowest peak of the S_{11} plot.

Figure 3 presents simulated strain distribution in the longitudinal direction on the aluminum plate and the antenna sensor, when the applied strain in the plate is 2,000με. Approximately uniform strain distribution is achieved around the center of the aluminum plate. On the other hand, the strain distribution on top copper cladding has large variations that are highly dependent on the slotted pattern. Figure 4(a) shows simulated S_{11} plots at different strain levels. As expected, the resonance frequency of the antenna sensor reduces as the strain increases. The resonance frequency is 910.9 MHz at zero strain level, and decreases to 909.44 MHz at 2,000 με. Figure 4(b) illustrates linear regression between resonance frequency and corresponding strain level. The slope of the regression is the strain sensitivity,



(a) S_{11} parameter

(b) Resonance frequency versus strain

Figure 4. Strain simulation results of the antenna sensor generated by COMSOL

which is the ratio of the resonance frequency change over the applied strain. The value of -732 Hz/με means 1με increment in the base structure generates 732 Hz decrease in antenna resonance frequency. The figure also shows the coefficient of determination (R^2) is 1, which indicates a strong linearity between resonance frequency and strain.

SUMMARY AND DISCUSSION

This paper presents the mechanics-electromagnetics coupled simulation of a newly designed slotted patch antenna sensor using COMSOL. By introducing slots to the top copper pattern of the antenna, the sensor footprint is largely reduced, compared with a previous folded patch antenna sensor. Strain effect on the antenna sensor is evaluated by a multi-physics simulation, which is more accurate and realistic compared with simulation by simple scaling. The more accurate results provided by multi-physics simulation can facilitate further improvement in antenna sensor design. Upon fabrication, laboratory tensile tests will be conducted to verify the strain sensing performance of the new slotted patch antenna sensor.

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