# Design of Passive Wireless Antenna Sensors for Strain Measurement

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**Abstract**— Metallic dampers in the bridge structures will suffer from a certain degree of deformation leading to a damage or destruction. To assess the deformation of metallic dampers and to decide whether to replace, a passive wireless strain sensor is needed. In this paper, we propose a scheme to design the passive wireless strain measurement system. We first investigate the possibility that a folded patch antenna is used as a strain sensor and then design such a folded patch antenna with a coaxial line feed. We establish a model for the antenna by using the HFSS and perform a series of simulations to find the relationship between the mechanical deformation of antenna and its resonance frequency. With the relationship, the deformation of metallic dampers can be predicted by measuring the resonance frequency shift of the antenna.

## 1. INTRODUCTION

Metallic dampers in a bridge structure will suffer from a certain degree of deformation which could result in a serious damage and destruction. To assess the deformation of metallic dampers and to decide whether to replace them, we need to measure their strain value [1]. Traditional monitoring methods generally use an active-cable-resistive strain sensor to measure the value, but it is of high cost and poor mobility and also requires an external power source [2, 3]. Passive wireless antenna sensors have been developed to overcome those problems in recent years and have been applied in strain measurement [4].

First of all, we study the possibility that a folded patch antenna is used as a strain sensor. We know that electromagnetic backscattering techniques have been exploited for wireless strain sensing [5]. Since the electromagnetic resonance frequency of an antenna is related to the antenna's physical dimensions, the resonance frequency changes when the antenna is subject to an applied strain. With a mathematical deduction, we find that there is a good linearity between the resonance frequency shift and the applied strain [6]. After bonding or embedding the antenna to a structure, this relationship between the resonance frequency and the strain can be used for the strain measurement.

We then design a folded patch antenna with a coaxial line feed. We use the HFSS to establish its electromagnetic simulation model. The simulation results show that the folded patch antenna with the coaxial line feed has a large power reflection coefficient, and there is an approximate linearity between the resonance frequency shift and the applied strain. Furthermore, the sensing sensitivity in a longitudinal direction is better than that in a transverse direction. With these observations, we design a passive wireless measurement system with the antenna sensor to monitor the deformation of bridge structures.

## 2. BASIC PRINCIPLE

In this paper, we study the probability that folded patch antenna can applied as strain sensor. For a folded patch antenna, the resonance frequency of the antenna under strain, $f_{res}$, can be approximated with the following equation [1].

$$f_{res} = \frac{c}{2\sqrt{\varepsilon_{re}}}\frac{1}{L + 2\Delta L_{oc}} \tag{1}$$

where $c$ is the speed of light, $L$ is the physical length of the top copper cladding, $\varepsilon_{re}$ is the effective dielectric constant of the substrate, and $\Delta L_{oc}$ is the additional electrical length compensation determined by the substrate width-to-thickness dimension and the dielectric constant. The effective dielectric constant of the substrate $\varepsilon_{re}$ is related to the relative dielectric constant of the substrate, the physical width of the top copper cladding $W$, the antenna substrate thickness $h$:

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + 10h/W}} \tag{2}$$

The additional electrical length compensation $\Delta L_{oc}$ is related to effective dielectric constant of the substrate, the antenna substrate thickness and the physical width of the top copper cladding.

$$\Delta L_{oc} = 0.412h \frac{(\varepsilon_{re} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{re} - 0.258)\left(\frac{W}{h} + 0.813\right)} \tag{3}$$

Assuming that if strain $\varepsilon_L$ increases, the antenna substrate thickness and the physical width of the top copper cladding will change.

$$\begin{aligned} W &= (1 - \nu_P \varepsilon_L) W_0 \\ h &= (1 - \nu_S \varepsilon_L) h_0 \end{aligned} \tag{4}$$

$\nu$ is the Poisson's ratio, which is the absolute ratio between transverse strain and longitudinal strain of the antenna when force is applied longitudinally. $\nu_F$ is the Poisson's ratio of top copper, $\nu_s$ is the Poisson's ratio of top copper, dielectric substrate. Assume that $\nu_F$ and $\nu_s$ is the same or similar, the ratio $W/h$ will not change when strain increasing. So the relative dielectric constant of the substrate has no relationship with the strain and there is a direct proportion relationship between the additional electrical length compensation $\Delta L_{oc}$ and the antenna substrate thickness. The resonance frequency of the antenna under the strain $f_{res}$ can be redefined in the following equation.

$$f_{res} = \frac{c}{4\sqrt{\varepsilon}_{re}} \frac{1}{L + 2\Delta I_{oc}} = \frac{C_1}{L + C_2 h} \tag{5}$$

where, $C_1 = \frac{c}{4\sqrt{\varepsilon_{re}}}$, $C_2 = 0.824 \frac{(\varepsilon_{re}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{re}-0.258)(\frac{W}{h}+0.813)}$. If strain $\varepsilon_L$ increases, the resonance frequency be estimated in the following equation:

$$f_{res}(\varepsilon_L) = \frac{C_1}{L(1 + \varepsilon_L) + C_2 h(1 - \nu \varepsilon_L)} \tag{6}$$

With Equations (5) and (6), $\varepsilon_L$ can be approximated with the following equation.

$$\varepsilon_L = \frac{L + C_2}{L - \nu C_2 h} \frac{f_{res}(\varepsilon_L) - f_{res}}{f_{res}} = C \frac{\Delta f_{res}}{f_{res}} \tag{7}$$

where, $\Delta f_{res} = f_{res}(\varepsilon_L) - f_{res}$.

$$f_{res}(\varepsilon_L) = -\frac{C_1(L - \nu C_2 h)}{(L + C_2 h)^2} \varepsilon_L + \frac{C_1}{L + C_2 h} = K \varepsilon_L + f_{res} \tag{8}$$

From the above equation, we can find $K \approx -f_{res}$. The sensing sensitivity of strain sensor is related to its working frequency and the material of dielectric substrate. We know that if the longitudinal strain increases, the resonance frequency decreases. If the transverse strain increases, the resonance frequency also decreases due to the Poisson's effect. However, the change is obviously smaller than the former one. Therefore the relationship between the resonance frequency and the applied strain in the longitudinal direction can be used for strain measurement.

## 3. DESIGN

To drastically reduce the size of the sensor that is typically a half-wavelength patch antenna, a quarter-wavelength folded patch antenna topology is adopted. The quarter-wavelength folded patch antenna has the same $Q$ with full-sized patch antenna. Its top copper and dielectric substrate was short circuit in the edge. The length of top copper $L_{1/4}$ can be calculated by the following equation.

$$L_{1/4} = \frac{\lambda}{4\sqrt{\varepsilon}_{re}} - \Delta L_{oc} \tag{9}$$

where $\lambda$ is the length of wave. Due to folded patch antenna using coaxial line feed, the feed point location $L_1$ where impedance is $50\,\Omega$ can be calculated by the following equation.

$$L_1 = \frac{L}{2}\left(1 - \frac{1}{\sqrt{\varepsilon}(re)}\right) \tag{10}$$

Table 1. Dimensions of folded patch antenna with coaxial line feed.

| Name | Size parameters | Variable | Value (mm) |
|---|---|---|---|
| Dielectric substrate | Thickness | $H$ | 1.6 |
| Radiation patch | Length | $L0$ | 14 |
| | Width | $W0$ | 20 |
| Coaxial line feed | Feed point location | $L1$ | 2 |
| | Radius of inner core | $R1$ | 0.6 |
| | Radius of port | $R2$ | 1.5 |

The material of dielectric substrate is FR4 whose dielectric constant is 3.4. The material of ground plane is copper. Other dimensions are shown in Table 1.

The HFSS has a strong function for electromagnetic modeling and simulation. We establish the model of folded patch antenna with a coaxial line feed according to the geometric parameters listed in Table 1. The model is presented in Figure 1.

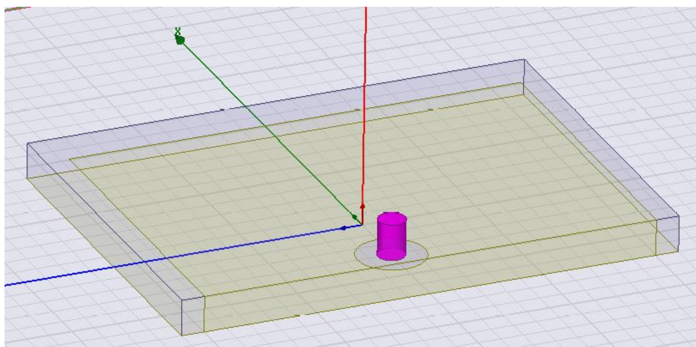

Figure 1. The model of folded patch antenna with coaxial line feed.

## 4. SIMULATION

We have finished theoretical calculation and modeling on the folded patch antenna with coaxial line feed. But in order to verify the expected result, there is a good linearity between simulated resonance frequency shift and the strain, further more simulation is needed. In order to simplify the simulation, we made two assumptions. First, ignoring the deformation and the impact on the relative dielectric constant; second, assuming that the dielectric substrate, top copper and ground plane has the same strain during deformation process. The unit of strain is dimensionless, which is usually denoted as $\mu\varepsilon$ (micro strain). One $\mu\varepsilon$ means $1 \times 10^{-6}$ or 1 ppm (parts per million) relative change in length ($\Delta L$). The proportion of strain means $(L + \Delta L)/L$. Firstly, we do the tensile simulation on the strain sensing performance which strain range is from $10000\mu\varepsilon$ to $50000\mu\varepsilon$ (the range of $n$ is from 1.01 to 1.05). The tensile load is configured so that an approximately $10000\mu\varepsilon$ increment is achieved at each step. Figure 2 shows that power reflection coefficient under different strain changes is less than $-30$ dB. The attenuation is easy to be detected and it is one of the conditions to be strain sensor.

Then, we continue to do the tensile simulation on the sensing performance of longitudinal strain and transverse strain. We obtain the fitting curve of relationship between resonance frequency and strain from the simulation results. Figure 3 shows that sensing sensitivity in longitudinal strain is 17 bigger than that in transverse strain. So the relationship between resonance frequency and longitudinal can be used for strain measurement.

However, sensing sensitivity in the longitudinal strain is $-2.2091$, which is different from the approximate value $-2.45$. Therefore we improve the maximum number of passes in the HFSS and perform the simulation again. We then get the new curve of relationship between the resonance frequency and the longitudinal strain. The sensing sensitivity is $-2.4$ which is similar to the approximate value.

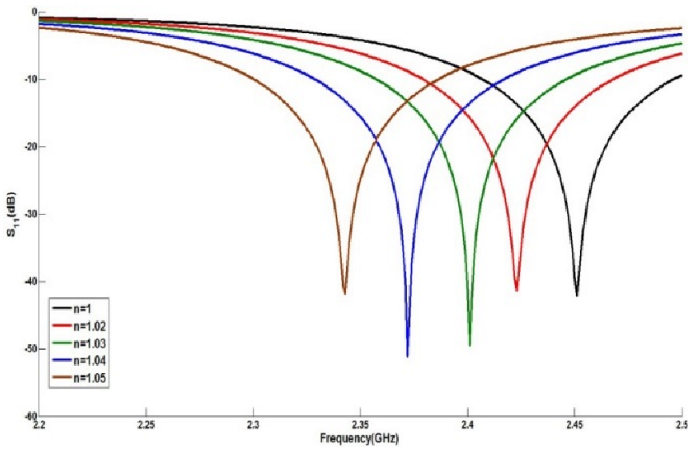


Figure 2. Normalized resonance frequency change $\Delta f_{res}$ versus strain $\varepsilon_L$.

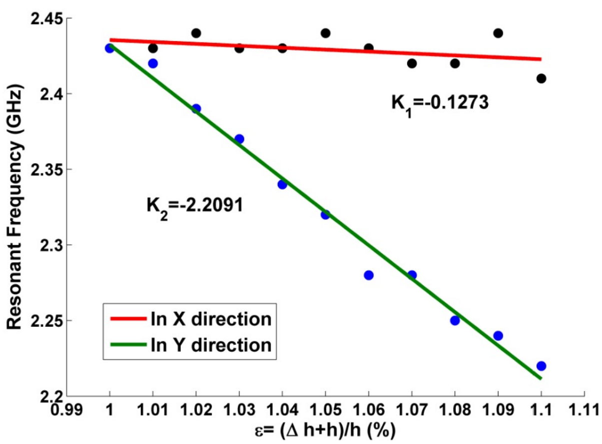


Figure 3. Sensing sensitivity in longitudinal strain and transverse strain.

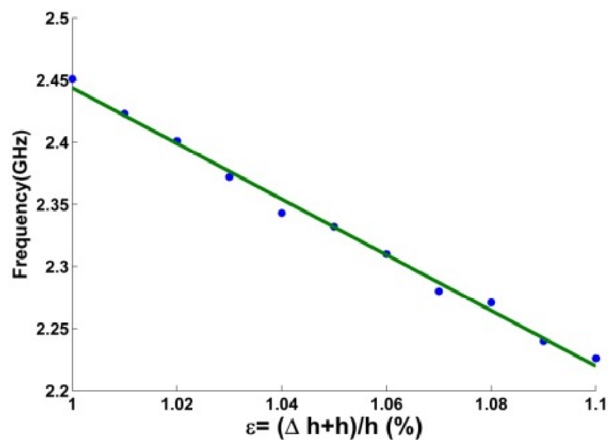


Figure 4. Sensing sensitivity in longitudinal strain and transverse strain.

## 5. CONCLUSION

In this paper, we have developed a technique on the passive wireless strain measurement. We first prove the possibility that a folded patch antenna can be used as a strain sensor and then design such an antenna with a coaxial line feed to measure the deformation. We then conduct a systematic simulation with the HFSS to figure out the relationship between the applied strain value and the resonance frequency shift. It is found that the relationship is roughly linear within a certain range and a bigger strain value will lead to a higher resonance frequency and a better sensing sensitivity. With the relationship, we design a measurement system to monitor the deformation of bridge structures.

### REFERENCES

1. Sohn, H., C. R. Farrar, F. M. Hemez, D. D. Shunk, D. W. Stinemates, and B. R. Nadler, "A review of structural health monitoring literature," Los Alamos National Laboratory, NM Report No. LA-13976-MS, 1996–2001.
2. Lynch, J. P. and K. J. Loh, "A summary review of wireless sensors and sensor networks for structural health monitoring," Vol. 38, 91–130, Shock Vib Digest, 2006.
3. Mohammad, I., V. Gowda, H. Zhai, et al., "Detecting crack orientation using patch antenna sensors," *Meas. Sci. Technol.*, Vol. 23, 015102, 2012, doi:10.1088/0957-0233/23/1/015102.
4. Lee, H., K. Naishadham, M. M. Tentzeris, et al., "A novel highly-sensitive antenna-based 'smart skin' gas sensor utilizing carbon nanotubes and inkjet printing," *2011 IEEE International Symposium on Antennas and Propagation (APSURSI)*, 1593–1596, IEEE, Spokane, 2011.

5. Thai, T. T., G. R. DeJean, and M. M. Tentzeris, "A novel front-end radio frequency pressure transducer based on a dual-band resonator for wireless sensing," *Microwave Symposium Digest, MTT'09. IEEE MTT-S International. Boston: IEEE*, 1701–1704, 2009.
6. Lee, H., G. Shaker, V. Lakafosis, et al., "Antenna-based 'smart skin' sensors for sustainable, wireless sensor networks," *Industrial Technology (ICIT), 2012 IEEE International Conference on. Athens: IEEE*, 189–193, 2012.