Circular Microstrip Patch Antenna Strain Sensor for Wireless Structural Health Monitoring

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***Abstract*—In this paper the feasibility of using a circular microstrip patch antenna to detect strain has been investigated. The theoretical model shows a linear relationship between strain and the shift in the resonant frequency of the antenna. A circular patch antenna has been designed and fabricated to work at 1.5GHz. Both Finite Element Analysis (FEA) and experimental tests have been undertaken to corroborate the relationship between strain and frequency shift. The ultimate intention of this work is to configure antennas or resonators for the detection of relatively small damage zones in structures and to do so wirelessly.**

***Index Terms*—Microstrip Antenna, Structural Health Monitoring, Strain Sensor, Wireless Sensor.**

I. Nomenclature

a	radius of microstrip patch antenna
a_e	effective radius of microstrip patch antenna
a_{es}	effective radius of microstrip patch antenna after applying strain
c	speed of light in free space
c_1	constant number one
c_2	constant number two
f_r	resonant frequency of antenna
f_{rs}	resonant frequency of antenna after applying strain
h	thickness of antenna substrate
t	thickness of microstrip patch antenna
TM_{110}	dominant transverse magnetic mode of a circular microstrip patch antenna
ε	strain
ε_0	permittivity in free space
ε_r	relative permittivity of antenna substrate
μ_0	permeability of free space
∇f	shift in resonant frequency

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II. Introduction

The need for a structural health monitoring (SHM) system which could be more reliable and accurate to locate the damage in structure and specify its size and location still exists. Ideally such an in-situ monitoring system should be smart and functional while the structure is in service to alert the operator of the early stages of damage.

Staszewski in [1], states that none of the damage monitoring techniques will alone be capable of meeting all the specification requirements for monitoring aerospace structures. Even if all the benefits of the existing methods are considered, there are still major issues to be solved. These techniques are costly, complicated, in some cases they need complex signal processing and require advanced technology for manufacturing them, and could not locate initial damage in all cases. Most importantly, all the techniques mentioned above use wired sensors. These sensors have many disadvantages such as the need for installation during construction. The initial setup and cabling of sensors is a very time consuming process especially when the number of sensors increases. Wires also limit the structures' functionality, add more complexity to it and increase the weight of the structure. Therefore, the number of sensors that could be applied is limited [2]–[4]. Hence, a structural health monitoring system able to work wirelessly is required to achieve a comprehensive and practical monitoring technology.

Wireless sensors can eliminate the wiring problem of the traditional SHM systems and reduce the maintenance costs associated with it [5]–[7]. Wiring is especially difficult for rotating composite components such as helicopter blades, rotor shafts, and wind turbine blades. A wireless sensor reduces the weight of the structure and its complexity.

Most of the work in the literature investigates the feasibility of applying a wireless communication device to existing sensors to transfer information or power to and from sensors in different disciplines such as civil industry [8]–[11], and medical applications [12]–[15].

Although a substantial amount of work has been done regarding wireless sensors and their applications in SHM, all these technologies have major problems. These drawbacks include the need for a battery which has a limited life time, need for a separate sensor and antenna which increases the complexity, size and weight of the sensory unit, need for a costly technology to fabricate sensor nodes which make them costly, and finally need for a wireless sensor network which need complicated software and data acquisition units.

In [16], the electrical conductivity of carbon fibre has been used to model a structure as a dipole antenna and therefore the presence of damage and its location could be identified wirelessly. However, this innovative approach is able to detect one type of damage and only in lateral direction when the crack has already reached a critical length, after which catastrophic failure is unavoidable. In addition, these techniques could only be applied to one type of material and their damage detection capabilities are limited.

Recent work has shown the effect of different parameters on the resonant frequency of microstrip patch antennas [14], [17]–[22]. A meta-material based wireless strain sensor consisting of an array of split ring resonators has been proposed recently [23]. This sensor is suitable for medical applications where the short distance between sensor and receiver is not a problem. However, for industrial applications such as SHM the effect of distance from reader, and the ability to locate larger strains makes it impractical.

Tata in [24] shows that rectangular microstrip patch antennas could be used not only for communication between sensor and receiver, but also, as a strain sensor itself. However, it assumes that the Poisson's ratio of the antennas' substrate and patch metal are the same. The designed antenna needs to work in two different frequencies and only detects strain in two directions while a circularly polarized circular patch antenna could be able to detect strain regardless of its direction.

In this work the relationship between strain and the resonant frequency of a circular microstrip patch antenna has been investigated. A linear relationship has been derived from theoretical formulas and experimental studies and finite element analysis prove this concept. It has been shown that strain could be detected using a circular patch antenna and therefore could be detected wirelessly.

III. Analitical Model

In recent years microstrip antennas have been widely used in microwave frequencies and have been integrated in many electronic devices [19], [25]. This popularity is because of their compact and adaptable size, inexpensive printed circuit board technology, and ease of integration with related electronics [25]. A typical circular microstrip patch antenna is shown in Fig 1.

According to [26] the resonant frequency of a circular patch antenna with the radius of a , and substrate thickness of h and relative permittivity of ε_r , in its dominant mode (TM_{110}) is:

$$(f_r)_{110} = \frac{1.2412c}{2\pi a_e\sqrt{\varepsilon_r}} \qquad (1)$$

Where

$$c = \frac{1}{\sqrt{\mu_0\varepsilon_0}} \qquad (2)$$

&

$$a_e = a\left\{1+\frac{2h}{\pi a\varepsilon_r}\left[\ln(\frac{\pi a}{2h})+1.7726\right]\right\}^{1/2} \qquad (3),$$

is the effective radius of antenna.

If we consider that $\varepsilon^{1/2} << \varepsilon$ then we could conclude that after applying tensile strain the following statement does not change significantly and therefore could be considered constant:

$$\left\{1+\frac{2h}{\pi a\varepsilon_r}\left[\ln(\frac{\pi a}{2h})+1.7726\right]\right\}^{1/2} = c_1 \qquad (4)$$

Thus, from (3) and (4)

$$a_e = c_1 a \qquad (5)$$

And from (1)

$$f_r = \frac{c_2}{a_e} \qquad (6)$$

Where

$$c_2 = \frac{1.2412c}{2\pi\sqrt{\varepsilon_r}} \qquad (7)$$

After applying strain, effective radius of antenna is:

$$a_{es} = a_e(1+\varepsilon) \qquad (8)$$

Thus, from (6) and (8) resonant frequency of antenna is:

$$f_{rs} = \frac{c_2}{a_{es}} = \frac{c_2}{a_e(1+\varepsilon)} \qquad (9)$$

Hence, the frequency shift is:

$$\nabla f = f_{rs} - f_r = \frac{c_2}{a_e}\left(\frac{1}{1+\varepsilon}-1\right) \qquad (10)$$

Thus,

$$\frac{\nabla f}{f_{rs}} = \left(\frac{\frac{1}{1+\varepsilon}-1}{\frac{1}{1+\varepsilon}}\right) = -\varepsilon \qquad (11)$$

As we can see the percentage of frequency shift has a linear relationship with strain. Without using the above assumption and by calculating resonant frequency using (1), (2), and (3) in MATLAB same results were obtained (Fig 2). The slope of line, however, is slightly different from (11).

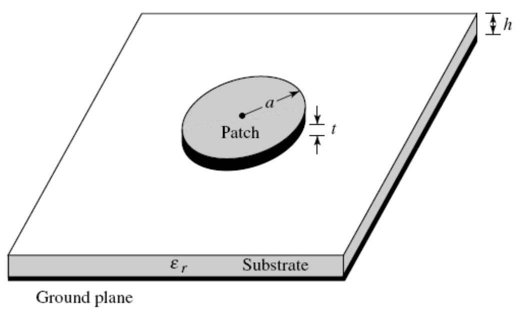

Fig 1 A typical circular microstrip patch antenna

These results are based on pure tension and with the assumption that the radius of the patch antenna changes in all directions with the same rate. To investigate the relationship between frequency shift and strain, the investigative steps shown below have been undertaken.

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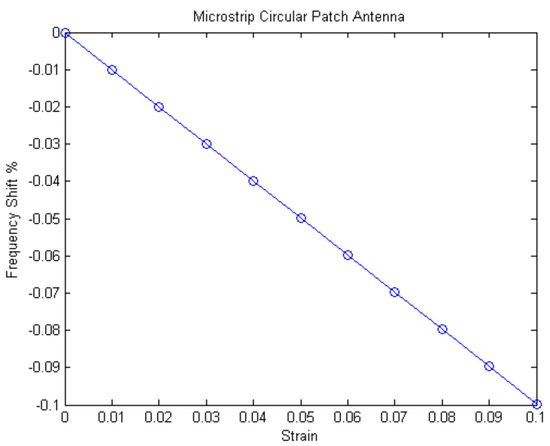

Fig 2 Linear relationship between frequency shift and strain

IV. Finite Element Analysis

Finite Element Analysis (FEA) reduces costs of experiments by simulating the actual conditions of the antenna under a 3-point bend test and helps predict the actual results. From various FEA packages available, ANSYS was chosen because of its ability to perform both structural and electromagnetic simulations. However, it is not possible to perform both analyses at the same time or even connect them to each other using basic tools in the software for high frequency electromagnetic analysis. In order to do both analyses at the same time a program using ANSYS parametric design language and FORTRAN has been written, thus enabling the coupling of structural and high frequency electromagnetic analyses.

The antenna structure and the plate behind it have been modelled using SOLID186 element for bending simulation. After structural analysis, HF120 element has been used for frequency sweep of the antenna in the region of 1GHz to 2GHz. In order to reduce the simulation time and computational domain, half of the structure has been modelled due to mechanical and electromagnetic symmetry of the structure. Figs 3 & 4 show strain distribution on the assembly and contour of electric field after 10mm displacement, respectively. Adaptive meshing could not be used with HF120 element; therefore, different configurations were checked to achieve the best mesh for both analyses. In the electromagnetic analysis PML (Perfectly matched layer) elements were used to model the radiation boundary and minimize computational domain. The assembly was subjected to a 3-point bend configuration. The maximum central plate deformation was 10mm with an increment of 0.5mm load steps and strain and the scattering parameter (S_{11}) of the antenna was derived.

V. Experimental Validation

A circular microstrip patch antenna has been designed and fabricated to work at 1.5GHz. The antenna is made of FR4 substrate with the thickness of 1.5mm. The antenna is fed with a coaxial probe which acts as a 50 ohm matched load. The antenna was attached to an aluminum plate to detect the strain. In order to attach the antenna to the plate, a 2cm hole has been drilled in the centre of aluminum plate; therefore, two strain gauges attached to the back of the plate in each direction in order to obtain the strain in the near and far field zones (Fig 5).

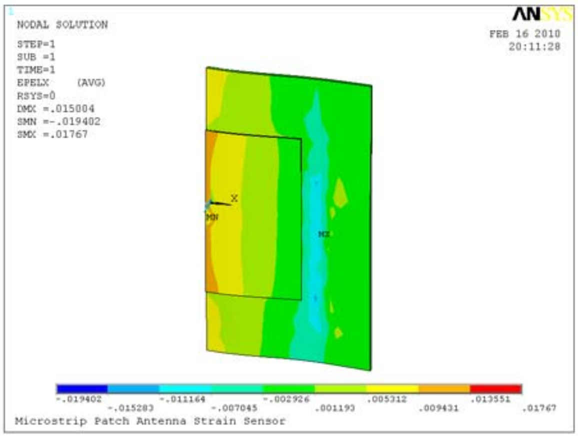

Fig 3 Contour of strain after 10mm displacement at the center of aluminum plate (half of the structure is modeled)

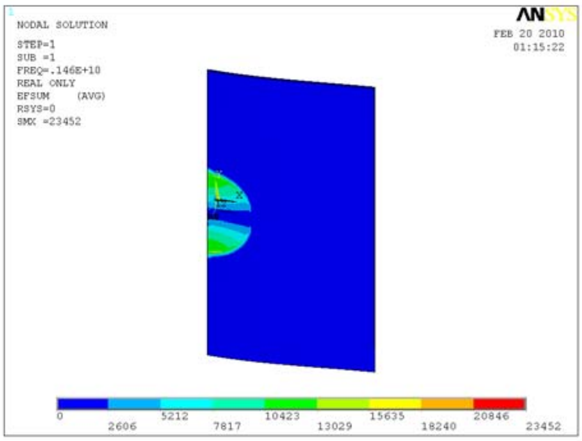

Fig 4 Contour of electric field magnitude 10mm displacement at the center of aluminum plate (half of the structure is modeled)

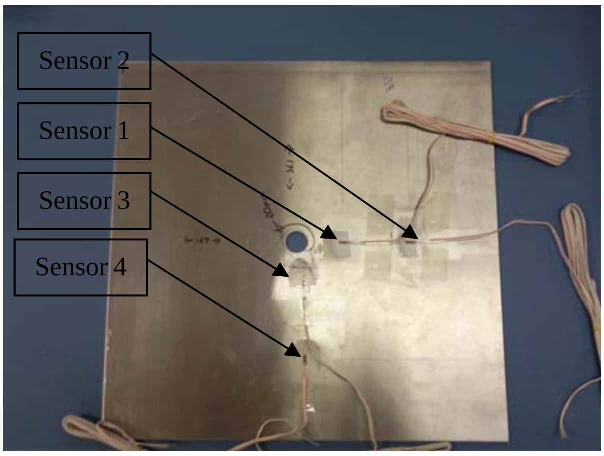

Fig 5 A 35cm×35cm aluminum plate, strain gauged for strain measurement

The assembly has been placed on a 50kN test machine for a 3 point bend test. In order to avoid contact of the antenna with the metal jig and reduce the effect of metal material close to antenna a wooden jig has been designed and fabricated. Fig 6 shows the final setup including a network

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analyser which was used to measure the antennas S_{11}.

The assembly was bent up to 10mm (central axis of the plate) in 0.5mm steps and in each step strain and S_{11} of antenna was measured.

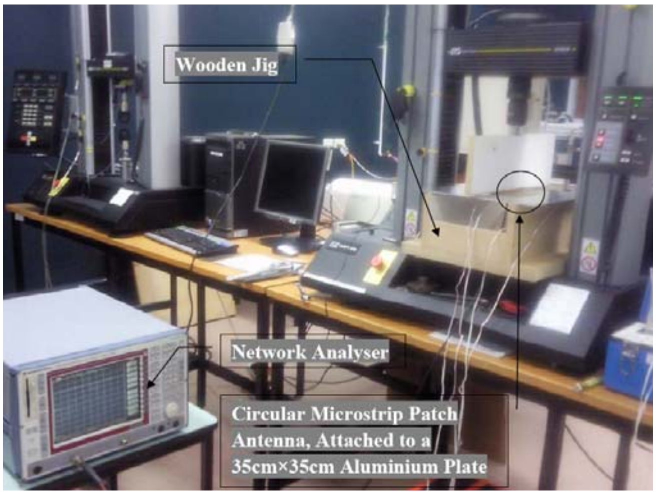

Fig 6 Final setup for the 3-point bend test

VI. Results

The results derived from experimental study and FEA are illustrated below which shows a linear relationship between strain and frequency shift. Both experimental and FEA results confirm the analytical formulations. A clear shift in resonant frequency of the antenna is achieved which is shown in Fig 7. The experimental relationship between strain and frequency shift in comparison with Theoretical Model (11) and FEA results are shown in Figs 8 & 9, respectively. Both theoretical model and FEA show good agreement with experimental results. There is general agreement up to about 0.0015 μstrain between the theoretical, analytical and computational results. The reason for the non-linear deviation of the FEA and experimental results after 0.0015 μstrain in Fig 9 is presently unclear.

The difference between experimental results and FEA results with analytical formulation is because of the difference in bending and pure tension and also is because of the assumptions made in theory such as pure tension.

Information derived from different strain gauges shows that the intensity of the strain is directly related to the slope of the line (Fig 10). This could be used to detect the intensity of strain in addition to its existence.

Finally, the feasibility of detecting strain using a circular microstrip patch antenna has been shown using theoretical studies, experimental results, and finite element analysis. A miniature microstrip patch antenna could detect strain and possibly damage in the structure with more accuracy because a small strain will make a bigger shift in the resonant frequency of the antenna. It seems that an array of antennas or meta-materials has the potential to detect damage wirelessly for in-situ health monitoring. As a result weight, cost and complexity of the SHM system could be decreased. Therefore, more sensors could be embedded in a structure which results in a better performance and increases the reliability of the monitoring system.

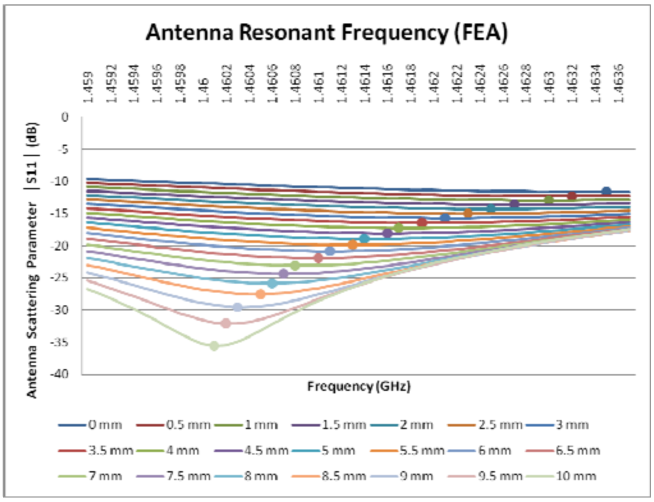

Fig 7 FEA results of antenna scattering parameter $|S_{11}|$ in 0.5mm steps of bending

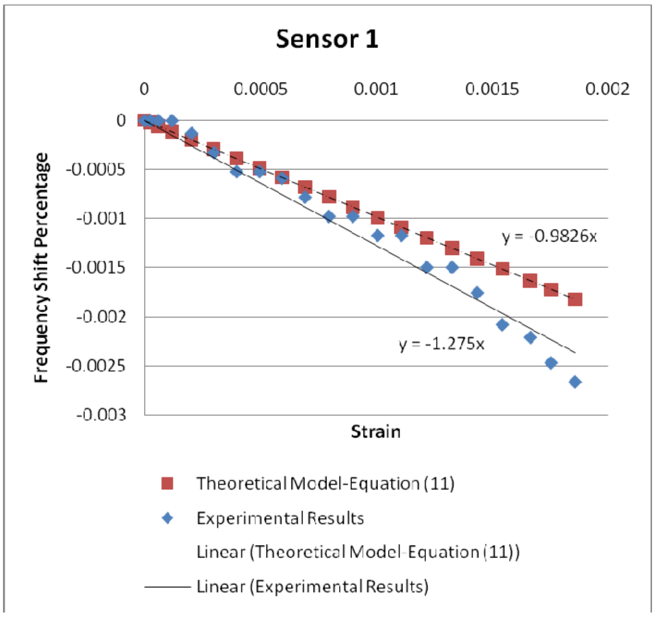

Fig 8 Comparison of measured and theoretical results of strain (at the location of sensor 1) and frequency shift

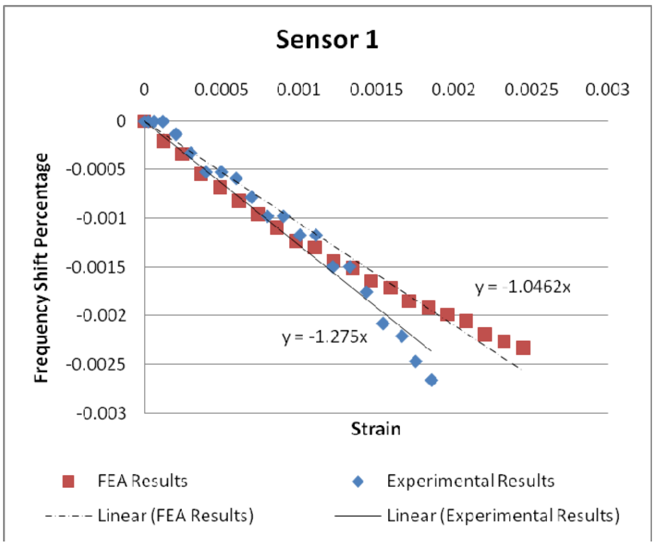

Fig 9 Comparison of measured and FEA results of strain (at the location of sensor 1) and frequency shift

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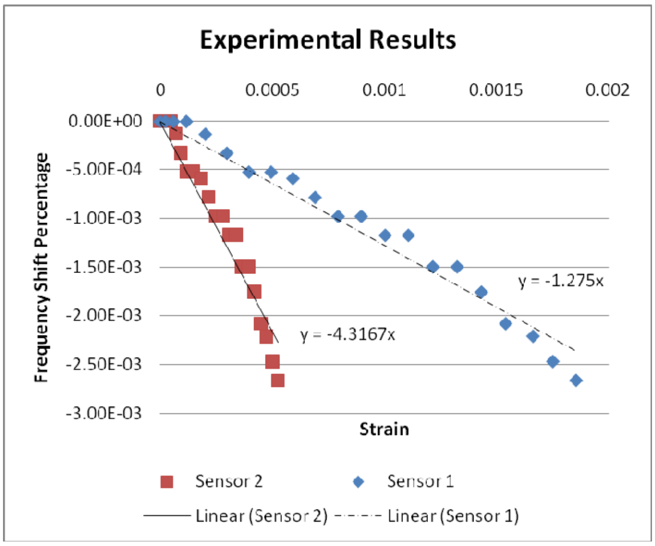

Fig 10 Test results of strain and frequency shift (Sensor 1 is close to the hole in the plate, and sensor 2 is in the middle of the plate)

VII. Conclusion

The relationship between the shift of the resonant frequency of a circular microstrip patch antenna and the strain applied to the antenna discussed in theory has been compared. As seen in Figs 8 & 9, there is general agreement up to about 0.0015 μstrain between the theoretical, analytical and computational results. The reason for the deviation of the FEA and experimental results after 0.0015 μstrain in Fig 9 is presently unclear.

The formulation derived shows a linear relationship between strain and frequency shift. To evaluate this linear relationship, a FEA simulation by ANSYS software was performed. The connection between structural analysis and electromagnetic analysis was achieved using ANSYS APDL and FORTRAN. The simulation was based on a 3-point bend test of the microstrip patch antenna attached to an aluminum plate. Finally, an antenna was designed and fabricated to work at 1.5 GHz and tested under the same conditions of the FEA simulation.

Both FEA and measured results showed reasonable agreement with theoretical results which confirmed the feasibility of using a circular patch antenna to detect strain. This antenna sensor could be further developed for wireless SHM applications. A wireless sensor could eliminate the use of wires in SHM applications and therefore decrease the complexity and weight of the sensory unit. This also increases the reliability of the SHM system because wires inherently increase the potential disconnection points in a wired sensory network. The antenna sensor also has an advantage over available wireless sensors by obviating the need for a battery.

VIII. Future Work

The relationship between different types of damage and specific antenna types will be investigated. The challenge in this field is the determination of the smallest damage zone (relative to the size of the structure) that is detectable using this technique. Finally, depending on the results from this challenge to detect relatively small damage zones, the wireless aspect of this project will be investigated.

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