Slotted Circular Microstrip Patch Antenna Application in Strain Based Structural Health Monitoring

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Abstract

In this paper, the effect of a rectangular slot on the sensitivity of circular microstrip patch antenna strain sensors is investigated. Theoretical studies, experimental tests, and Finite Element Analysis (FEA) show that circular microstrip patch antennas are capable to detect and measure strain. A slotted circular microstrip patch antenna could increase the sensitivity of the antenna sensor three-fold. In order to investigate the effect of slot in the patch antenna both FEA and experimental tests are considered. Antenna sensor is tested under 3-Point bend test and simulated using two established proprietary packages. The effect of aluminium and carbon fibre materials and direction of bending on sensitivity of the antenna sensor is also investigated. Based on the results obtained, the antenna sensor can be recommended for use in structural health monitoring for strain-based damage detection in aerospace structures.

Keywords: Circular Patch Antenna, Strain Sensor, Structural Health Monitoring

Introduction

The use of composite materials in aerospace structures is increasing every day. Mechanical properties of these materials which results in light weight-structures attracts aerospace industries to apply them in commercial airplanes like BOEING 787 which more than half of its structure is made of composite materials. Apart from huge amount of work in the literature, there is still a gap in Structural Health Monitoring (SHM) systems for the detection of different types of defects in these materials.

One important part of any SHM system is the sensor which is used to detect the damage and is common in most of the techniques, where as the damage detection method is different from one system to another. Many of the sensors available for SHM are wired and therefore have practical limitations in order to be embedded into the structures, like strain gauges, piezoelectric transducers, fibre optic sensors, and micro-fibre composite actuators. On the other hand, wireless sensors currently available in the market use batteries as an energy source which has a limited lifetime and increases the sensor size and weight; therefore, could not be used widely in the structure. In some cases where the sensor receives its energy through an antenna the sensory unit is too complicated.

In recent years, there has been work reported to use carbon fibre conductivity to detect damage in composite structures and develop multifunctional composites [1]. While many of these works are based on measuring conductivity with wires, use of the whole carbon fibre

composite as a dipole antenna to wirelessly detect the crack in the structure has been reported [2]. However, this innovative approach is able to detect one type of damage and only in the 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.

Recently also, the effect of different parameters on the resonant frequency of microstrip patch antennas has been reported [3-5]. A meta-material based wireless strain sensor consisting of an array of split ring resonators has been proposed recently [6]. 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 [7] shows that rectangular microstrip patch antennas could be used not only for communication between sensor and receiver, but also, as a strain sensor. 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. Daliri in [8] uses circular microstrip patch antennas to detect strain in composite materials. It is showed that there is a linear relationship between strain and percentage of shift in antennas resonant frequency regardless of the materials used for antenna manufacturing. This antenna sensor is capable to detect strain in carbon fibre composites as well as aluminium; however, the shift in the resonant frequency of the antenna is 100 KHz for every step of loading.

In order to make the antenna sensor more sensitive a new circular microstrip patch antenna with a rectangular slot in the middle of the patch is proposed in this work. The presence of the slot in the patch antenna introduces a new resonant frequency above the second resonant frequency of the patch. This new antenna sensor is 3 times more sensitive to strain than the initial sensor which makes detecting the strain easier and therefore more suitable for SHM applications. In the following sections of this paper Finite Element Analysis (FEA) and experimental tests are described where as the results are discussed in the results section.

Antenna Design and Finite Element Analysis

In order to design the antenna sensor with a slot in the middle of the circular patch the HFSS software is used because of its capabilities in high frequency electromagnetic analysis for antennas such as adaptive meshing and different types of frequency sweep. The optimisation feature of the software is used to find the best length and width of the slot; therefore, a very narrow resonance for the slot is designed. The location of the feed point is selected for the best impedance matching of the slot resonant frequency rather than the patch frequency. The final dimensions of the designed antenna are shown in Fig. 1. The simulated resonant frequency of the antenna is illustrated in Fig. 2.

After the antenna was designed in order to optimise the design for strain sensitivity and also to avoid inordinate experiment-based costs and time in the future, the antenna is simulated using two commercial software packages. ANSYS software is used for structural analysis while HFSS software is used for high frequency electromagnetic analysis. In previously reported work, ANSYS software was used for both types of analyses by performing coupled field analysis with the help of FORTRAN software. However, because the adaptive meshing

capability in the HFSS software is more powerful and could be used in antenna design, the combination of ANSYS and HFSS is used in this work.

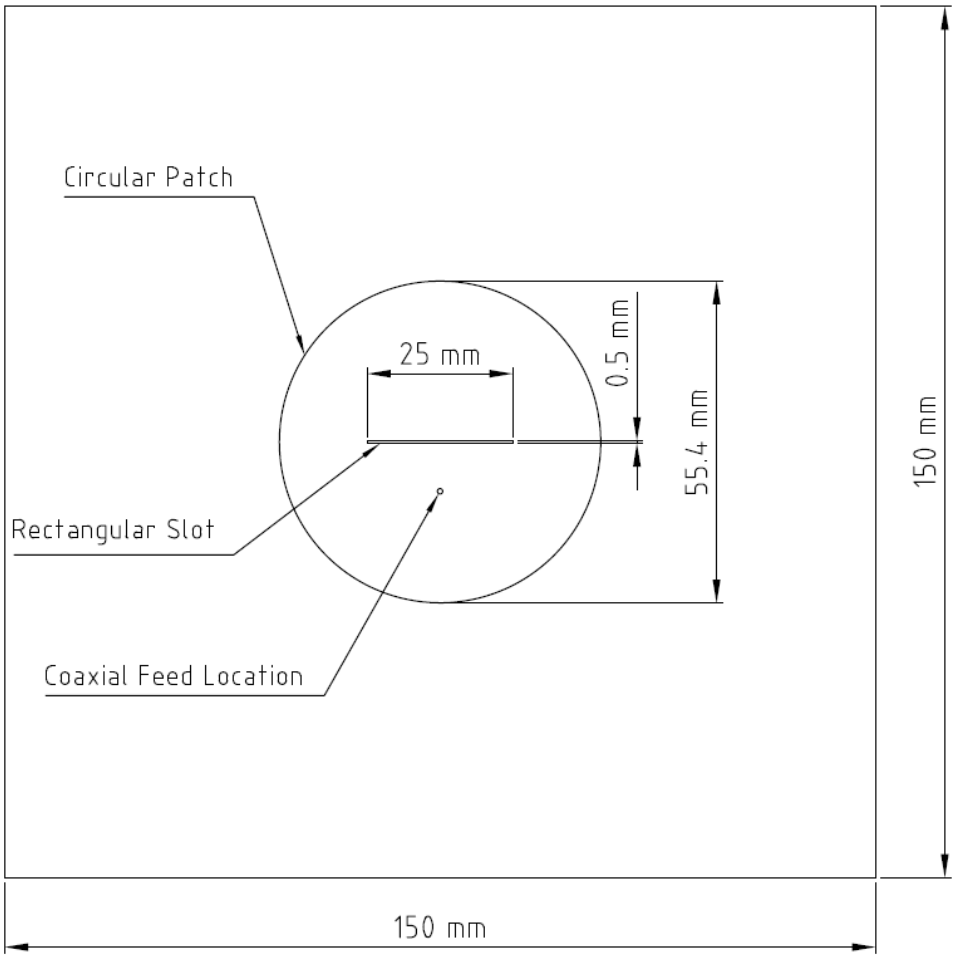


Fig. 1: Dimensions of slotted circular microstrip patch antenna

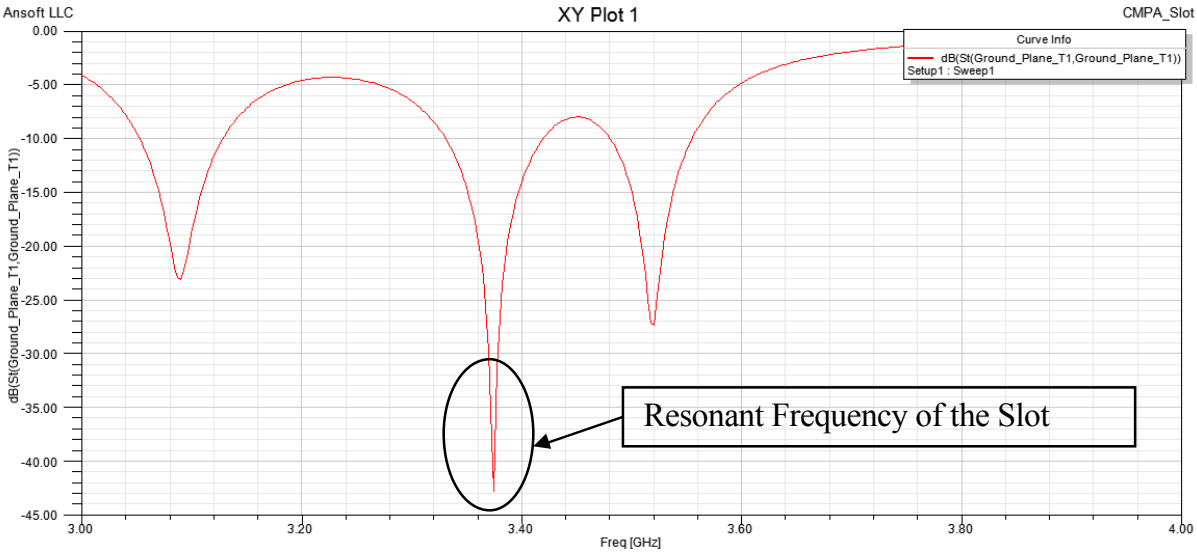


Fig. 2: Simulated resonant frequency of the slotted circular microstrip patch antenna

First, the antenna is simulated with the ANSYS software under 3-point bend loading, similar to that used in experimental tests. The antenna is attached to an aluminium plate for FEA and is bent up to 10 mm in 5 mm steps of displacement. After extracting strain in four locations according to location of strain gauges attached to test plates after each step of bending, the deformed shape of the antenna is transferred to ANSYS Finite Element Modeller to be saved as a Parasolid format. Fig. 3 depicts the strain distribution in the antenna and aluminium plate after the 10 mm bend.

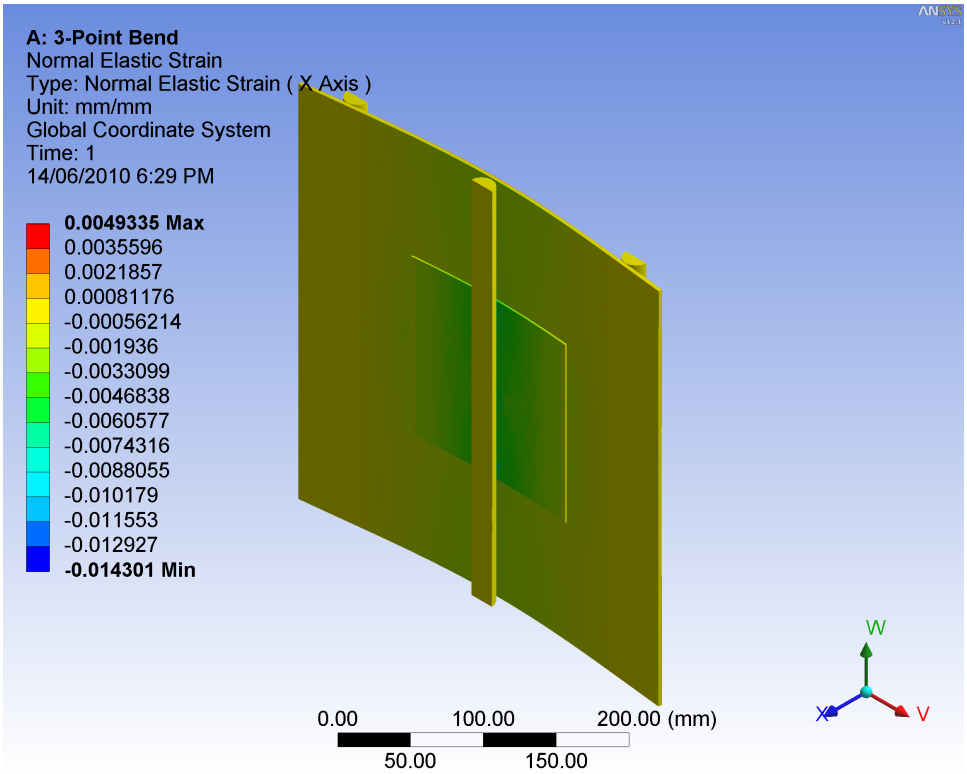


Fig. 3: Contour of elastic strain in antenna sensor attached to an aluminium plate after the 10 mm bend

Then the deformed shape of the antenna is imported into HFSS software where additional air layers and PML elements are added to the model. Finally, the antenna was simulated in HFSS to obtain the resonant frequency of the antenna. In order to see the shift in the resonant frequency a very fine mesh and very strict settings should be used in HFSS. The transferred deformed shape of the slotted antenna in HFSS software is shown in Fig. 4 where air box and PML elements around the antenna are hidden for clarity.

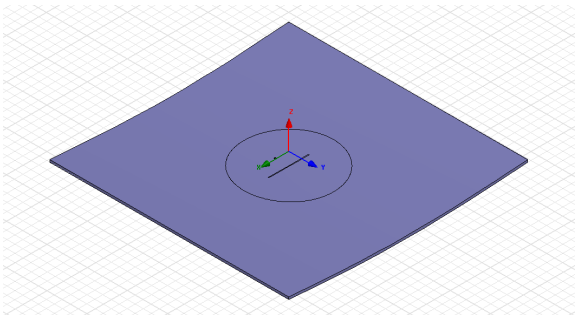


Fig. 4: Transferred deformed shape of the antenna sensor in HFSS software

Experimental Validation

In order to validate the FEA results the designed slotted circular microstrip patch antenna is manufactured using standard PCB photolithography process. The substrate material used for the antenna sensor is the commercial FR4 Epoxy with permittivity of 4.4 and the thickness of 1.5 mm. The operating frequency of the circular patch is 1.5 GHz while the operating frequency of the slot is 3.4 GHz. After the antenna is fabricated it is attached to a carbon fibre plate and an aluminium plate with the dimensions of 35 cm × 35 cm and the thickness of 3 mm (Fig. 5). Four strain gauges are attached to the back of each plate to measure strain in two directions both close to the central hole of the plate and far from it (Fig. 6).

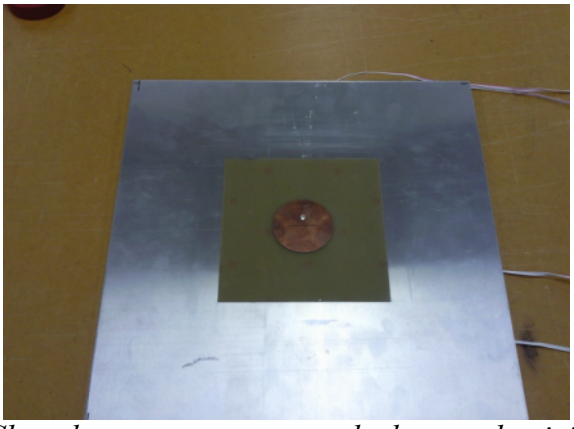


Fig. 5: Slotted antenna sensor attached to an aluminium plate

After preparing the samples they are placed on a wooden jig for 3-point bend test. The wooden jig was used in order to avoid the contact between the antenna and metal. In addition a rectangular slot is cut in the middle of the wooden jig to avoid the effect of wood on the resonant frequency of the slotted patch. Then plates with antenna sensor on top were bent up to 10 mm in steps of 0.5 mm in displacement using a 50 KN INSTRON machine. The plates are bent in both 0° and 90° to investigate the effect of strain on the frequency when the maximum strain is in the direction of slot length and sloth width, respectively.

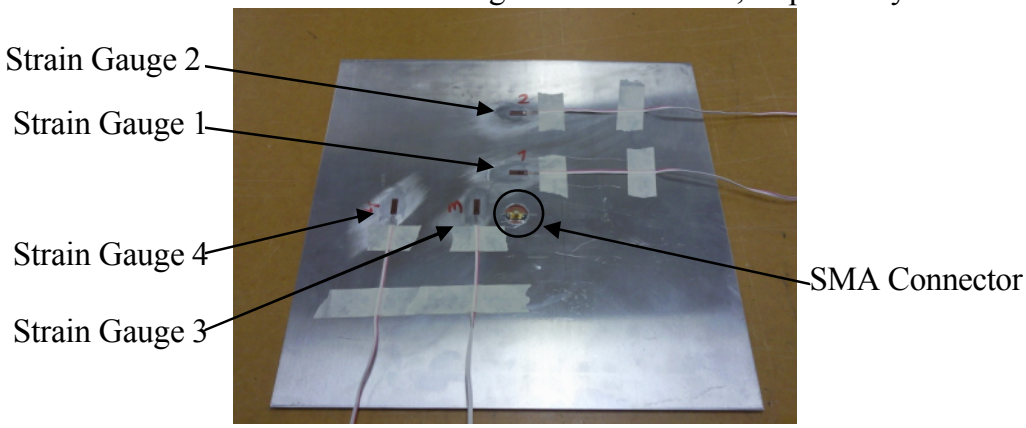


Fig. 6: Strain gauges locations at the back of aluminium plate

After each step of bending the resonant frequency of the antenna is measured using a vector network analyser in the form of antenna scattering parameter (|S11|) where as the strain data from strain gauges is collected separately. The antenna sensor is connected to the network analyser by a 50 ohm coaxial cable through an SMA connector attached to the back of the

antenna. A 2 cm hole is drilled in the back of the plates to connect the coaxial cable to the SMA connector. The final setup of the test is shown in Fig. 7.

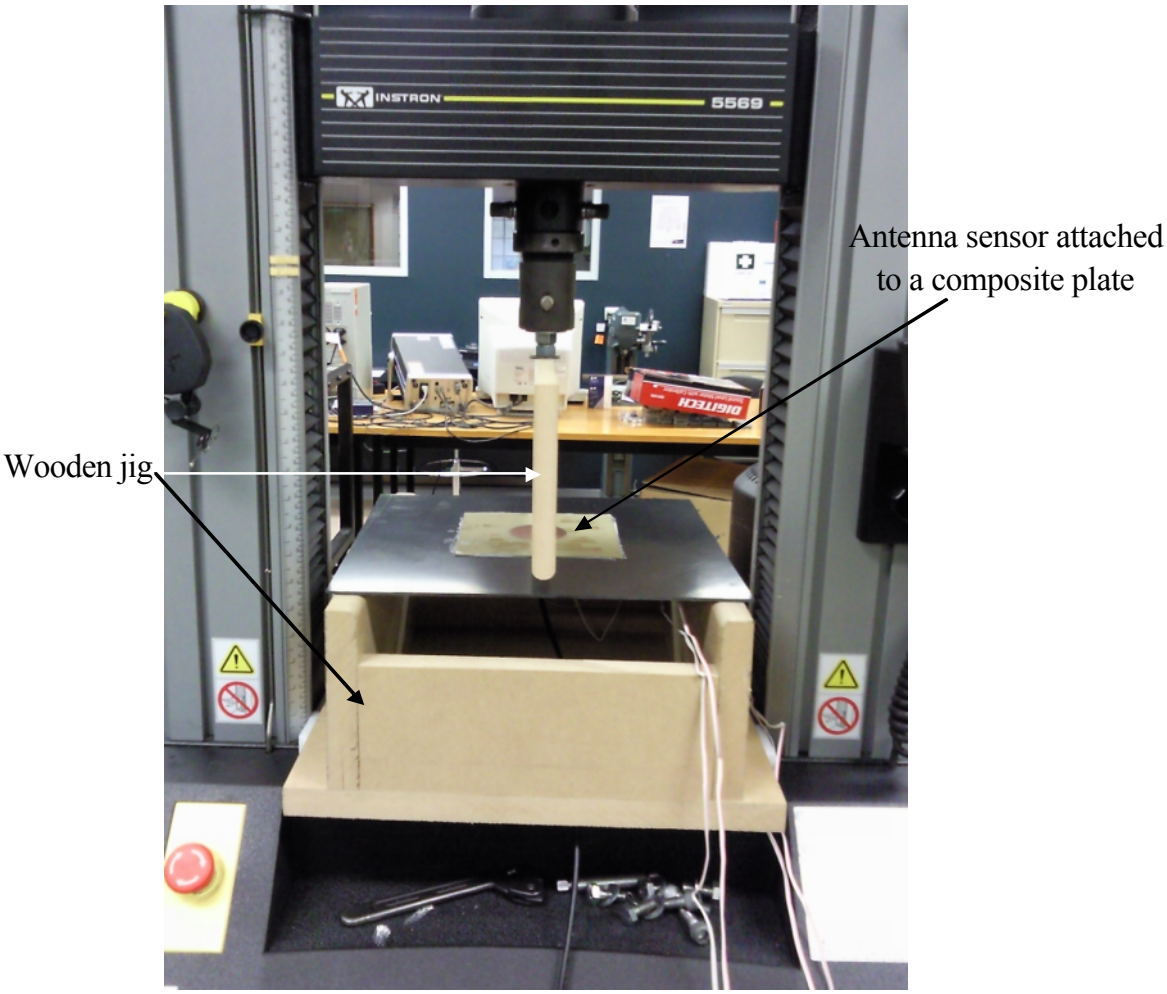


Fig. 7: Final setup for 3-point bend test (antenna attached to a composite plate)

Results and Discussion

The results derived from FEA and experiments are shown in the following figures. Here, the data from three steps (0 mm, 5 mm and 10 mm) of bending are used in order to compare FEA results with experimental results. The orientation of the 3-point bend configuration is the relative angle between the upper part of the wooden jig and the slot in the circular patch where 0° and 90° happen when the jig is perpendicular and parallel to the slot, respectively.

Fig. 8 shows the shift in the resonant frequency of the slot at different steps of loading where the antenna is attached to the aluminium plate and is bent in the 90° orientation. The total amount of shift after 10 mm bend is about 6 MHz in 90° and 3 MHz in 0° which are 3 and 1.5 times the amount of shift in the resonant frequency of a circular patch without the slot.

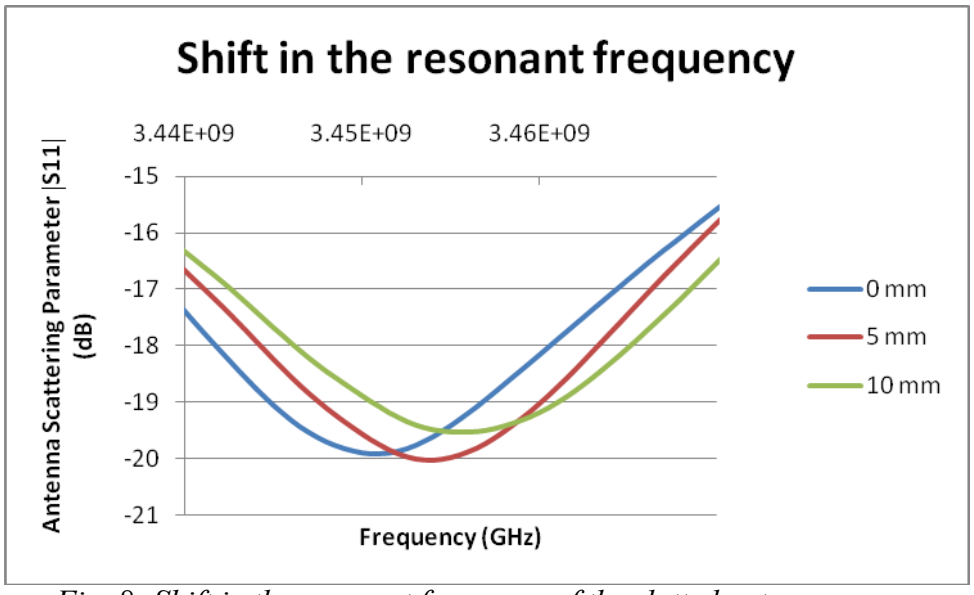


Fig. 8: Shift in the resonant frequency of the slotted antenna sensor

The percentage of the frequency shift for the carbon fibre plate and the aluminium plate are illustrated in Fig. 9 and Fig. 10, respectively where the effect of bending orientation is compared for each panel. For the carbon fibre panel the amount of shift in both 0° and 90° are the same up to 5 mm bend and two lines start to diverge from then. In the aluminium panel the slope of line related to 90° bend is higher which causes the two lines to be separated from the beginning. The reason for this difference is presumably because the slot frequency is known to be more sensitive to changes in its width rather than its length.

The comparison between the FEA results and experimental results are shown in Fig. 11 and Fig. 12. The FEA model is based on the antenna sensor attached to the aluminium plate. The results from both materials are in good agreement with FEA results where as the results from aluminium plate is closer to FEA results. The difference in the results of the carbon fibre plate can be accounted for given the micro-heterogeneity in the composite materials, which was not taken into account in the FEA model. The close comparison of the simulated and experimental results is essentially a validation of both techniques and particularly, the simulation technique used in this study. The consistent increase in the frequency shifts with strain from the simulated results (when compared with experimental results) might be accounted for by some of ideal conditions assumed with the simulations such as material dimension consistency and true material homogeneity.

When the plates are bent at the 0° orientation, the maximum strain is in the direction of gauges 1 and 2 and because strain gauge 1 is closer to the centre of the plate where a 2 cm hole is drilled in the plate it has the maximum strain. For the same reason when the bend is in 90° strain gauge 3 has the maximum strain. The comparison of results from different strain gauges in Fig. 13 and Fig. 14 shows that the slope of the line in the graph is directly related to the location of strain gauges. Therefore, the slope of the line can be used to measure strain in different locations of the plate, provided further experiments clarify their exact relationship.

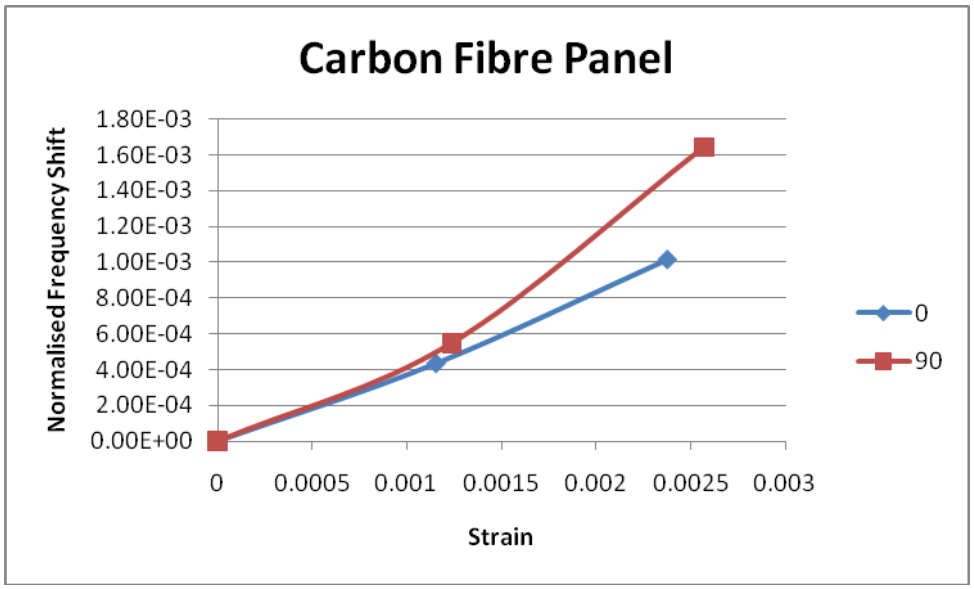


Fig. 9: Experimental strain-frequency shift relationship for carbon fibre panel (Strain gauge 1 at 0° orientation and strain gauge 3 at 90° orientation)

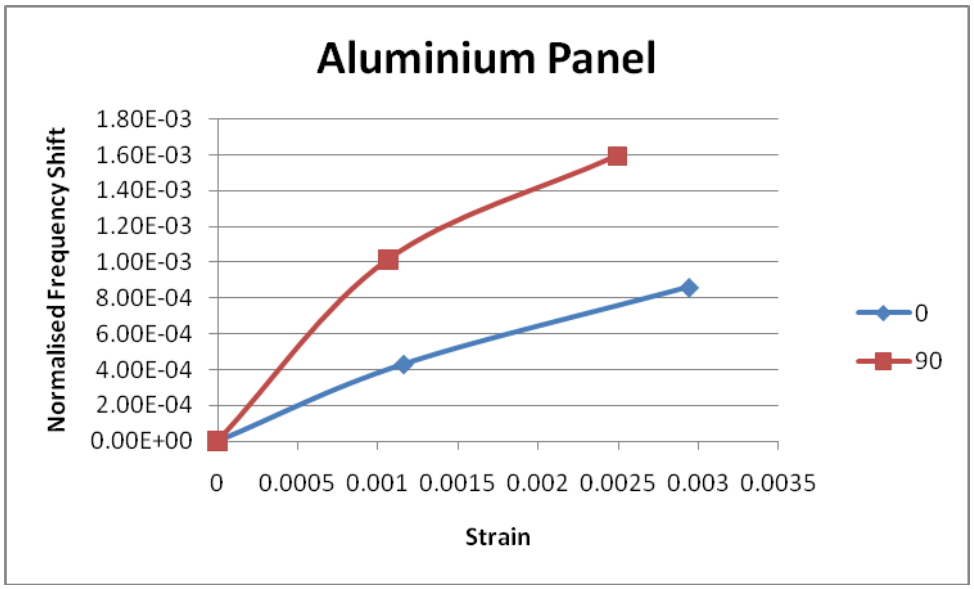


Fig. 10: Experimental Strain-frequency shift relationship for aluminium panel (Strain gauge 1 at 0°orientation and strain gauge 3 at 90° orientation)

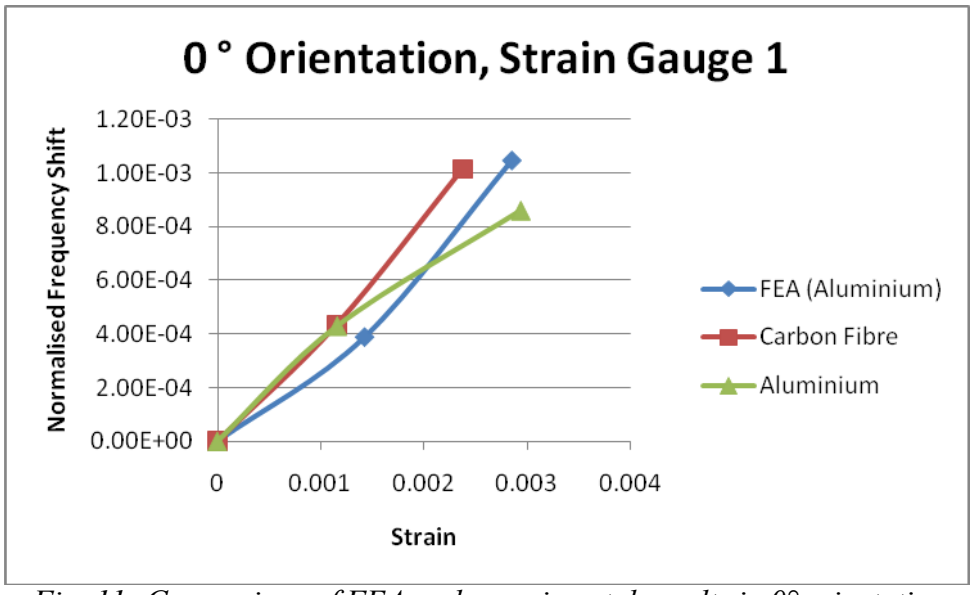


Fig. 11: Comparison of FEA and experimental results in 0° orientation

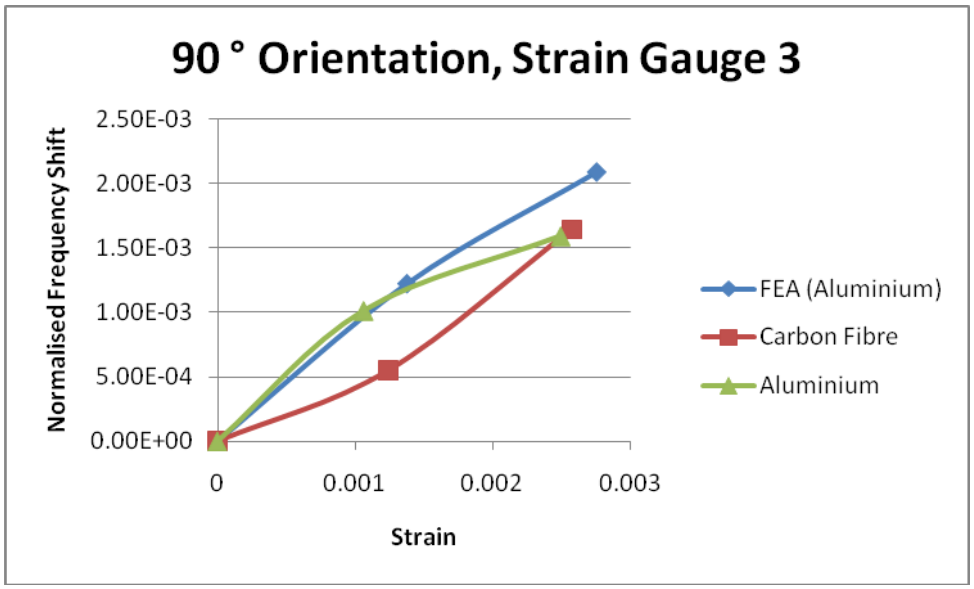


Fig. 12: Comparison of FEA and experimental results in 90° orientation

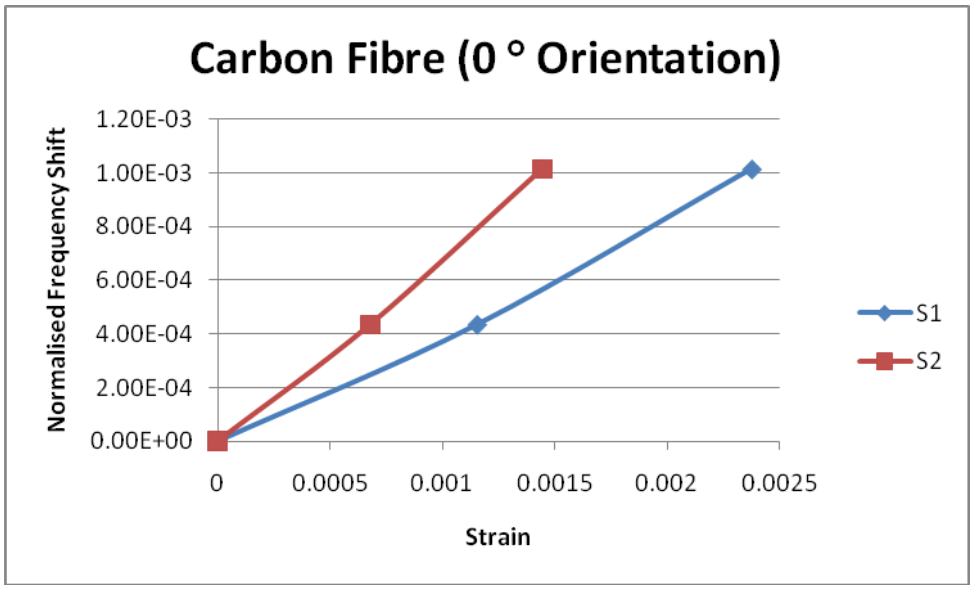


Fig. 13: Effect of strain intensity in 0° orientation

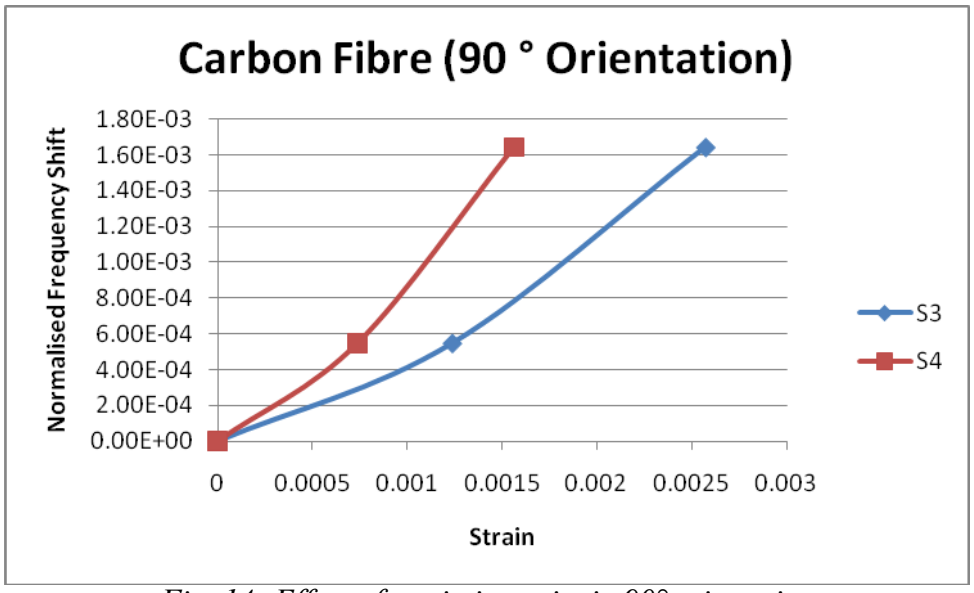


Fig. 14: Effect of strain intensity in 90° orientation

Conclusion

The new slotted circular microstrip patch antenna strain sensor proposed in this paper is 3 times more sensitive than previously proposed circular microstrip patch antennas. The effect of the slot in the patch makes strain measurement easier while the working frequency of the slot is more than double the frequency of the simple patch. The sensitivity of the antenna sensor depends on the relative direction of strain and slot length (or width). This could be used for detecting strain in different directions by using a combination of antenna sensors.

Both Finite Element Analysis and experimental results are in good agreement and show that the slotted patch is able of detecting strain in aluminium and carbon fibre composites. The FEA was successfully performed by combining two different commercial FEA packages (ANSYS and HFSS). This method of FEA could be used for further investigation on antenna sensitivity to strain and also for developing damage detection techniques.

This newly proposed antenna sensor could be used in structural health monitoring techniques and by further developments could be communicated wirelessly. 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 heighten weak points in a wired sensory network because of the need to connect these wires. The antenna sensor also has an advantage over available wireless sensors by obviating the need for a powered or battery source.

Future Work

To investigate the relationship between strain and the shift in resonant frequency of the antenna sensor different loading configurations should be studied. For example, by stretching the antenna the effect of the curvature in antenna will be eliminated. Also, the effect of wooden jig on the resonant frequency of the slotted antenna should be investigated by developing new experimental setups. The antenna should become more sensitive with physically smaller sizes to be able to detect localised strain and damage in the structure. Finally, wireless reading of strain using this type of sensors and system configuration will be studied.

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