DISTRIBUTED STRAIN SENSING IN COMPOSITE MATERIALS BY USING A CAPACITIVE SENSOR SHEET WITH CRAKED ELECTRODES.

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Abstract: *Distributed strain sensing, i.e., the ability to measure strains at different locations, has become especially important for detecting expected damage locations in structures. To date, monitoring distributed strain with high spatial resolution in composite structures is limited due to several technical limitations. Our solution is based on creating multiple sensing regions within the area of a single capacitive sensor body by considering the sensor as an analogical transmission line, reducing the connections to only two wires and simplifying the electronic interface. The proposed distributed sensor is a stretchable parallel-plate capacitor comprising two cracked electrodes separated by a dielectric layer. The piezoresistivity of the electrodes induces the transmission-line behavior in the entire sensor at radio frequencies. The transmission line behavior allows the sensing signal to be attenuated by high-resistance electrodes along the capacitive sensor's length. Different regions of the capacitive sensor can then be moitored by changing the sensing frequency and creating a virtual sensor length. Our system that allows free movements of deformable systems can be an alternative solution to detect local strain in composite materials without affecting their mechanical properties.*

Keywords: Monitoring Large structure, SHM, Distributed strain sensor, Transmission line, Cracked electrodes, Minimizing wiring

1. Introduction

Composite materials-based structures such as aircraft, composite pipes, gas tanks, and wind turbines deteriorate over time, resulting in unexpected failure when exposed to extreme loads. Moreover, lack of follow-up and maintenance can accelerate structural degradation, leading to shortened lifetimes. Consequently, monitoring composite structure is essential because localized degradations due to a high strain can propagate and lead to catastrophic effects [1]. However, composite materials' anisotropy and complex nature result in relatively unpredictable behavior, which makes monitoring composite structures more difficult than monitoring structures based on classical materials such as metal and concrete. Until today, The nondestructive testing tools (NDT) [2] are the most used techniques in the industrial market to analyze composite structures quality like visual inspection, radiography, and ultrasonic testing, but these methods are still very expensive and time-consuming [3]; in addition, they have some limitations in detecting barely visible damage in structures. Some cannot withstand harsh environments and are difficult to deploy over large structures or have a short lifespan.

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Earlier, structural health monitoring (SHM) came to assist in monitoring the structure and taking appropriate action before the catastrophic loss by integrating a real-time system in a decision framework. SHM provides techniques to observe and analyze a system over time to monitor changes to the material, which can be used to identify structural degradation and provide maintenance guidance so that early signs of damage prior to structural failure can be flagged. Several methods have been investigated for SHM applications, including capacitive and resistive strain gauges[4], accelerometers [5], passive acoustic sensors [6], *etc.* Moreover, classical strain monitoring-based methods [3], such as strain gauges, are also frequently used to analyze structures, as they have long demonstrated a high capacity to measure accurate strain in local areas. At a later stage, researchers have developed these electrical strain sensors from wires connected to wireless communications by including the strain gauges in electronic packaging that communicate with the interrogation system without wiring [7]. Some work has gone further by introducing a new model of sensors based on converting the sensor to an RFID tag with passive interaction where no direct power supply is required [8]. Furthermore, fiber Bragg grating (FBG) is a popular technique used in SHM for composite, especially for large-scale [9], but this technique still faces limitations such as intrusivity and the need for wired interrogation systems.

The development of reliable methods to monitor large structures remains one of the main challenges for multi-point and distributed sensing techniques. These methods should be able to detect the damage position even if it is not known with sufficient precision a priori with suitable physical and spatial resolution. Therefore, to effectively detect incidental damage in a structure of industrial complexity, a dense array of sensors distributed over the entire structure is a viable option. However, using traditional wired sensors is difficult due to the cost of deploying and maintaining a dense wired network. It has become preferable to use a network of remote sensors to cover a large area of what is known as wireless sensor networks (WSN) [10]. Over recent years, significant advances in the field WSN have produced innovative and powerful solutions, especially for damage detection in large composite structures [11]. WSNs are attractive because they offer increased robustness through decentralization,however, transferring all the measured information to a central station using wireless sensors is difficult because of power requirements and bandwidth limitations. Wireless data transfer is challenging, particularly if the sensors are embedded in anisotropic and conductive materials such as carbon fiber-reinforced polymer (CFRP). The electromagnetic shielding effect of this kind of material limits the wireless communication between the sensor and its acquisition system[12]. Therefore, to avoid electromagnetic shielding in composite structures, the industry has obligated, in some cases, to integrate a network of analog sensors wired to the central controller. In these systems, wiring sensors to a central node in a large structure is expensive and cumbersome; it may also be detrimental to system reliability as wires may be damaged and severed.

Based on the above remarks, reducing the high cost and complexity of the available methods is an essential requirement. It has become urgent to develop new and innovative methods to monitor large composites structures without losing a large part of the information by shielding or through wires. This paper describes our experience with a new distributed sensing system based on a transmission line model where we replace a network of local sensors with one sensor sheet. We demonstrate a distributed strain-measurement technique using a single-sheet capacitive sensor, which minimizes the quantity and complexity of wiring numbers where we are able with our technology to detect strain in multi-point of a large structure with one sensor body that operates only with two-wire. Building such a system aims to facilitate the transition to fully distributed SHM applications.

We describe in this paper the mechanism of the transmission line-based sensor and how to benefit from the signal dissipation in a capacitive sensor to localize the strain. We also present the evaluation results and discuss the possibility of using such a sensor to follow the strain location and magnitude. We finish with some perspectives concerning using this technology for the replacement of available distributed sensing methods.

2. Result and discussion

2.1 Strain localization by transmission line model

Our strategy is to use the transmission line model in a parallel plate capacitor (PPC) to replace a network of n local sensors with 2n wires with a one-sheet sensor with only two wires that can detect strain in multi-point, as shown in **Figure 1**.

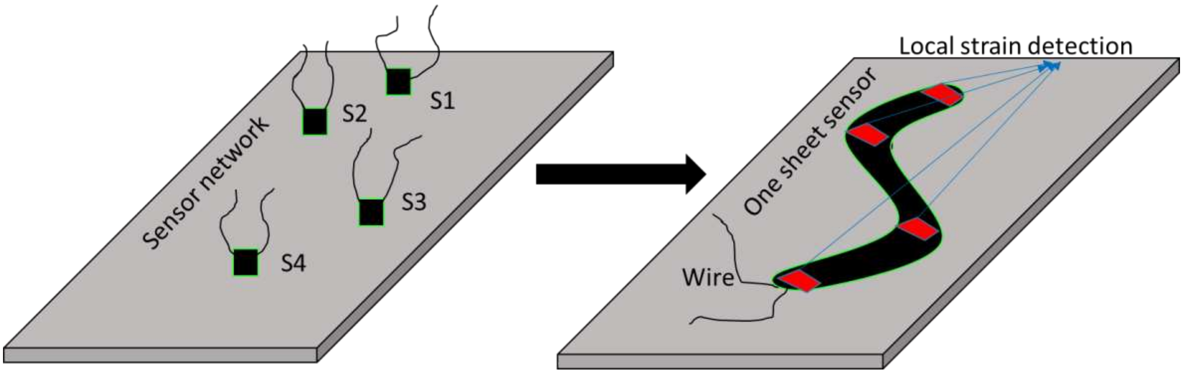

Figure 1. The transition from sensors network system to one sheet sensor While maintaining the same result with a lower number of sensor/wires, the sensor resolution is correlated to the number of red zones.

The transmission line model is frequently used in radio and telecommunications engineering to describe any physical structure that guides electromagnetic waves. A capacitor with relatively resistive electrodes is represented as distributed R–C chains at high frequencies, forming the transmission line model [13]. By creating piezoresistive electrodes in the PPC, we can guide the electromagnetic wave propagation in the PPC, which transforms into a distributed capacitive strain sensor. Some resistance in the electrodes attenuates the electromagnetic wave propagation in the sensor until it disappears before it reaches the end of the sensor. Based on the voltage dissipation mechanism resulting from the electrodes resistance variation, a virtual length (L_V) is created starting from the beginning of the sensor to the point where the signal is totally attenuated [14]. The total electromagnetic signal dissipation happens when the electrodes resistance (R) and/or the interrogation frequency (f) are relatively high [15]; injecting a high-frequency signal allows the whole signal attenuation even with low electrodes resistances. Furthermore, creating local resistance in a one-sheet PPC can drop the signal to the same level where a portion of the sensor is stretched **(Figure 2)**. Thus, the location of the strain can determine by measuring the total capacitance of the PPC and deduce than the level that reached the signal by the classical capacitance equation that links the geometric of the PPC by the capacitance,C, as follow:

$$L = \frac{Cd}{\varepsilon_0 \varepsilon_r \omega} \tag{1}$$

Where *L* is the length of the PPC that transforms to L_v in the transmission line model, d is the thickness of the dielectric materials and *w* is the width of the PPC , ε_0 and ε_r are the vacuum permittivity and the permittivity of the dielectric materials respectively.

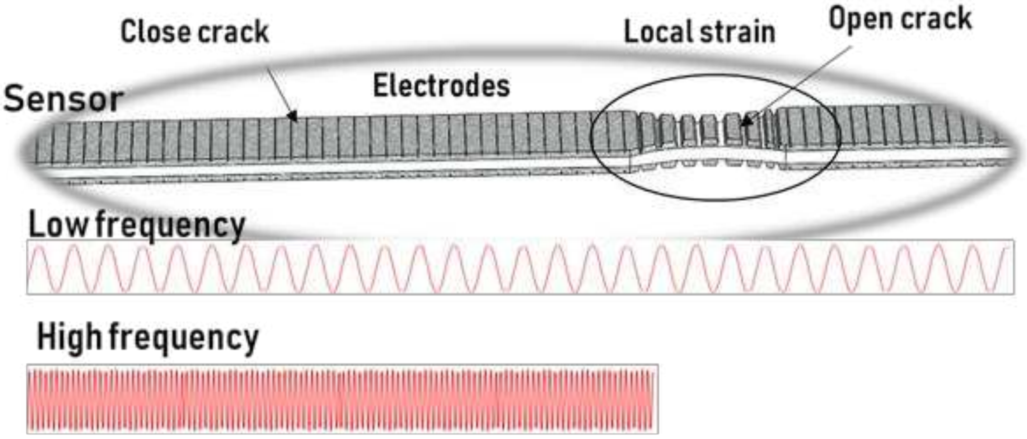

Figure 2: Schematic illustrates the mechanism of the capacitive sensor sheet with variable-resistance electrodes where a new virtual length is created at a high frequency after local deformation that changes the effective capacitance of the sensor.

In order to realize this mechanism, we fabricate a stretchable PPC with piezoresistive electrodes based on PDMS as dielectric materials and cracked carbon nanotube (CNT) paper as electrodes encapsulated on the top and bottom by PDMS layer **(Figure 3,a)**. The Fragmented CNT paper is well known for its excellent piezoresistivity, where we confirm previously an ultra-high resistive gauge factor (GF) of over 4.2 × 10^4 at 150% strain [16]. The significant change in resistance of the fragmented CNT (from Ω to MΩ) under strain allows PPC to reach the transmission line effect quickly, even for low strain, where we determined a total signal dissipation for 3% strain at 7 MHz [15]. Our 30 mm sensor is divided virtually into 3 zones named Location #1,#2,#3; etch zone of 10 mm length is stretched separately to study the possibilities of positioning, as **Figure 3,b** clarify. Two-wire fixed at the beginning of the top and bottom electrodes are used to inject the electromagnetic signal with variable interrogating frequency in the sensor, where the signal feedback is used to measure the total capacitance of the sensor. The mechanical loading/unloading was applied using a 5944 Instron universal testing frame where the evolution of the capacitance is monitored by an LCR meter (Agilent E4980A).

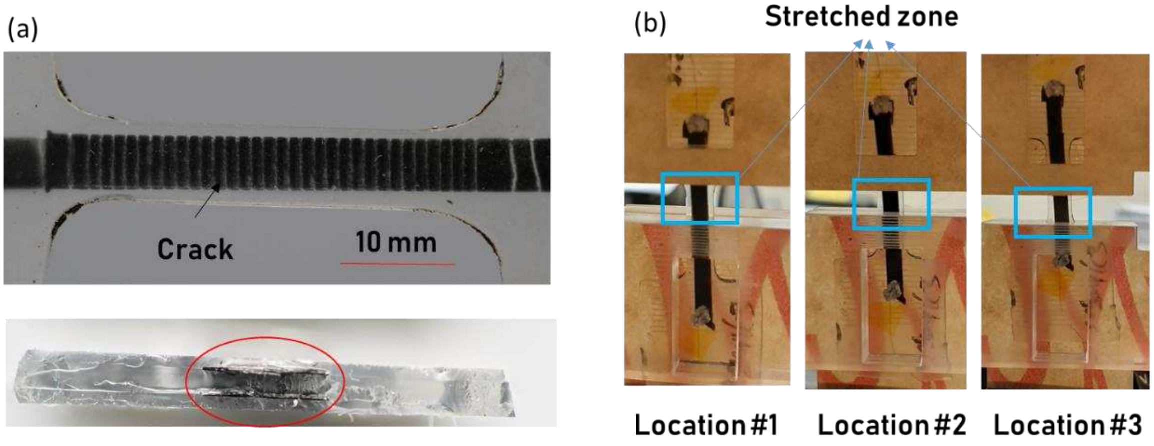

Figure 3: (a) Top view and cross-section of the parallel plate capacitor fabricated by cracked CNT paper and PDMS (b) Experimental process for applying local strain. The local strain is applied by changing the gap between the PMMA grips as only the space between the grips is subjected to strain.

Equation 1 is used to achieve the active length (which represents the distance reached by the electromagnetic signal before attenuation) after measuring capacitance for the different stretched zone. . **Figure 4,a** shows that the active sensor length is 70% of the initial length (L_0) after Applying 10% strain at 600 KHz to location #3. This active length decreases to 42% and 1% when locations #2 and #1 are stretched. The capacitance saturation refers to the signal behavior inside the sensor after applying a local strain (stretching one zone). This signal behavior is illustrated in **Figure 2** where the signal can easily cross the nonstretched zones, as the low electrode resistance ensures no dissipation. However, when the signal reached the high-resistance stretched zone, it dissipated and eventually faded completely. At high *strain* and *frequency*, the signal disappeared within the stretching zone and was absent thereafter; thus, the active sensor length corresponds to the length of all unstretched zones before reaching the area that experiences saturation. Localizing lower strain is possible by increasing the interrogation signal frequency, where we can achieve the attenuation for only 3% strain if we inject 7 MHz signal as mentioned above [15].

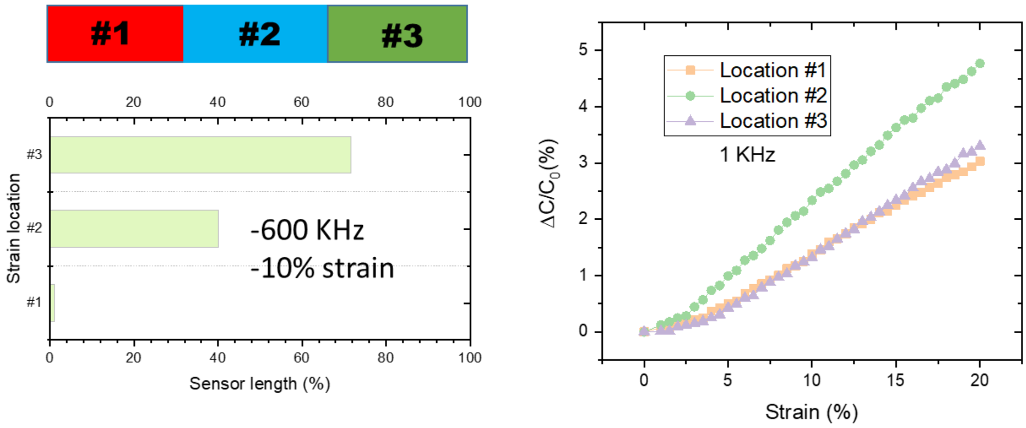

Figure 4: (a) Detection of the strain location applied to a portion of the sensor by following the signal dissipation through the sensor length at 600 kHz interrogation frequency and 12% strain (b) Strain

amplitudes for 3 different portions of the one-sheet sensor by measuring the capacitance variation at low frequency (1 kHz)

2.2 Strain intensity by the geometric effect

On the contrary to the high-frequency case, a complete propagation of the electromagnetic signal is realized for low interrogation frequency even if we have a significant strain; this fact is helpful in discovering the amount of strain applied. At low frequency (some KHz), the capacitance variation is independent of the transmission line model and related only to the geometrical extension of the sensor/PPC length (L) [17]. From equation 1, we can deduce the strain amplitude by measuring the capacitance variation at low frequency. Figure 4,b, where the measurement is made at 1 kHz, shows an increase of the relative capacitance variation as a function of strain with a sensitivity GF of 0.2. The sensitivity was low because the strain was applied to part of the sensor, whereas the capacitance was measured over the entire sensor. The three different strain locations show relatively similar capacitance behavior under strain witch whose sensitivity is related to the stretched length.

The results in **Figure 4** show that our cracked capacitive sensor can simultaneously record the strain magnitude and the strain location simply by measuring the sensor capacitance with interrogation frequency adjustment. This strain measurement and localization method can be applied more widely with much longer sensors and higher spatial resolution. This one sensor sheet is suitable for obtaining accurate strain information on a large scale by minimizing the number of wiring, giving a chance to this technology to replace the available methods such as independent sensor networks and optic fiber. This sensing technology with a reduced number of wires and a simple electronic interface will increase sensing reliability while reducing its cost and complexity.

3. Conclusion

This study presents innovative methods to monitor large-scale composites structures with a minimal number of wires and high spacial resolution that serve as an alternative to limited available technology. Our technology is based on transforming long 2D sensors into a transmission line model by using a stretchable parallel plate capacitor with piezoresistive electrodes and then used as a distributed strain sensor. We selected PDMS and cracked CNT paper as materials to build the sensor. In this work, we demonstrate that by a sensor divided into three virtual zones, our cracked capacitive sensor can simultaneously record strain in each zone by measuring the sensor capacitance at a high frequency. Moreover, we confirm that by changing the frequency from high to low, our sensor is able to measure the local strain amplitudes. Combining the geometrical model with the transmission line mechanism, we confirmed that our sensor detects the strain distribution and amplitudes in deformable systems with a minimal number of individual sensors.

Acknowledgements

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4. References

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