STRUCTURAL HEALTH MONITORING OF FIBER-REINFORCED COMPOSITE USING WIRELESS MAGNETOSTRICTIVE SENSORS

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ABSTRACT

Composite materials are extending the horizons of designers in all branches of engineering. These materials have numerous advantages and improved structural properties such as high strength to weight ratio, high stiffness to weight ratio, lightweight, structural strength, and excellent durability. This has led to their use in several applications i.e. automobile, aircraft, and military defense devices. However, these materials experience various types of deformations and damage modes during their service life that are at times challenging to detect. This has led to the development of various non-destructive methods for structural health monitoring (SHM) of the damages in these complex material systems. There are different methods of SHM, which include both wired and wireless techniques. Most of current wireless sensing techniques use relatively large sensors, which are difficult to embed into the composites. This paper presents a small wireless sensor made from magnetostrictive materials that allows continuous monitoring of the local condition within the composites. This sensor can be either attached on the surface of the composites or embedded within the composites. The sensor response during the tensile loading on the composites is monitored. The wireless monitoring using the magnetostrictive sensor can be a convenient in-situ method for SHM of composite structures.

1. INTRODUCTION

Composite materials have increased applications in the aerospace and automobile industries due to their light weight and high strength to weight ratio. Therefore, there is an increased need to develop structural health monitoring (SHM) techniques to ensure the safety of the composite materials during service. Since composites consist of different types of constituents with significantly different mechanical properties, damage tends to occur within and at the interfaces between the constituents. These damage developments occur sequentially as shown in Figure 1 [1] and under continuous loading the interactions between these damage modes leads to final failure of these materials. These local failures inside the composite are difficult to be detected by conventional non-destructive techniques. Acoustic sensors attached onto the surface of the composites are limited by their penetration depth in the fiber reinforced polymer (FRP) composites. Other types of detection methods, such as X-ray micro tomography, provide large penetration depth but cannot provide real-time information during the material's global or local deformation. Embedding small sensors inside the composites could alternatively provide local

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SAMPE Conference Proceedings. Charlotte, NC, May 20-23, 2019. Society for the Advancement of Material and Process Engineering – North America.

damage information by measuring the strain inside these materials that can be correlated to specific damage modes under specific loading conditions.

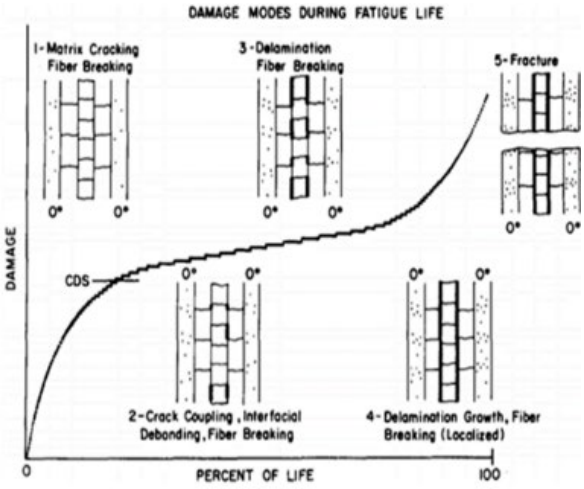


Figure 1: Damage modes in a unidirectional composite during fatigue [1]

Magnetoelastic materials behave uniquely under an external magnetic field which leads to their uses in various sensor applications. These materials can also change their shape and dimension under an external magnetic field which is known as magnetostrictive effect [2, 3]. The inverse magnetostrictive effect is known as the Villari effect which shows the opposite behavior, i.e. a change in magnetization due to stress in these materials [4]. This causes a change in the local magnetic flux which can be measured by a conducting coil. Using these properties, many sensing applications have been developed such as position sensors [5], viscosity sensors [6], force sensors [7], strain sensors [8, 9], biosensors [10, 11], and voltage sensors [12].

In this paper, a wireless, in situ technique has been developed that uses small sensors to detect local damage development in the composites. This sensor is based on magnetostrictive materials, which change their shapes under alternating magnetic fields; and vice versa. The change of the local strains inside the composites causes a change in the magnetization of the sensor materials. The magnetic flux change at the sensor is wirelessly picked up by a planar coil placed close to the composite surface. The sensitivity to the tensile stress/strain is investigated.

2. EXPERIMENTATION

2.1 Fabrication of Composites with Embedded Sensors

Two types of composites were used in this study: carbon fiber reinforced polymer (CFR) composites and glass fiber reinforced polymer (GFR) composites. Both types of the composites embedded with sensors were fabricated following the Vacuum-Assist Resin-Transfer Method (VARTM). For each type of composites, four plies of fiber fabric with sizes of 20 × 20 cm were cut and positioned on a mold. Magnetostrictive thin film sensors with unit sizes of 16 mm × 4 mm were placed between two plies to make the composites embedded with sensors. The composites with surface sensors were prepared by placing the sensors at the top pf the plies. The schematic of composites with embedded and surface sensors is shown in Figure 2. The mold used for fabricating the composite panel was a metal plate laminated with vinyl mold release

compound. Epoxy resin made from diglycidyl ether of Bisphenol-F and a polyamine curing mixture was used as a polymer matrix. The mold with carbon fibers was then vacuum bagged and epoxy drawn using a pressure pump. Once the epoxy matrix was spread throughout the suction area with the carbon fibers, the sample was then left to cure for 24 hours. This therefore completed the fabrication of composites with embedded and surface sensor.

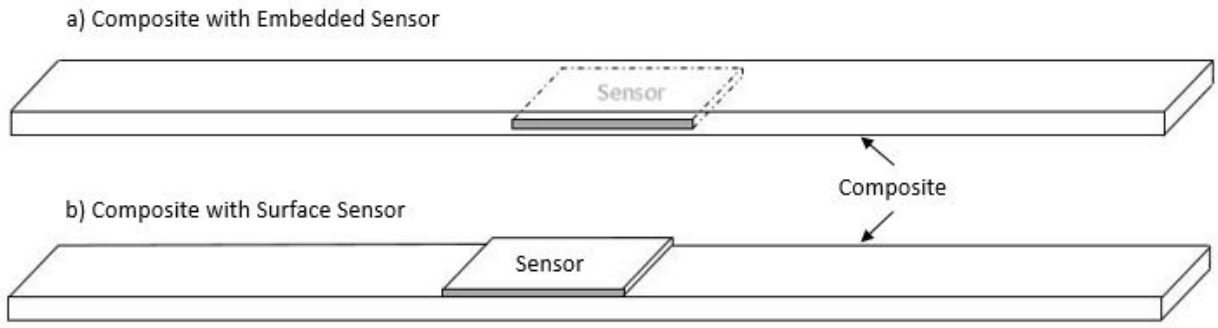


Figure 2. Fabricated composites with embedded and surface sensors.

2.2 Sensor Measurement under Tensile Loading

Three types of composites were investigated: composites with no sensors, composites with surface sensors, composites with embedded sensors. Each type was tested under uniaxial tensile loading using an MTS Servo-hydraulic test system, and the planar coils placed close to the composites were used to send the excitation signal and pick up the magnetic flux change at the sensor during the tensile loadings, as shown in Figure 3. The sample size was 14 × 1 cm. Discrete measurements and continuous measurements were both taken during uniaxial tensile loadings. For the discrete measurement, a tensile load was applied at three different load levels: 2 kN, 4 kN and 6 kN. At each of these three load levels, sensor measurements were taken over frequencies ranging from 0 Hz to 5 kHz. The continuous measurements were taken at 50 kHz and 100 kHz up to 4 kN, which was below the breaking load of most composite coupons.

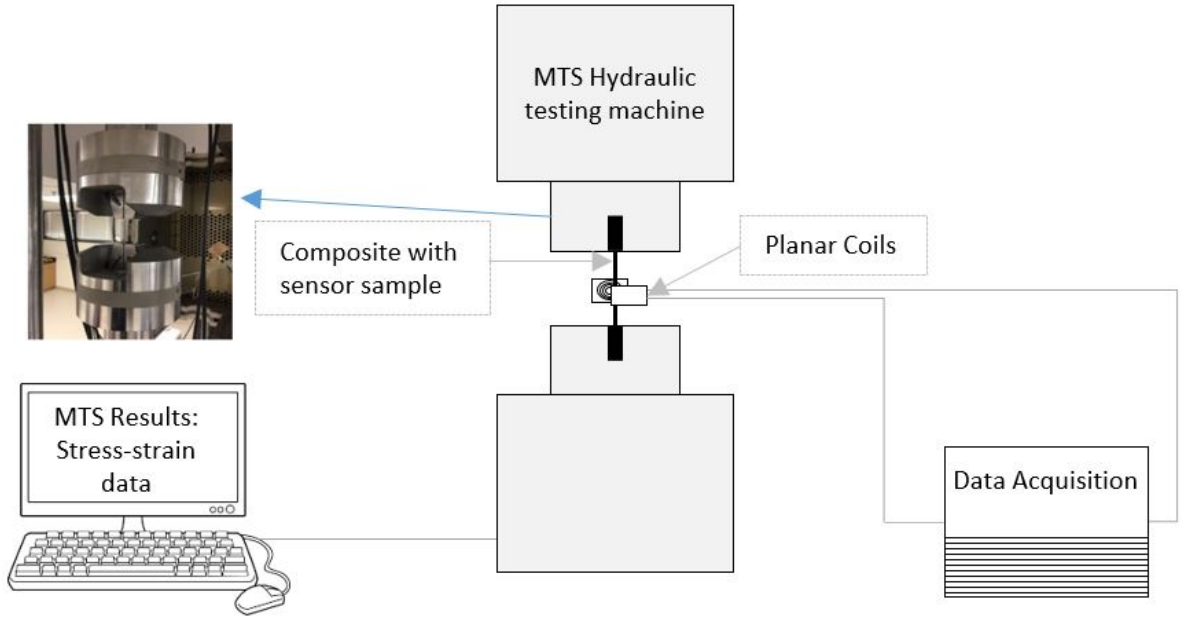


Figure 3. A schematic of the experimental set-up for sensor measurement during tensile loadings.

3. RESULTS

3.1 Discrete measurement

Measurements over frequencies ranging from 0 Hz to 5 kHz were taken at discrete uniaxial tensile loading conditions (2 kN, 4 kN and 6 kN). As shown in Figure 4, both composites with embedded sensors and composites with surface sensors gave a higher output voltage compared with bare composites without sensors. This becomes more significant at higher frequencies. Therefore, the continuous measurement in the next section were taken at relatively high frequencies. Both composites with embedded sensors and composites with surfaces sensors showed higher response amplitudes at higher tensile loadings at 6 kN, compared with those at lower tensile loadings of 2 kN and 4 kN.

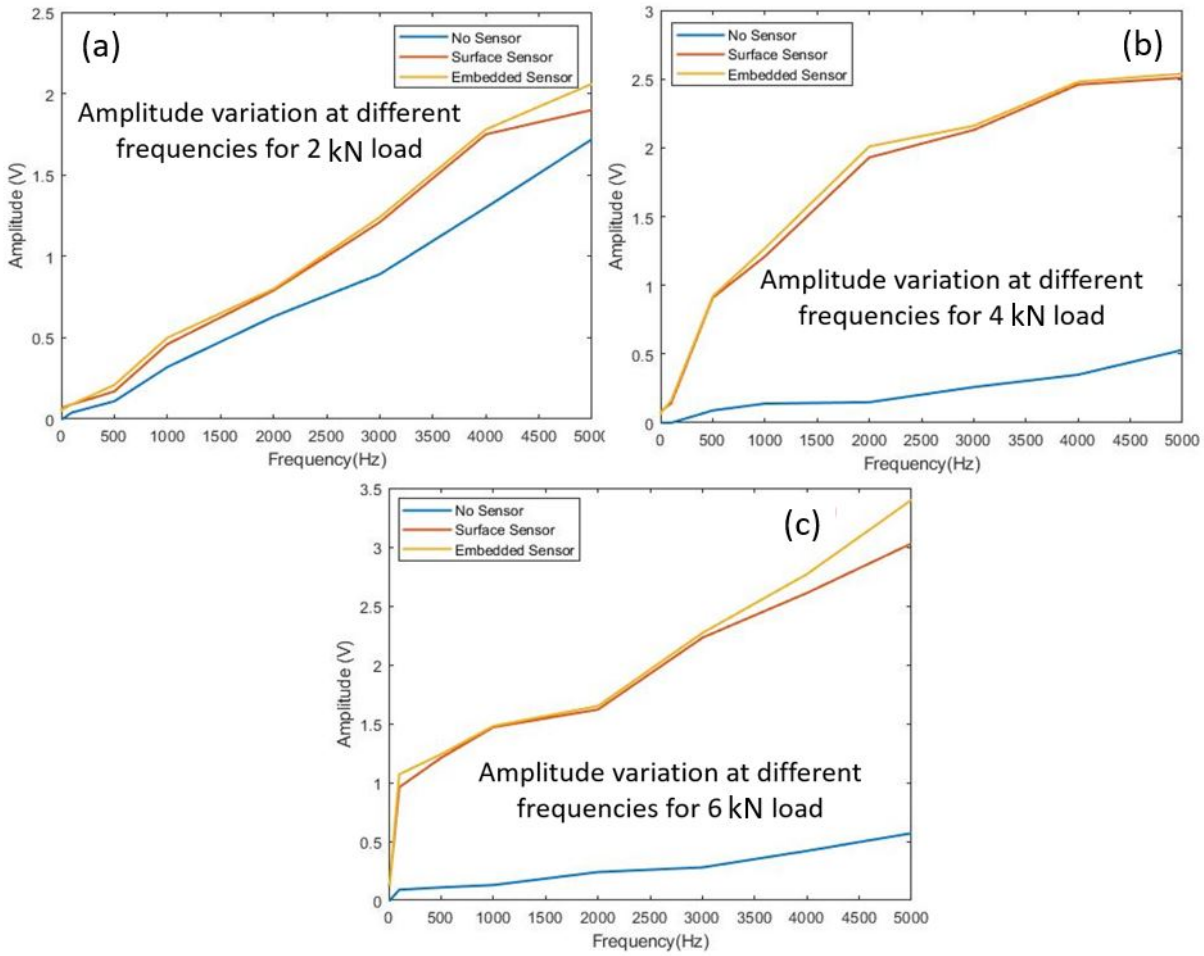


Figure 4. Amplitude variation at different frequencies for 2 kN, 4 kN and 6 kN load.

3.2 Continuous measurement

3.2.1 Composites with embedded sensors

This section gives details on the responses of the composites with embedded sensors during the continuous tensile loading of up to 4 kN, prior to the composite breaking point. Both the sensor output and composite stress-strain plots are shown in Figures 5 and 6. At low strains, the sensor output increases as the stress and strain of the entire composite increase. This increase in amplitude reaches a maximum at 0.63% ε for the detection at 100 kHz, and a maximum at 0.84% ε for the detection at 50 kHz. Beyond this point, the sensor output starts to decrease as the stress and strain of the entire composite continue to increase. The sensitivity of the sensor is taken from the lower frequency region before the sensor maximum amplitude point. The embedded sensor shows a sensitivity of 11.11 μV/με for the measurement at 100 kHz, and a sensitivity of 8.74 μV/με for the measurement at 100 kHz.

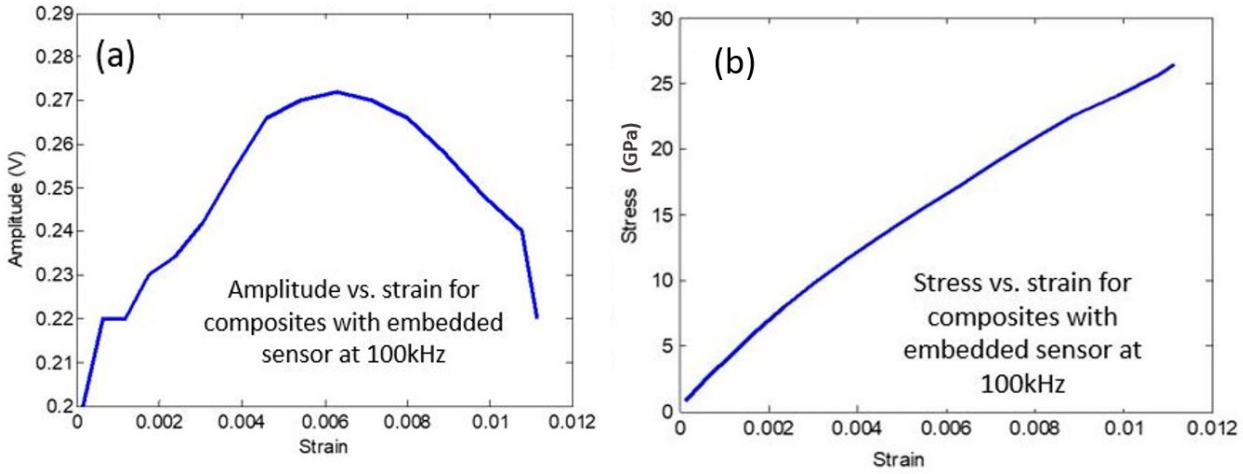


Figure 5. Responses form the composites with embedded sensor during the tensile loading of the composites. Sensor measurements were taken at 100 kHz.

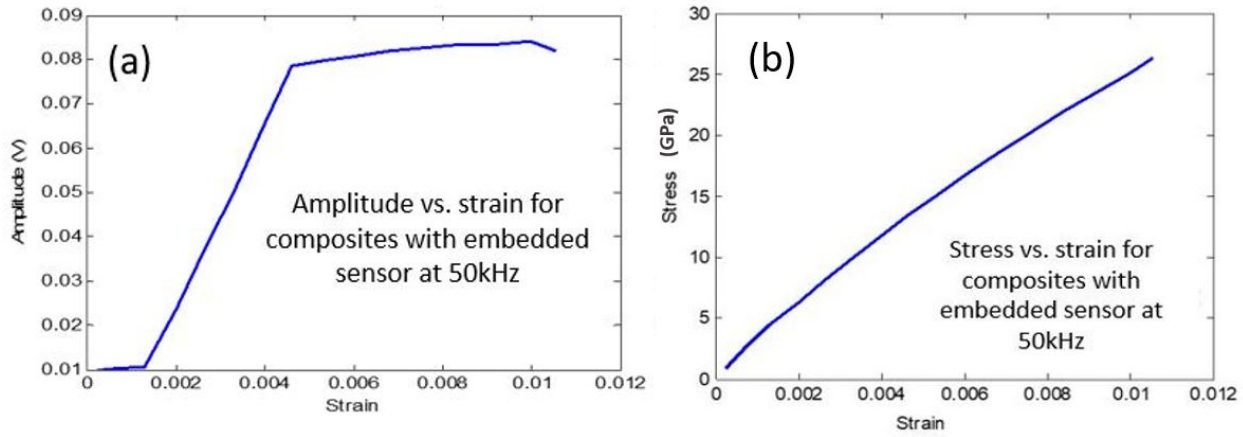


Figure 6. Responses form the composites with embedded sensor during the tensile loading of the composites. Sensor measurements were taken at 50 kHz.

3.2.2 Composites with surface sensors

Figures 7 and 8 show the responses from the composites with surface sensors. Similar to the composites with embedded sensors, the composites with surface sensors also show an increase in output voltage as the stress and strain of the entire composite increase at low strains. This increase in amplitude reaches a maximum at 1.15% ε for the detection at 100 kHz, and at 0.77% ε for the detection at 50 kHz. Beyond this point, the sensor output starts to decrease as the stress and strain of the entire composite continue to increase. The surface sensor shows a sensitivity of 2.48 μV/με for the measurement at 100 kHz, and a sensitivity of 3.64 μV/με for the measurement at 100 kHz. The responses from composites with both embedded sensors and with surface sensors are summarized in Table 1.

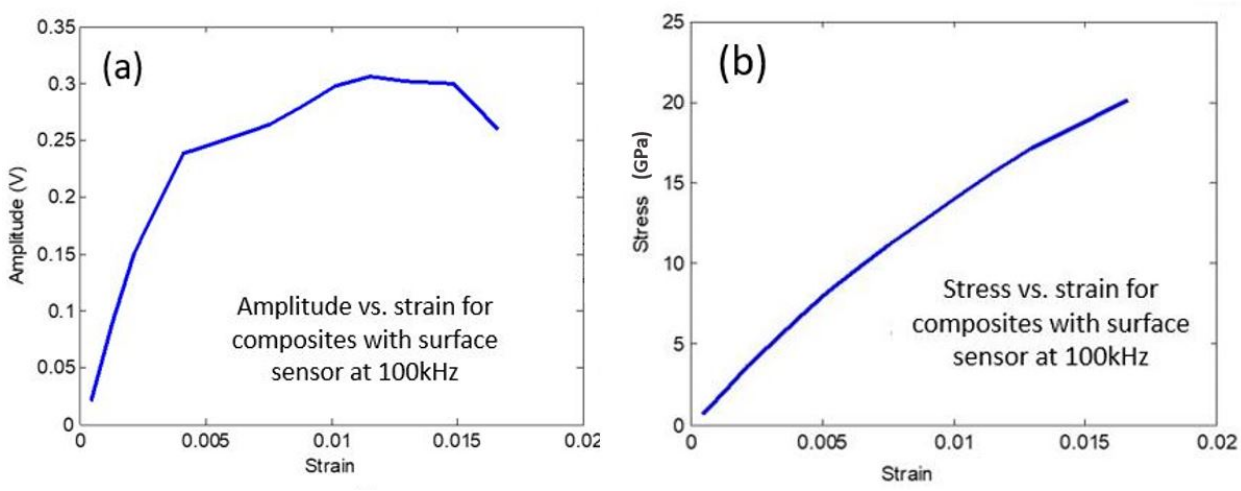


Figure 7. Responses form the composites with surface sensor during the tensile loading of the composites. Sensor measurements were taken at 100 kHz.

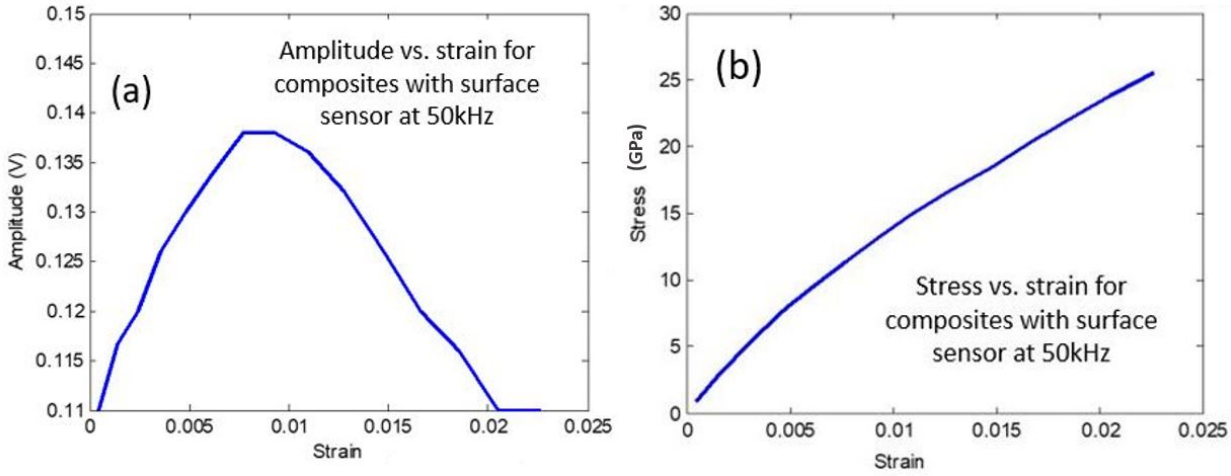


Figure 8. Responses form the composites with surface sensor during the tensile loading of the composites. Sensor measurements were taken at 50 kHz.

Table 1. Responses from composites with embedded sensors and with surface sensors.

Description	**Strain at Sensor Peak Response**	**Sensitivity (μV/με)**	**Max Stress (GPa)**
50 kHz embedded	0.0084	8.74	24.27
100 kHz embedded	0.0063	11.11	25.18
50 kHz surface	0.0077	3.64	25.53
100 kHz surface	0.0115	2.48	20.17

4. CONCLUSIONS

The response of surface mounted and embedded magnetostrictive sensors during the tensile loading of the composites is reported. The study showed that the sensor output increases as the loading of the composite increases. This increase in amplitude reaches a maximum at 0.63% ε for the detection at 100 kHz, and a maximum at 0.84% ε for the detection at 50 kHz. Beyond this point, the sensor output starts to decrease as the loading continues to increase. The sensitivity of the sensor is taken from the lower frequency region before the sensor maximum amplitude point. The embedded sensor showed a sensitivity of 11.11 μV/με for the measurement at 100 kHz, and a sensitivity of 8.74 μV/με for the measurement at 50 kHz. Therefore, this validates the application of a small wireless sensor made from magnetostrictive materials for continuous monitoring of local strain (damage) within the composites. However, we haven't correlated the change in amplitude with damage modes in composites currently and would include them in our subsequent publications. The improvement of the sensor adhesion will be also included as one of the objectives in future work. The wireless detection with the magnetostrictive sensor can be a convenient in-situ method for SHM of composite structures.

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