HIGH PERFORMANCE PIEZO ELECTRIC NANOCOMPOSITE SENSOR NODES FOR STRUCTURAL HEALTH MONITORING

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ABSTRACT

The increased usage of composite materials has raised the need for a more reliable damage detection strategy for structural health monitoring (SHM) systems. An important, and as yet unsolved, limitation of existing composite laminates is their susceptibility to impact damage. Low-velocity impact-induced damage is often hard to spot from the impacted side in a routine visual inspection, but it has a significant effect on the mechanical performance of laminates. This work investigates the possibility of embedding poly (vinylidene fluoride) (PVDF) as a sensor node for a passive SHM system in SE70 glass/epoxy laminates to monitor the damage while being subjected to an indentation test. The mechanical test results for the laminates both with and without embedded sensors indicate that the embedment of the PVDF sensors does not change the measured mechanical properties of the laminates. Acoustic emission (AE) signals obtained using the embedded PVDF sensor were compared with an identical PVDF sensor attached on the laminate's surface. The results showed the possibility of successfully embedding PVDF sensors in composite laminates and the functionality of the PVDF sensors after the embedding procedure, *i.e.* their ability to withstand the composite curing temperature without experiencing degradation. However, the amplitude level of the AE signals obtained with the PVDF is lower than that of the commercial sensor, which is due to the low coupling factor and dielectric constant of the PVDF. Therefore, the development of two- and three-phase AE sensors (lead zirconate titanate (PZT)/epoxy and graphene nanoplatelets (GnPs)) were also explored to improve the sensitivity of the embedded sensor. The fabrication methods have been developed and the fabricated sensors showed better performance than PVDF sensors during the Hsu-Nielsen Source test. This is a continuing project, therefore further research will be conducted to implant the PZT nanocomposite sensors into composite laminate plates to examine the applicability of these novel sensors as flexible and light weight embedded sensor nodes for structural health monitoring systems.

1 INTRODUCTION

Composites are widely used in the aerospace industry as they are stronger, stiffer and lighter than traditional materials. However, their application is limited because of their fragility in impact loading, in particular, barely visible impact damage (BVID) due to low velocity impacts. BVID can cause a significant amount of delamination that reduces the compressive strength by up to 60% compared with an undamaged laminate, even though the only external indication of damage may be a very small surface indentation [1]. Consequently, there is the need to develop improved and more efficient means of detecting such damage.

Current methods to avoid BVID used in the industry involve conservative design and frequent inspection of the composites [2]. However, these methods are not ideal because of the high manufacturing and maintenance costs. Developing a damage detection strategy to evaluate the internal damage becomes an important research topic for the maintenance of composite structures. Non-destructive evaluation (NDE) methods, such as X-ray, C-scan and ultrasonic bulk wave, can obtain images of the internal damage without destroying the structure. Thus, they are better suited to inspect the composite for maintenance and research purposes. However, expensive equipment and specialist operators are required to perform most NDE procedures. In addition, the structures must usually be taken out of service during testing. Consequently, for most aerospace industrial applications, NDE methods require large maintenance expenditure and long vehicle downtime. For space transportation vehicles or satellites, such maintenance opportunities are not possible [2].

Acoustic emission (AE) is a passive NDE method that offers great potential for real-time global monitoring of active damage mechanisms in composite structures. The AE method uses piezoelectrical sensors, as shown in Figure 1, as transducers to detect any high-frequency sound waves generated by cracks and fractures. AE has proved its reliability in detecting the dynamic processes throughout the delamination of the composites when compared with other NDT methods [3-6]. It is also capable of locating the damage and is sensitive to processes that generates a stress wave. Overall, AE is a reliable method for the passive detection of internal damage of the structure.

By implementing AE as a damage detection strategy, an integrated SHM system can be installed within the composite structure to provide rapid BVID detection. An SHM system uses permanently installed AE sensors to detect the location of the BVID, evaluate the residual structural integrity, and quantify the severity of the BVID throughout the service period of the composite structure. AE sensors can detect failure that has occurred during operation and transmit details to the controller. This SHM system requires no vehicle downtime and less specialist operators to evaluate the composites as it can passively collect the information during the composite’s service life. It can, therefore, reduce the maintenance costs for the current aerospace industry. The structure will also become safer as any BVID damage will be instantly detected. Thus, the composite’s weight can be reduced for a smaller safety factor. New environmental targets set for the industry will benefit from the potential weight reduction as well.

As mentioned above, an SHM system requires permanently installed AE sensors. Most previous work has focused on embedded sensors within the composite structure during the manufacturing stage [7-9]. Embedding sensors within composites is a better option than attaching sensors to structures for a variety of reasons. Sensors attached to the surface can potentially be detached by temperature and pressure differences. Thus, embedded sensors are more stable than non-embedded sensors. At the same time, attached sensors could be a challenge to install when the surface is curved, etc., while embedded sensors within the composites can avoid this. Embedded sensors within composites also have the potential to provide a better aerodynamic surface for aerospace applications.

However, there are some challenges when embedding sensors within composites. The first challenge is that commercial AE sensors, as shown in the right of Figure 1, are difficult to conform to complex shapes and it is practically impossible to embed them within the structure, due to their size and weight. In addition, commercial piezo electric sensors are brittle and not easy to form. Thin and flexible sensors are preferred for embedding within the composite with less influence on the composite’s mechanical properties. Thus, researchers have been focusing on fabricating advanced piezoelectric sensors [7-9]. Polymeric and piezoelectric composites have received interest as sensory applications. Nevertheless, it remains a challenge to further improve their response for advanced applications such as health monitoring systems.

The aim of this work is to investigate the possibility of embedding PVDF as a sensor node for a passive SHM system in SE70 glass/epoxy laminates to monitor the damage while being subjected to an indentation test. This work also involved the development of three-phase (lead zirconate titanate (PZT)/epoxy and GnPs) innovative AE sensors, as shown in the middle of Figure 1, to optimise embedded AE sensors.

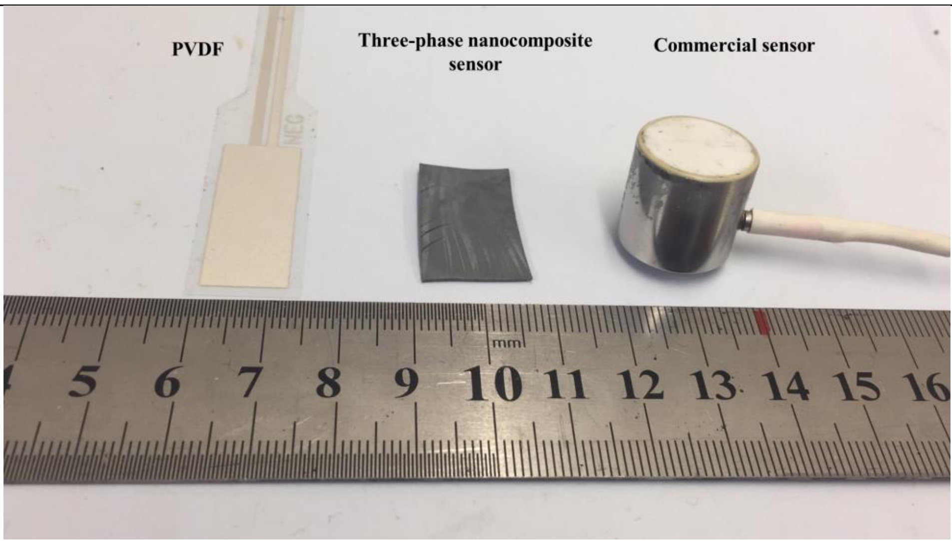

Figure 1: Summary of different types of AE sensors.

2 EXPERIMENTAL PROCEDURES

2-1- Three-phase nanocomposites

Figure 2 illustrates the fabrication process of a three-phase nanocomposite. PZT particles (70 wt%) were suspended in Tetrahydrofuran (THF) solution using an ultrasonication bath, for 20 minutes. The percentage of PZT followed the same proportion as in the experiment reported by Nasser *et al.* [8]. A period of 20 minutes would be sufficient for the PZT particles to be fully suspended within the THF solution. Prime 20LV (30 wt%) was then added into the PZT-THF solution as an epoxy base. The solution was then mixed with magnetic stirring (1000 rpm) on the hotplate (IKA ETS-D5) at room temperature for 30 minutes. The PZT-Prime 20-THF solution was fully mixed after this mechanical mixing. To increase the distribution of the solution, the mixture needed to be sonicated for another 30 minutes. Extra-slow hardener with weight ratio 1:0.26, as recommended by supplier, was then mixed and dissolved by stirring and 15 minutes of sonication. All sonication procedures, except the last, were carried out with a lid on top of the container. The last ultrasonication aimed to evaporate the THF within the solution and left a uniformly distributed PZT-Prime 20-hardener solution. A two-phase composite sensor (PZT sensor with Prime 20 as its epoxy base) can then be cast without adding GnPs. For a three-phase composite, a weighed portion of powdered GnPs, dependent on the weight percentage required, was suspended in another THF solvent using ultrasonic baths for one hour at room temperature. The main reason for the ultrasonic process is to suspend the GnPs uniformly within THF solvent. For the three-phase composite, a GnPs solution needed to be added within the PZT-Prime 20 solution after the mechanical mixing. The same experimental procedures for fabricating the two-phase composite sensors were operated to fabricate the three-phase composite sensors.

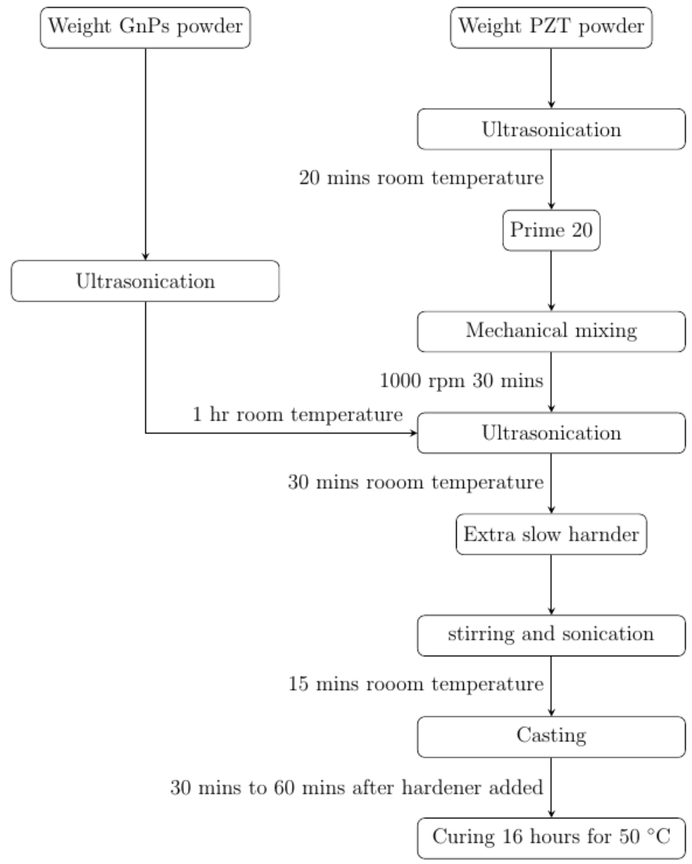

Figure 2: Summary of fabrication procedures for the two- and three-phase composite sensors.

2-2- Embedment procedure

PVDF sensors (FDT series) were purchased from Measurement Specialties, Inc. [10]. They are rectangular elements covered with silver ink screen-printed electrodes with a thin, protective polyurethane layer. The FDT series have polymer tails that extend from the active sensor area of the piezo film, with very flat, flexible leads with connectors at the end, as shown in Figure 1. The dimension of these sensors is 235 mm x 16 mm x 12 µm (length x width x thickness). The PVDF sensors were embedded between laminates during the manufacturing stage and connected to the Mistras AE system for AE monitoring by a BNC connecter. Composites without embedded PVDF sensors were also fabricated for comparison.

The laminates made from SE70 glass/epoxy with lay-up sequence $[45/90/0/-45]_{2s}$, where numbers represent the ply orientations. This is a quasi-isotopic stacking sequence, which is a standard layup for indentation tests [11]. Six specimens with dimensions of 170 mm x 100 mm x 4 mm (length x width x thickness), as shown in Figure 3, were cut from the panels using a dedicated composite cutting machine with a diamond-coated cutting blade. Each specimen had one sensor embedded under the top ply (*i.e.* between the 45 and 90 plies) at the same location. The other six specimens, without embedded sensors, were also cut the same way for comparison.

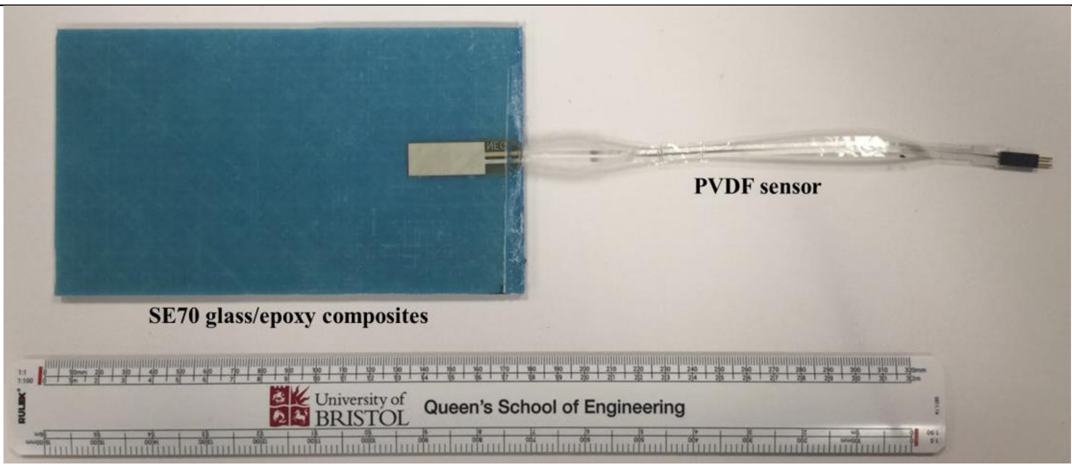

Figure 3: SE70 glass/epoxy composite plate with embedded PVDF sensor.

2-3- Testing procedure:

AE signals were collected by an AE data acquisition system (PAC) PCI-2 with a maximum sampling rate of 40 MHz. The test sampling rate was 5 MHz during the experiment. Commercial AE sensors are PAC R15 resonant-type, broadband, single-crystal piezoelectric transducers with a frequency range of 20-900 kHz. The preamplifier and the threshold were set to 40 dB and 65 dB for all the sensors. The surface of the sensor was covered with silicon grease to improve acoustic coupling between the specimen and the sensor.

The setup for characterizing the sensors is shown in Figure 4. The PVDF, two-phase composite and commercial AE sensors were located on an aluminum panel with dimensions of 253.5 mm x 153.5 mm (length x width). Sensors were distributed on an 80 mm-diameter circle at the middle of the panel. AE sources were generated by the Hsu-Nielsen source method (pencil lead break method) [11] at the core of the circle. Therefore, signals originated from the pencil lead breakage test should be identical for all the sensors.

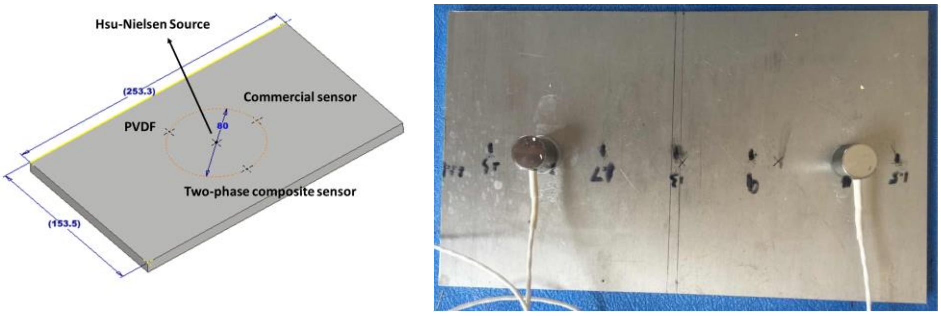

Figure 4: The basic setup for the characterization of the sensors.

A steel tub (diameter 16 mm) was mounted on an INSTRON 8872 servo-hydraulic testing machine. The specimen was loaded by the indenter and simply supported over a 125 mm x 75 mm window, as shown in Figure 5. The indentation tests were controlled at a rate of 1 mm/min for all scenarios under displacement control. The dynamic and rate effects of the laminates can be neglected under this operation speed. A sampling rate of 20 Hz was used to acquire the load and displacement of the indenter of the test. The specimens were loaded until multiple load drops occurred due to the fibre breakage in the tension side. The PVDF and commercial AE sensors were placed at positions illustrated in Figure 5 to monitor the composite plate during the indentation test.

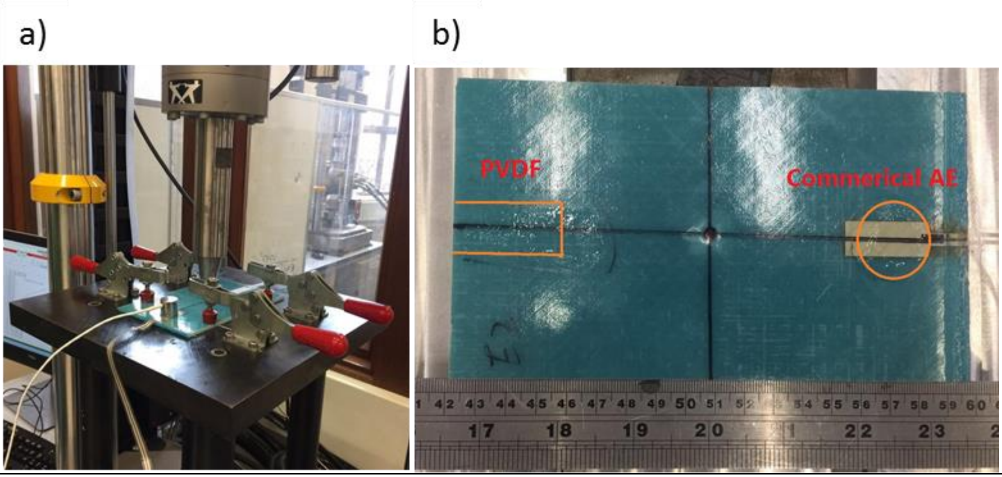

Figure 5: a) Indentation test setup and b) position of the embedded and attached sensors.

3 RESULTS AND DISCUSSION

3-1- Indentation Results:

Figure 6 shows the load-displacement diagrams obtained during the indentation tests for the investigated laminated composites, with and without the embedded PVDF sensors. A similar global behaviour can be found for both configurations. The mechanical results show the different damage evolution stages during the loading: a) The elastic linear behaviour in the beginning of the loading, b) appearance of the non-linearity due to the indentation induced damages such as delamination, and c) fibre breakage in the end tension side of the composite plate.

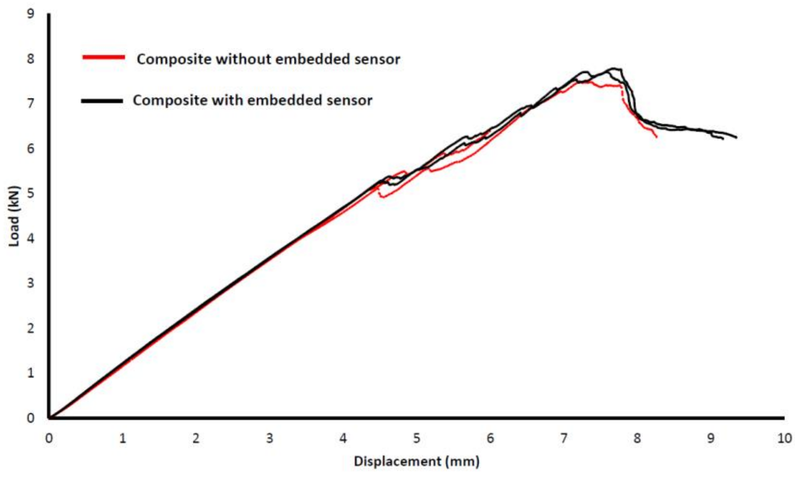

Figure 6: Load-displacement for the composite plates with and without embedded sensors subjected to indentation.

Figure 7 illustrates the distribution of the AE signal amplitudes over time obtained using the embedded PVDF sensor and the PVDF and commercial sensors attached on the laminate's surface, as indicated in Figure 5. The AE signals with lower amplitude level start to appear in the linear part of the load-time diagram (around 120 seconds) indicating local indentation effects, matrix cracking damage, *etc.* However, these damage mechanisms do not have a significant effect on the mechanical integrity of the laminate. The significant AE signals appear close to the non-linearity point, where there is a significant damage such as delamination in the laminate. The embedded and attached PVDF sensors show very similar acoustic emission behaviour, and the general trend is close to the commercial sensors. This shows that the embedded sensor was not affected by the embedment procedure, *i.e.* ability to withstand the composite curing temperature without experiencing degradation. Although the general AE response is similar, the commercial sensor is more sensitive and it received a higher number of AE signals. This indicates the existence of some low-amplitude level signals that the PVDF sensors are not able to detect. This result has been verified by comparing the PVDF, the two-phase composite and the commercial AE sensors in the following section.

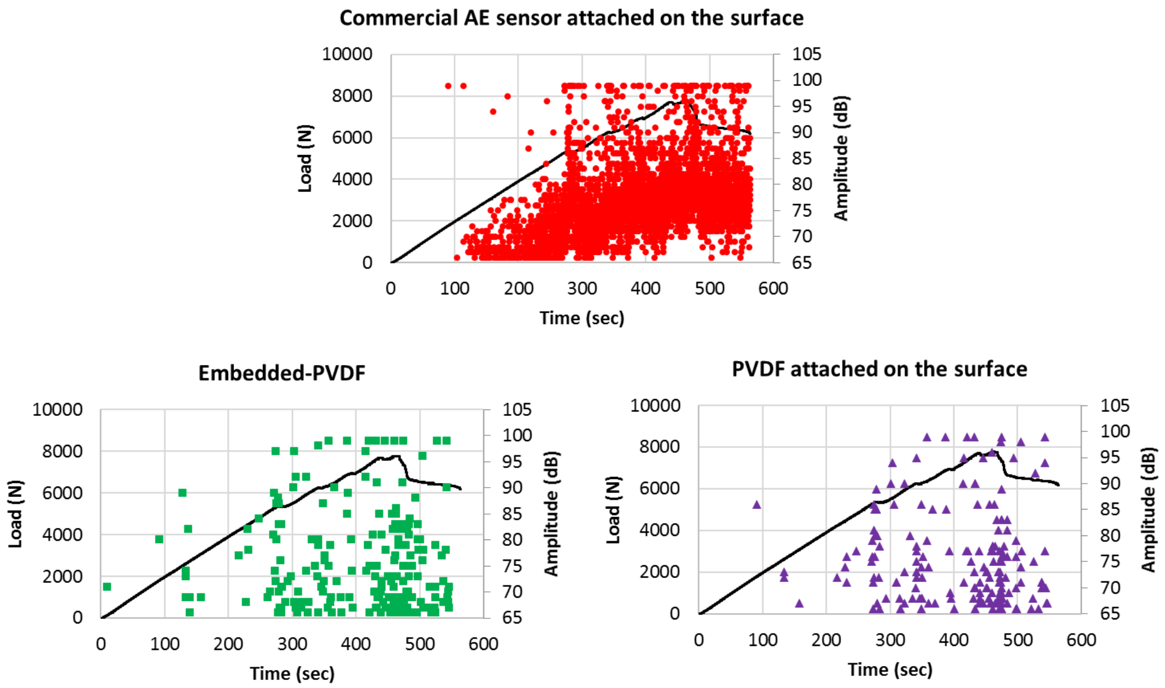

Figure 7: Mechanical load and AE amplitude distribution versus time for the indented composite plates with the embedded sensor.

3-2- Hsu-Nielsen Source Results:

Figure 8 shows the results obtained by the pencil lead breakage test according to the Hsu-Nielsen Source test using the PVDF, the two-phase composite and the commercial AE sensor. It can be seen that the pencil lead breakage test generates an acoustic emission signal with 100 dB as recorded by the commercial sensor. The amplitude level of the AE signal obtained by the two-phase composite sensor is similar to the commercial sensor. The amplitude of the signals recorded by the PVDF sensor is around 70 dB, much lower than that for the commercial and the two-phase composite sensors (both near 100 dB). This is potentially caused by the low coupling factor and dielectric constant. The PVDF sensors could potentially ignore some low-energy signals due to this issue. PVDF can still be used as an AE sensor but a higher amplifier could be necessary to improve the performance.

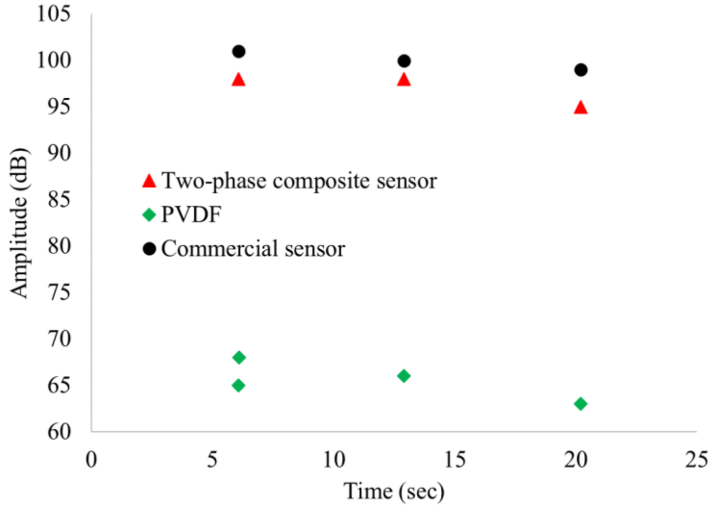

Figure 8: AE signals collected by the commercial, the two-phase composite and the PVDF sensors.

4- CONCLUSIONS

This work presents an experimental study on improving the mechanical and electrical behaviour of AE sensors as embedded piezoelectric sensor nodes for SHM systems. Embedded PVDF was used as an AE sensor node in the SE70 glass/epoxy laminates subjected to indentation tests. The mechanical results showed the embedment of the PVDF sensors does not have a significant effect on mechanical properties of the laminates. The AE results showed the successful embedding procedure for the PVDF sensors in composite laminates, and the functionality of the PVDF sensors did not change after the embedding procedure. Comparing the AE signals, the commercial sensor is more sensitive than the PVDF sensor. Therefore, this work also considered development of the two-phase and three-phase AE sensors that can improve the sensitivity of the embedding sensor. The fabrication methods have been developed and the sensors showed better performance than PVDF sensors during the Hsu-Nielsen Source test. This is a continuing project, therefore further research will be conducted to implant the PZT nanocomposite sensors into composite laminate plates to examine the applicability of these sensors.

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