Performance Comparison Between Fiber-Optic and Piezoelectric Acoustic Emission Sensors

Mario Sorgente[1], **Aydin R. Zadeh**[1], **Abdelkrim Saidoun**[2]
[1] *Optics11, Amsterdam, the Netherlands*
mario.sorgente@optics11.com
[2] *CETIM, Senlis, France*
abdelkrim.saidoun@cetim.fr

Abstract

Fiber-optic acoustic emission (AE) sensors have been investigated throughout the years as solutions for AE testing under extreme environmental conditions. This paper investigates the performances of the fiber-optic acoustic emission system recently released by Optics11: OptimAE. The fiber-optic sensors were tested in a lab environment and directly compared with state-of-the-art PZT sensors to evaluate sensitivity, directivity, and localization accuracy. The fiber-optic system showed performances equivalent to the PZT electrical system, proving that OptimAE could extend the benefits of state-of-the-art AE testing to challenging environments such as extreme temperatures, high voltages, radiations, explosive hazardous areas.

Keywords: Optical AE, Fiber Optics, PZT, Comparison, SHM, NDT, OptimAE, CETIM, Optics11, Acoustic Emission

Introduction

Thanks to its wide range of applications and its reliability, acoustic emission (AE) is nowadays a well-established technique in the fields of non-destructive testing (NDT) and structural health monitoring (SHM). AE is a non-invasive technique that allows to detect damages in materials and track their evolution in real-time. Events such as cracks, delamination, corrosion and debonding release energy in the form of high-frequency sound waves which travel across materials. By measuring such sound waves, AE sensors allow to detect and locate faults in complex structures. The formation of cracks in engineering structures results in the generation of transient acoustic (or elastic) waves throughout the structure. This phenomenon is called acoustic emission, and it can occur in many different types of materials, namely metal, concrete and composite structures

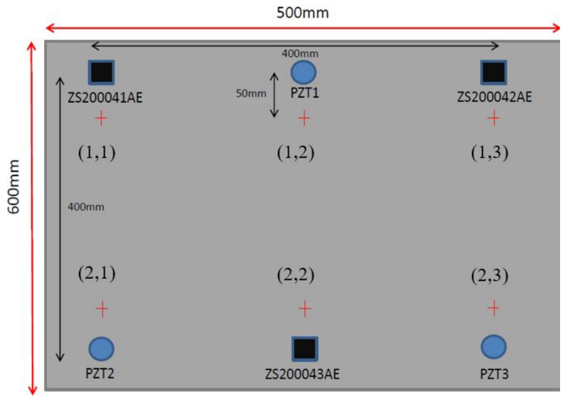
AE sensors based on piezoelectric transducers (PZT) are to-date the most diffused sensor types. However the intrinsic limitations of PZT transducers have limited the fields of application of these sensors in many industries. This is because a standard piezoelectric sensor has a limited operating temperature and is not usually suitable for cryogenic or high temperatures of above 80°without protection, and it is not robust against, nuclear radiation and electromagnetic interferences. In such context, fiber-optic transducers have been investigated through the years as a possible solution. Thanks to their passive nature, fiber optic sensors (FOS) can outperform electrical sensors in challenging operational environments.

Recently, a new product "OptimAE" was introduced by the company Optics11, which uses fiber-optic technology for the detection and recording of acoustic emission signals for the first time on a commercial scale. Using interferometry as a measurement principle, OptimAE achieves state-of-the-art sensitivity while enabling AE measurements in harsh conditions spacing from extreme temperatures, high voltages, radiations, to explosive hazardous areas.

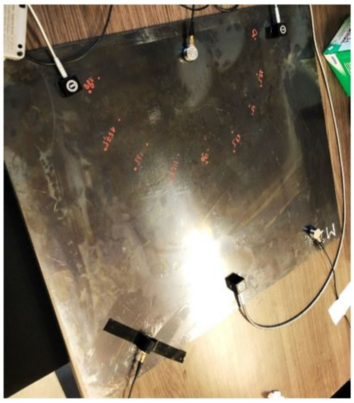
This paper compares the performance of the OptimAE acoustic emission system, to the electrical Vallen AMSY-6 system using PZT sensors. This research is in collaboration with the company CETIM and it addresses comparisons in terms of sensitivity of both optical and electrical sensors, their directivity in response to AE events at different angles, and their performance in acoustic event localization.

Optical Sensing Technology

The operating principle of the OptimAE system is based on interferometry, where the differential change in path length of two optical fibers due to the acoustic wave is detected with high sensitivity. The fibers in such setup are densely coiled in a package inside the acoustic emission sensor. The sensitive coil is attached to the surface of the specimen, with the metallic mandrel in direct contact with the structure for optimum transmission of the surface acoustic wave (also called Rayleigh wave) to the fibers. The sensor is fixed in position using either a magnetic clamp, or a rubber clamp, or using an adhesive material.



(a)



(b)

Figure 1: (a): The physical setup with FOS and PZT sensors in place. (b): Black square: FOS – Blue circle: PZT – Red crosses: PLB events.

Upon the passing of the acoustic wave through the optical sensor, the elastic energy stretches the fibers on the coil, and the resulting interferometric signal is transferred to the OptimAE box for signal acquisition, demodulation of the acoustic emission signal, and communication to a computer with the OptimAE software for acoustic event detection and further processing.

Test and Setup

For a direct comparison of the performance of the PZT sensor and the optical sensors, the pencil lead break (PLB) test was chosen as an established method for generating reproducible and artificial acoustic emission signal. To guarantee reproducible events for all the measurements, the pencil was equipped with Hsu-Neilson Source. The optical setup consisted of a 4-channel OptimAE system with 3 optical AE sensors (version 05) with a resonance frequency of around 215 kHz. The electrical setup consisted of a commercial Vallen AMSY-6 hardware, with 3 PZT sensors (VS 150) with a resonance frequency of around 150 kHz. Both sets of sensors were placed on the test plate with a silicon grease coupling liquid, and without clamping. The test plate is made of isotropic steel with dimensions of 600x500x3 mm. The schematic setup is depicted in Fig. 1a, and the physical setup is shown in Fig. 1b.

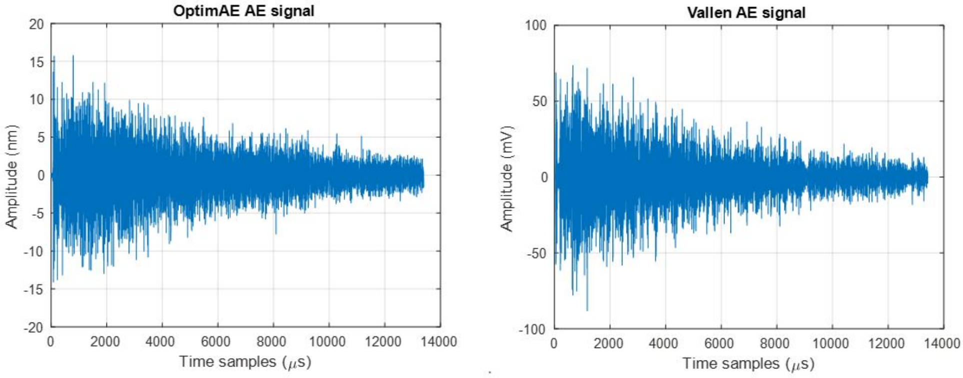


Figure 2: Waveform comparison PZT/FOS.

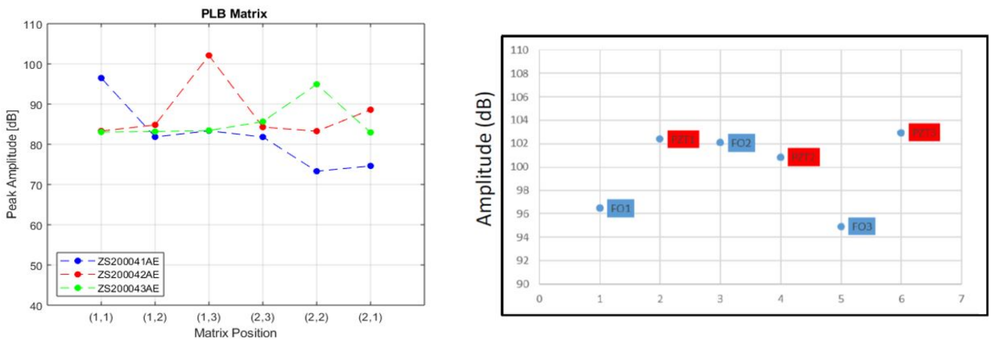
Experimental Results

The two systems are compared with respect to the following performance test criteria:

- Sensitivity test
  - Five PLB events at 50 mm from each sensor
  - Maximum amplitude per hit averaged and plotted per each sensor
- Localization test
  - Three PLB events at 150 mm from PZT1
  - Tracked time of arrival and location retrieved by triangulation
- Directivity test
  - Three PLB events on the semicircle with radius 150 mm from the sample sensor at different angles
  - Maximum amplitude per hit averaged and plotted versus each angle

Since the nature of optical and electrical AE signals are different, some prior remarks and definitions are necessary to allow a direct comparison. First of all, the measured signals will be represented in different physical units and are scaled differently. Optical signals are resulted from optical path length changes in the interferometer arms induced by the surface acoustic waves, and have units of length, whereas electrical signals are induced by the piezoelectric effect in the PZT sensor in response to such acoustic waves, and thus, have units of voltage. Fig. 2 shows the recorded signals from both systems, with a PLB at a distance of 50 mm from each sensor, or considering the schematic design of Fig. 1a, PLB at a 50 mm distance from PZT1, and another PLB at a 50 mm distance from ZS200043AE. As it is evident from this figure, the PZT signal is represented in milli-Volts, whereas the fiber optic sensor (FOS) signal is in nanometers, and the scale of the two signals are also different. It is qualitatively visible the similarity between the collected acoustic signals.

In order to have a clear comparison between the two waveforms, the following measures were defined. The first measure is a unitless parameter



(a)

(b)

Figure 3: (a): Peak amplitude trend, FOS. (b): Peak amplitude FOS and PZT. The different dB reference does not allow an unbiased one-to-one comparison.

representing the amplitudes, defined by

$$A_{FOS}(dB) = 20\log_{10}\left(\frac{\text{Amplitude [nm]} \times 1000}{\text{1pm}}\right), \quad (1)$$

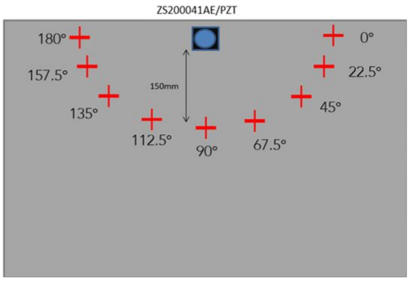
for the fiber optic sensor (FOS), and

$$A_{PZT}(dB) = 20\log_{10}\left(\frac{\text{Amplitude [mV]} \times 1000}{1\mu\text{V}}\right), \quad (2)$$

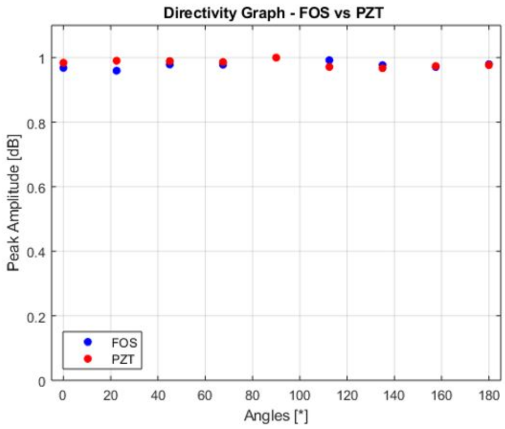
for the PZT sensor.

Sensitivity Test

With the above definitions, the two signals of Fig. 2 were compared in terms of their sensitivity, and the results are summarized as follows. The peak amplitudes were consistent across several measurements, with PLBs at 50 mm distance from the other PZT and optical sensors. More specifically, taking Fig. 1a as a reference, at each red cross 5 AE events were created. The average of the peak amplitude (dB) of these events with respect to each sensor is plotted in Fig. 3a, and Fig. 3b depicts the average sensitivity of the fiber optic sensors and PZT sensors alongside each other when the PLB was at 50 mm distance from each sensor. The peak amplitude parameter is not indicative for comparison since the dB reference is different between FOS and PZT. Despite having different references, the average of the peak amplitude is comparable as shown in Fig 3b.



(a)



(b)

Figure 4: (a): Red crosses represent the location of the PLB at different angles. (b): Maximum amplitude normalized per each set of data, both for FOS and PZT.

Directivity Test

In the second set of tests, the directivity of both sensor types was investigated. This experiment was conducted for both sensor types separately, by subjecting each sensor to the PLB at different angles. Fig. 4a shows the set-up configuration, where three PLB events were generated at each angle, 150 mm from the sensor. The maximum amplitude per each event was averaged over the 3 hits. The results in Fig. 4b show a very close correlation between the directivity of the fiber optic sensor and the PZT sensor, both performing equally uniform in response to PLBs at different angles.

Localization test

The OptimAE system tracks the time of arrival of an acoustic event with a microsecond resolution. The events were located for each PLB and compared with the real event location. The actual PZT/FOS comparison was performed by generating 3 PLB hits at 150 mm from PZT1 as shown in Fig. 5. We developed a triangulation algorithm for the localization of the PLB events, and the results are presented in Fig. 6, showing a sub-centimeter accuracy and precision, comparable with the PZT sensors. In a test plate with dimensions of Fig. 5, the mean Euclidean distance of the retrieved event locations from the localization algorithm to the real event location was 0.86 cm, with a standard deviation of 0.1341 cm. The same algorithm was run for PLBs at other locations as well, including PLBs at a 50 mm distance from all the sensors (optical and PZT), and the accuracy and precision of the localization algorithm were consistently below 1 centimeter.

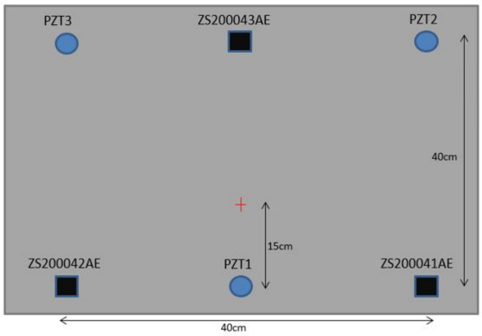


Figure 5: PLB at 150 mm from PZT1.

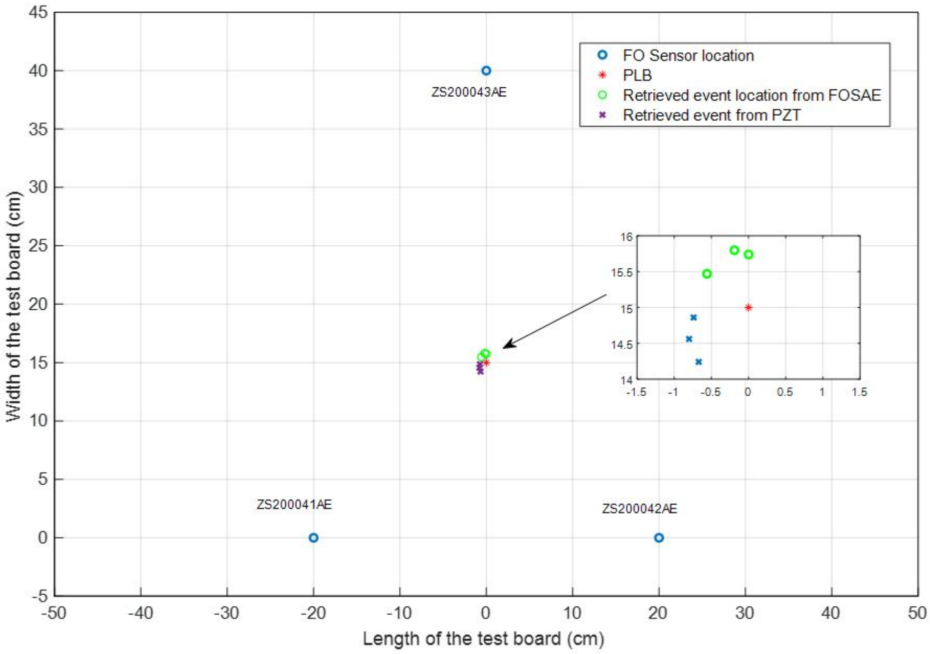
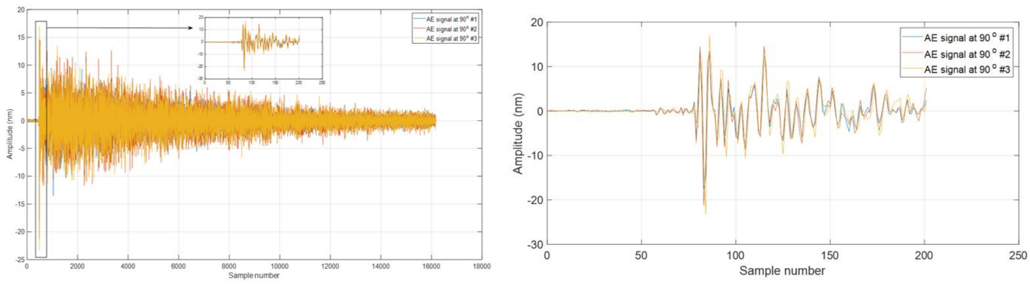


Figure 6: FOS/PZT event localization.

Waveform Comparison

As a final experiment, the reproducibility of the optical sensor signals was investigated. The objective was to compare the optical sensor output waveforms to a PLB at a distance of 50 mm from the sensor but recorded at different times. For such analysis, the 3 waveforms recorded during the directivity test at 90° angle from the optical sensor were taken into account. Fig. 7a shows the three different waveforms alongside each other. For the first 200 samples, the correlation between the three signals is more than 96%, Fig. 7b, which indicates the reproducibility of the recorded signals in the time domain. Eventually, the waveform comparison FOS/PZT was conducted. Displaying the normalized data, allows to appreciate the high qualitative similarities between FOS and PZT waveforms.



(a) (b)

Figure 7: (a): Three waveforms recorded at 90° angle from FOS. (b): Reproducibility of the first 200 samples.

Conclusions

In this paper, the performance of PZT and optical acoustic emission sensors were compared. Standard piezoelectric acoustic emission sensors are difficult to operate in challenging harsh environments. Fiber optic sensors (FOS) - thanks to their passive nature – can easily deal with extreme temperatures like cryogenic or high temperatures, nuclear radiation, electromagnetic interference and liquids, however can only be considered as an alternative when they have comparable performance. The experiments were conducted by Optics11 in collaboration with CETIM, and the sensors were compared by their sensitivity, localization accuracy and precision, directivity and their AE induced waveforms. The results of the experiments showed strong comparable performance between the sensitivity of the two sensor types, which were consistent along several measurements. Further, both sensor types had a uniform amplitude response to AE events measured from different angles, making the positioning of the sensors independent from the test setup or the measurement signals. The localization accuracy and precision of both systems to the AE events in a triangular setup were also comparable. In particular, the localization accuracy of the optical sensors in all the performed tests was below 10 mm. These results show that all the above-mentioned properties retrieved for the FOS are in accordance with the PZT performance despite the different resonance frequencies and principle of operation. The successful tests show that the optical acoustic emission sensors are a comparable alternative in terms of performance with the existing piezoelectric ones, opening new measurement scenarios in harsh-environment conditions and extending the benefits of AE testing to new industries.

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