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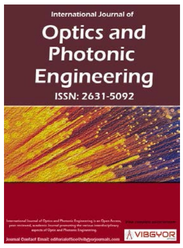

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Enhancing the Performance of FBG Sensors with a Wide-Band Interrogation System

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Abstract

We demonstrate diagnosis of several machine-condition failures using wide frequency-band interrogation of FBG sensors. In collaboration with Israel's national water company Mekorot Ltd., a scaled-down version of a semi-submerged pumping system was constructed. By monitoring broadband signals from DC to ultrasound (> MHz), at different points of the engine and the submersed pump, the system was able to diagnose incipient cavitation, faulty bearings and submerged dynamic water-level measurements. These results prove that wide-band data acquisition, together with advanced analytics, could open a variety of new applications in the fields of structural health and machine-condition monitoring.

Keywords

Structural health monitoring, Machine condition monitoring, Fiber optic sensor, Fiber Bragg grating, Predictive maintenance, Nondestructive testing, Interrogation

Introduction

There is a growing interest in the use of FBG sensors in the fields of structural health monitoring (SHM) and machine condition monitoring (MCM) for civil and industrial needs. They are considered excellent sensing elements that provide static and dynamic measurements for a variety of parameters such as temperature, strain, pressure and vibrations. Their multiple advantages include their low weight, small size, flexibility, and reliability, due to their ability to withstand harsh thermal and environmental conditions, and their immunity to electromagnetic interference [1].

Although FBG sensors provide rich wideband information, most industrial applications use only quasi-static or low frequency measurements [2,3]. The reason for this is the lack of cost-effective interrogating devices that could acquire wideband information [4]. Commercial interrogators usually involve a wavelength sweeping technique that imposes an upper bound in the 1-10 kHz regime. Increasing the band towards the ultrasound regime is a very important issue, especially for predictive maintenance, since it gives the earliest warning of potential problems, and allowing detection of lubrication issues, cavitation, leakage and more [5].

In this work we demonstrate the detection of

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several failure conditions of a semi-submerged pumping system, taking advantage of the wideband information the FBG sensors provide. In addition, a pencil break test was carried out in order to explore the capability of performing acoustic emission testing along with traditional strain measurements for early crack development detection. The RF phase-shift FBG interrogator, which was described in details in a previous paper [6], is expected to serve as a low-cost wide-band device doe to its off-the-shelf all-telecommunication-based design.

Experiments

A semi-submerged vertical pumping system was constructed. The system consists of a semi-submerged pump (Standart SNVB 40-125) having the following parameters: Diam: 148 mm, flow rate: 8 m^3/hr, power: 0.55 kW, 1500 RPM. Figure 1 displays the system construction and components. The pump length was 1.5 meters submerged within a water tank having a closed-loop piping enabling for water to circulate, and a hand-controlled choke for regulation of flow-rate Two optical fibers were used. One fiber was glued along the outer casing of the shaft and the motor, having FBG sensors attached near the bearings, along the shaft and next to the impeller at the bottom of the pump. The other optical fiber had an FBG-based water-pressure sensor (Technica T620) attached on its end, and was submerged at the bottom of the water basin.

We first recorded the interrogator signals as the pump was operated under different normal conditions. We focused primarily on the signal spectrum (FFT), and the effect on the spectrum

Figure 1: Left: Semi-submerged vertical pumping system consists of a 1.5 m submersed pump in a water tank with a flow-controlled water circulating pipe. Right: Sensor installation.

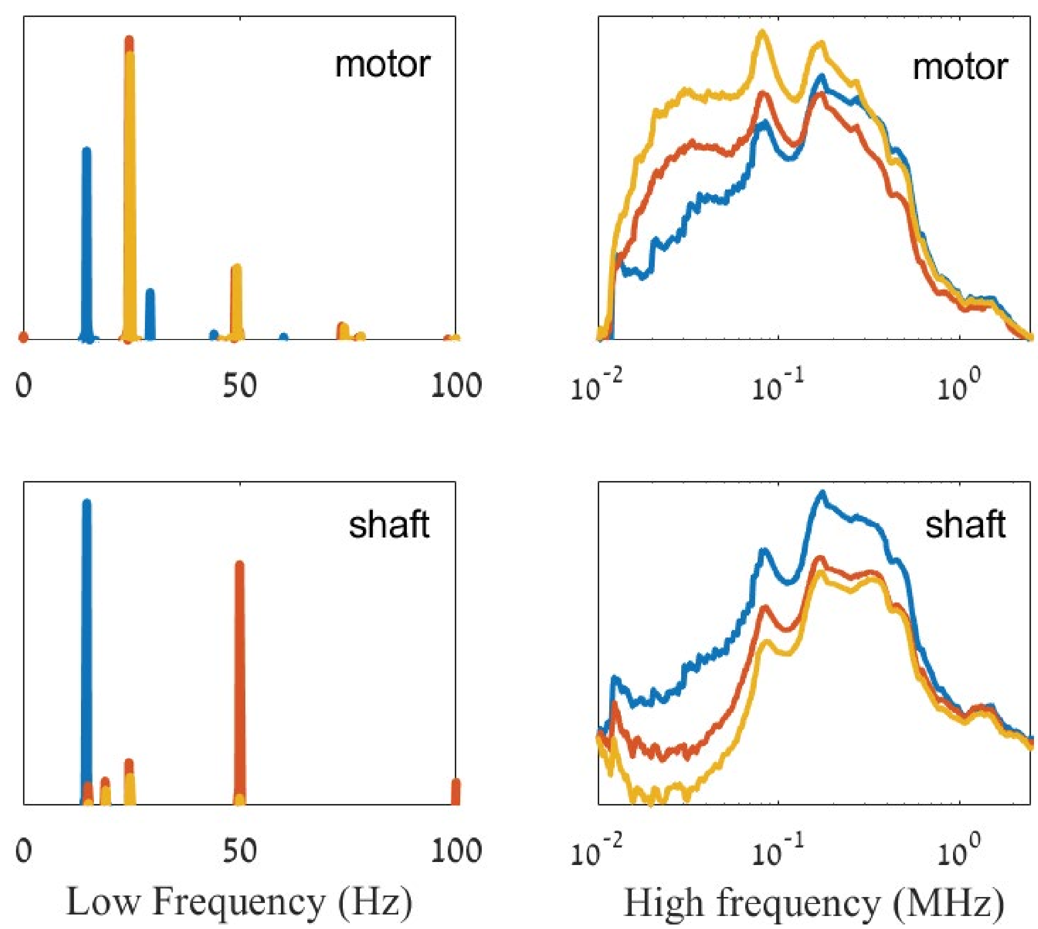

Figure 2: Spectrum of the signals obtained by a sensor attached to the motor and a sensor on the outer case of the shaft, at three different operation modes: 30 Hz open choke (blue), 50 Hz open choke (red), 50 Hz closed choke (green). High-resolution/Low frequency (left), regular resolution/High frequencies (right).

of changes in the operating parameters. Two operating parameters were controllable: the power supply frequency on the motor (using a frequency converter), and the water flow out ejected from the pump (using a choke). Three different combinations of these two parameters were employed during the experiments: 1) Open choke and 30 Hz, 2) Open choke and 50 Hz, 3) Closed choke and 50 Hz. Two sets of measurements were taken during each session: High spectral resolution within the spectral band from DC to 100 Hz, and regular resolution for DC to 2.5 MHz bandwidth measurements.

Figure 2 shows a comparison of the power distribution for the three different conditions. The results were obtained by two sensors, one positioned on the non-submerged motor and the other on the submerged shaft in the water.

The high-resolution low-frequency spectrum of the motor-sensor shows the basic harmonics of the motor rotating frequency, hence in the 30 Hz operation mode peaks appear at 15, 30 and 45 Hz, and in the 50 Hz operation at 25, 50 and 75 Hz. In comparison with the shaft-sensor, the 30 Hz operation shows only the first harmonic of the rotational frequency, whereas in the 50 Hz operation the second harmonic is dominant for the open choke case and the first harmonic for the closed choke case.

The high-frequency measurements show a unique spectral signature for each case. The motor-sensor shows a wider power-density distribution for the 30 Hz operation case rather than the 50 Hz case, while in the shaft-sensor the distribution seems to be steady and change in frequency is reflected only by an amplitude reduction. In the case were the choke is closed a large increase in the magnitude is recorded in the motor-sensor, and a reduction in magnitude is monitored by the submerged shaft sensor. This is due to the high load conditions of the motor and a weaker water flow in the submerged environment near the shaft.

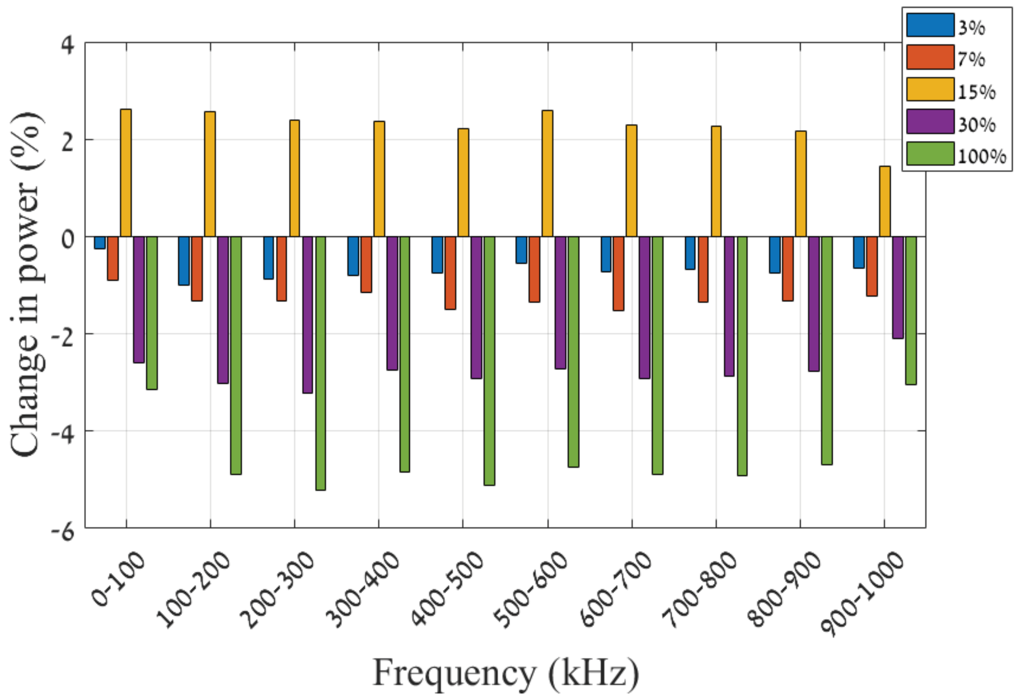

Figure 3: Change in power density distribution relative to fully opened inlet valve over a bandwidth of 1 MHz. The different bars correspond to the amount of closed valve.

In order to investigate the ability of detecting incipient cavitation, an adjustable valve was installed at the inlet of the pump. Cavitation conditions were created by slowly closing the valve until just below NSPHR (Net Positive Suction Head Required). A sensor was installed before the impeller to detect cavitation. The pump was operated at 25% load and 20 RPM. The inlet valve was gradually closed, while the output flow was monitored. Measurements were taken at 3%, 7%, 15%, 30% and fully closed valve. The recording sampling rate was 2 MSa/s enabling for a 1 MHz bandwidth spectrum acquire. The average change in power density relative to fully opened valve is plotted in Figure 3 for the different bands of the spectrum (100 kHz each).

It is clearly seen that closing the inlet valve causes a decrease of vibration intensity throughout the full MHz band due to reduction in water flow, except for anomalous behavior at 15% where more than a 2% increase in vibration power is measured. This behavior is an indication for incipient cavitation which is caused by collapsing voids accompanied by ultrasonic noise.

In addition, the average value of the measured signals corresponds to the mean strain that the FBG sensor feels, which in our case indicates the change in temperature. Figure 4 plots out the change in temperature while gradually closing the inlet valve.

Obviously closing the valve reduces the flow of water entering the inlet of the pump which is why we obtain a decrease in temperature. However, when the valve is 15% closed, we see a sudden rise in temperature which confirms the fact that the impeller experiences cavitation.

In order to explore the ability of measuring dynamic changes of water level in a well, an FBG pressure-sensing module was immersed at the bottom of the water tank. The interrogator output was recorded while operating the pump, which lowered the water level. Simultaneously, we recorded the actual water level with a transparent graduated pipe. The graph in Figure 5 displays the interrogator measurements vs. the actual water level.

It is seen that the interrogator can measure the water level to a resolution of approx. 0.5 cm. According to the sensor manufacturer, the sensor could measure pressure up to 150 psi which is equivalent to approx. 100 meters under water surface, leading to a dynamic range of 43 dB.

In another experiment we investigated the diagnostics of faulty bearings. FBG sensors were

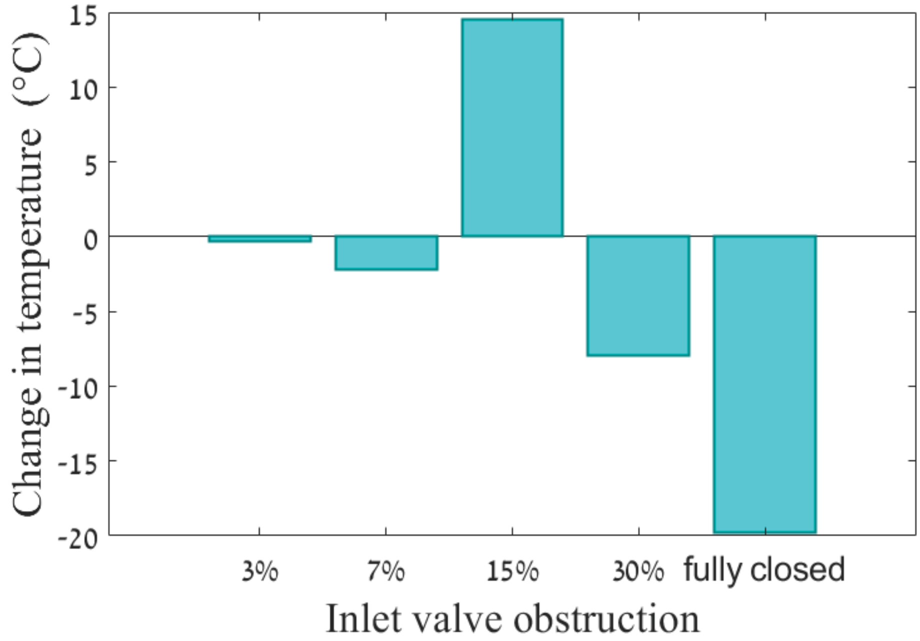

Figure 4: Change in impeller temperature due to reduction of the water flow caused by closing the inlet valve.

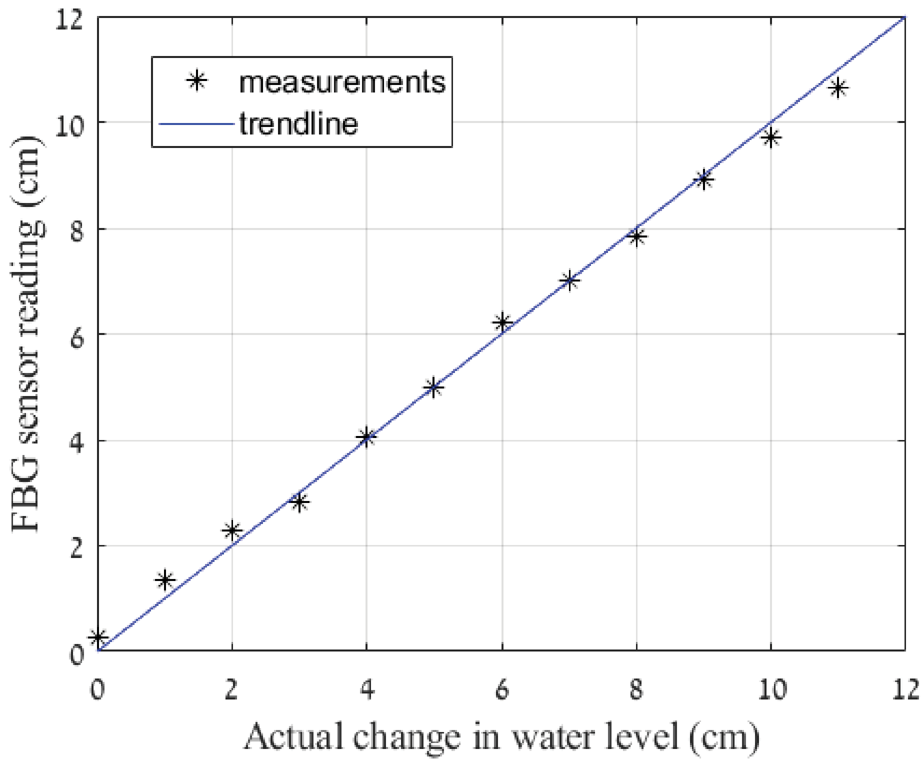

Figure 5: Dynamic water level measurement with an FBG pressure sensor.

attached near the rear bearing of two identical pumps (Pedrollo twin impeller pump P/N 2CP 25/14A, where the rotating freq. @AC 50 Hz is 2800 RPM, or approx. 47 Hz). One of the pumps was a used system, showing slight signs of deterioration. The other pump was a new unit. A comparison between the spectrum of both pumps around typical frequencies can reveal the type of fault exists. Figure 6 plots both spectrums in the region of 142 Hz which corresponds to the outer ring

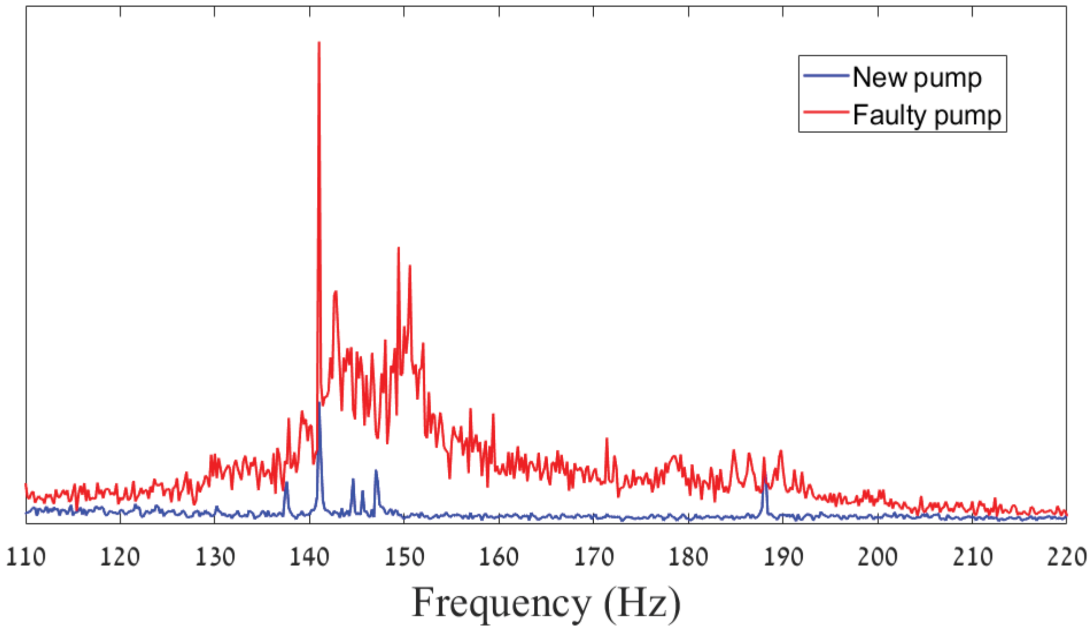

Figure 6: Spectrum in the region of the over-rolling frequency of the outer ring (142 Hz). Blue: New pump. Red: Faulty pump.

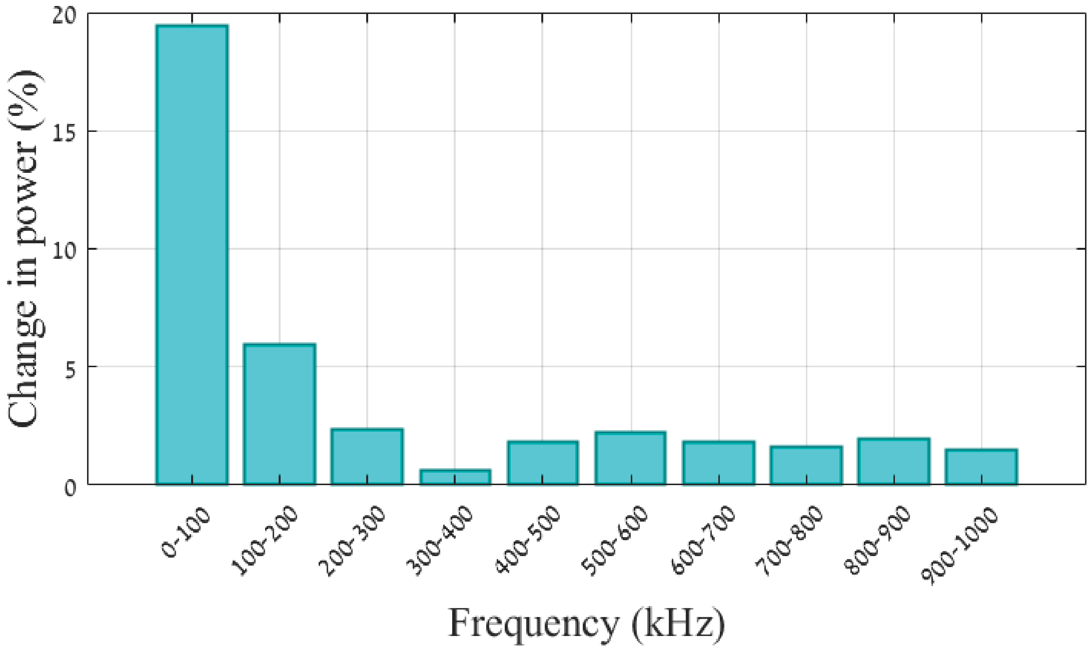

Figure 7: Change in vibration energy of faulty pump relative to a new pump.

over-rolling frequency, according to manufacturer calculations (for a deep groove ball bearing #6204 @2800 rpm).

It is interesting to see how the average vibration energy changed between faulty and normal condition over the wideband 0-1 MHz spectrum. Figure 7 shows the change in vibration power density between the faulty and the new pump. Clearly, there is an increase in energy throughout this spectral region.

A pencil break test was carried out in order to investigate the capability of performing real-time acoustic emission detection along with traditional strain measurements. An FBG sensor was glued on a metal plate next to a PZT accelerometer. A mechanical pencil with a 0.7 mm tip was pressed

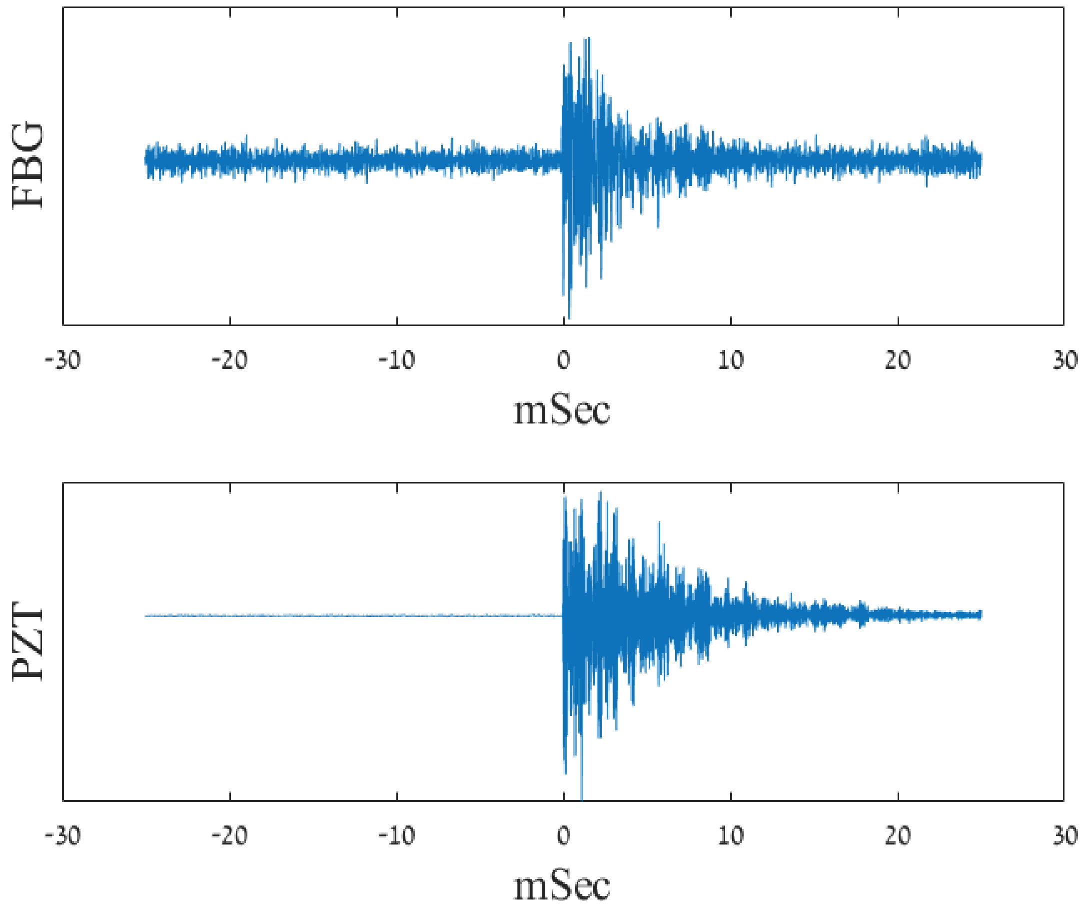

Figure 8: A pencil break test comparison between an FBG (top) and a PZT sensor (bottom).

until the tip was broken. Signals exiting the FBG and the PZT were recorded and plotted in Figure 8.

Good agreement between the two signals are obtained, however it is clear that the signal to noise ratio (SNR) of the PZT is much better. The superiority in performance of PZT over FBG sensors in the field of acoustic crack detection is a well-known issue, and the subject of many investigations that seek solutions to enhance the FBG performance [7-9].

Conclusion

This work describes the performance of a wide-band FBG interrogator from DC up to 1 MHz. The wide-band capability displays clear advantages in simultaneous monitoring of static and dynamic strain, opening up diverse applications in health monitoring and failure diagnostics of structures and rotating machinery.

Inception cavitation, bearing deterioration diagnostics, water-level measurements and acoustic emission signals were demonstrated, using the wide-band FBG interrogator based on the RF phase-shift technique. The fact that the RF phase-shift interrogator relays on the RF over fiber concept, using 'off-the-shelf' components, ensures a cost-effective price per sensor, which is the main drawback of state-of-the-art commercial technologies. The combination of low-cost sensors and multi-parametric wide-band information, enhances the potential of FBG sensors for many applications such as machine condition and vehicle monitoring. The rich data acquired by the FBG sensors constitutes an excellent platform for machine learning and advanced analytic techniques, allowing for predictive maintenance capabilities for the 4th industry revolution.

Acknowledgments

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