A Fiberoptic Sensing System for System Health Monitoring in Oil & Gas Industry Applications

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Abstract
Fugro is a worldwide oil and gas service operator with the core business of data acquisition offshore, onshore and in the air. In a world with increasingly complex and costly systems being installed, often in remote, harsh or difficult to access environments, large scale continuous monitoring of these valuable and critical assets is becoming an increasingly important challenge. These monitoring systems need to collect wide variety of data: strain, sound, vibrations, pressure, temperature etc.

FAZ Technology as part of the Fugro group has developed an ultra-high performance data acquisition system based on fiber optics, perfectly suited for acquiring large amounts of system and structural health and status data. We will present the concept, its performance and capabilities, and we'll present real field applications. A core example will be a system installed on the Fugro offshore survey vessel Pioneer, which monitors a large suite of performance and health data of this vessel allowing online diagnostics as well as prediction of upcoming failure events. The system allows many sensors on a single light weight optical fiber, long distance recording and is robust and stable in a harsh offshore environment. Its functionality is well-suited for various offshore and onshore O&G industry installations, including subsea systems. We will discuss the functional details of the system, its performance, field data, and give an outlook on further developments.

Keywords: Fiber Bragg Grating, Sensors, Interrogator, Monitoring, System

1. INTRODUCTION

For a range of applications, especially in oil and energy fields, there is a growing effort to construct ever more complex structures in areas that are increasingly more remote and difficult to access such as offshore and even deep subsea locations. Furthermore, the structures are operating in increasingly harsh conditions, pushing the limits of performance and efficiency. Such large scale assets, considering their operation and maintenance costs, are in clear need of continuous and remote monitoring, with minimal human interference, for a wide range of parameters, from pressure and temperature to strain and vibration, from a multitude of points distributed over long distances often in harsh and challenging conditions. Fiber optics, with its ability to transmit large rates of data with minimal loss over long distances, and its low production cost, provide an ideal platform as a backbone of a sensing network. Additionally, in many fields of operation, especially in the oil and energy applications, passive operation of fiber optic sensors where the sensing points do not require electrical power provides significant advantages in eliminating the need for power cabling, and allowing operation in potentially explosive environments such as pressurized containers of hydrocarbon products.

To fully leverage the benefits of the fiber optics for large scale sensing applications, two key components are needed; 1) a system of accurately generating coherent and controlled light, and precisely detecting changes in characteristics of light received back, and, 2) a method of generating interaction between the light and the external physical effects to be measured. Here, we present a system that combines these components and demonstrate a large scale multi-parameter fiber optic sensing solution for an offshore vessel. In the system presented here, the key enabling technology selected for fiber optic sensing is Fiber Bragg Gratings (FBGs); wavelength-specific narrow band reflectors formed in the core of standard optical fiber by inducing periodic refractive index variations such that effective wavelengths that are integer multiples of the periodicity get selectively reflected [1]. Due to the simplicity of this relation and the precise controllability of production parameters such as refractive index and periodicity of the variations, FBGs with a broad range of reflection (Bragg) wavelength, reflection bandwidth, location and reflectivity can be manufactured reproducibly according to application specifications, at large scale and low cost. Furthermore, such production ability has enabled the manufacturing of an array of reflectors with precisely pre-determined locations and reflection wavelengths in individually long chains of optical fibers with high robustness [2]. This enables multiple sensors even at large distances to be connected and recorded using a single fiber, further reducing system and installation costs.

Fiber Bragg Gratings, employed widely in telecommunication systems for various filtering applications, have grabbed interest in recent years for their sensitivity to temperature and strain effects, both of which result in a linear change of the Bragg wavelength of reflection with well-established sensitivities [3]. Combined with the array formation capability with wavelength multiplexing described above, Fiber Bragg Gratings started to be viewed as the ideal building blocks for quasi-distributed large area sensor systems needed for applications such as structural health monitoring.

However, due to the mechanical robustness of optical fibers, the optical effects on the light received from the fiber optic sensors is often miniscule, even when employing FBG-based sensing elements. While this provides a very broad and linear operation range, it also introduces the need for high precision optoelectronic recording equipment to enable the resolutions needed in the measurement applications. In the following section, a tunable laser based fiber optic interrogation system capable of monitoring a large number of FBG sensors simultaneously at high speeds is described. Furthermore, techniques for transduction of various physical effects, from strain and temperature to vibration and pressure are presented. Finally, a complete fiber optic multi-parameter monitoring system for a marine vessel installation is described along with initial results obtained.

2. TUNABLE LASER BASED FIBER OPTIC INTERROGATION

While Fiber Bragg Gratings, as described above, can be manufactured and tuned to reflect different wavelengths, also known as wavelength multiplexing, allowing for a large number of sensors from a single fiber to be recorded, it is important to be able to identify and track the different sensors with high precision and high speeds to achieve the performances required for sensing applications. Several techniques of measurement can be employed for interrogation of a large number of FBG sensors in each fiber. In one commonly used approach, a broadband light source to send out a wide spectrum of wavelengths with the reflection coupled to a narrowband selective detector scheme employed to separate the individual reflections upon arrival using various techniques from interference to filtering and demultiplexing.

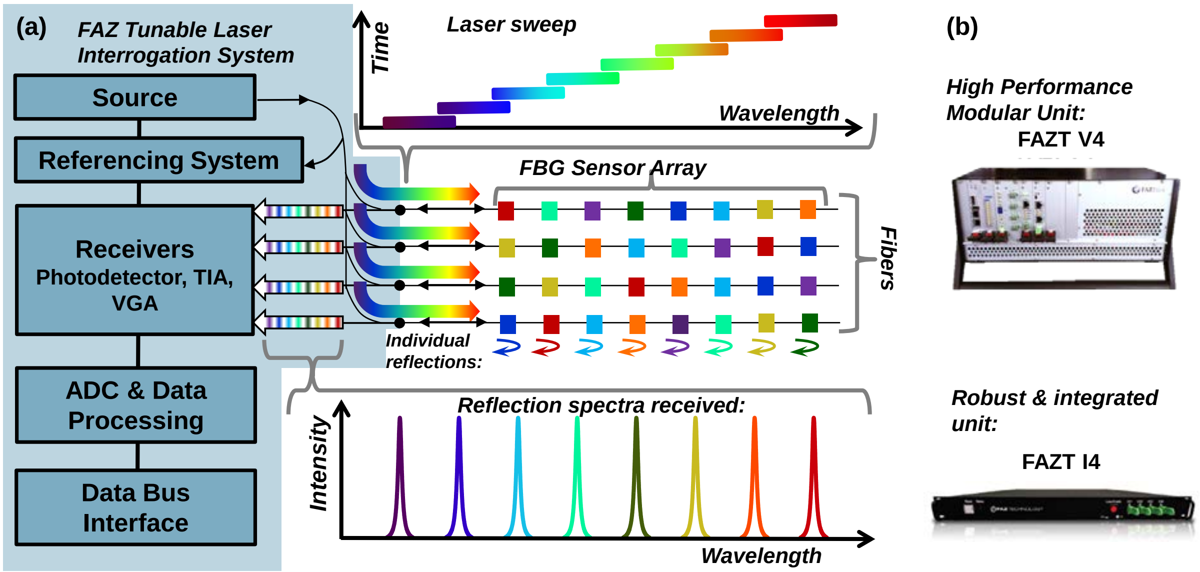

Figure 1(a) The tunable laser interrogation system, where the output wavelength of a narrowband tunable solid state laser is swept through a set of wavelengths and its output is split to multiple fibers in parallel. The integrated referencing system corrects for any thermal or aging related miniscule changes in the laser calibration settings in each recording cycle to ensure very high precision is achieved each measurement. The specific reflections from an array of Fiber Bragg Grating based sensors, organized in any reflection order or spacing the application requires, is collected on photodetectors and, with the input of the referencing system, the optical characteristics of the individual FBG sensors are determined with high accuracy. (b) The two tunable laser interrogator systems, with high performance modular construction reaching 44 kHz recording speed and low cost single board integrated stackable unit with up to 8 kHz measurement frequency.

In an alternative approach, it is possible to generate a narrowband light using a tunable light source such that only a specific wavelength is sent through the fiber at any instant illuminating each part of the spectra in a swept fashion and as such receiving the individual sensor responses consecutively, allowing for a precise identification and tracking of the wavelengths by accurate timing and referencing system. With the relatively recent developments in tunable semiconductor based lasers for telecommunication applications, precise control and adjustment of laser light at very high speeds has become possible. Figure 1(a) schematizes the operation of the tunable laser based fiber optic sensing approach employed by the FAZ Technology interrogation system. Here, a narrow band (with a linewidth <20 MHz) tunable laser output wavelength is swept across a color spectrum of wavelength range (typically 40 nm) using pre-calibrated settings. The generated laser output light is then split between four fiber outputs each with ~+3 dBm (~2 mW) of optical power, with some of the power also directed into an integrated referencing system which corrects for any minor fluctuations in the light output to ensure thermal effects, drift and laser aging issues are completely mitigated and corrected for in the field during operation [4]. The spectra of wavelengths are received by each Fiber Bragg Grating which individually reflect only specific wavelengths (colors) of light. The collective spectra received can then be correlated to individual sensors, such that any minor fluctuations in the wavelengths observed in the individual FBGs can be correlated to physical effects at the specific FBG locations. With a detection limit that allows for high precision tracking of FBGs returning power as low as -17 dBm (0.02 mW) and a programmable gain for each sensor, up to 30 sensors can be tracked on each fiber at millisecond sampling intervals. Figure 1(b) shows the two fiber optic interrogator units available; a modular high performance system that can reach sensor recording speeds up to 44 kHz and the compact low cost rack unit with fully integrated electronics, which can operate up to 8 kHz.

The typical Fiber Bragg Grating peak tracking performance of the tunable laser interrogation system is demonstrated in Figure 2, where the precision in tracking the differential wavelength of a pair of FBGs exposed to the same thermal conditions in an open environment is plotted. Figure 2(b) displays the histogram of the measurements achieved where a repeatability better than 0.1 pm is achieved for the measurements with an accuracy significantly lower than 1 pm. The achieved measurement resolution corresponds to a change of approximately 0.08 microstrains (με) or 0.01 degree thermal change under ideal conditions. While such resolutions are beyond the needs for field applications of strain and temperature sensing, the achieved performance enables a novel generation of temperature compensated strain-based FBG sensors that are finally competitive in performance to electronic sensors for pressure, acceleration, vibration and tilt [5], with all the added benefits of fiber optic sensing described above. The measurement performance achieved for the same FBGs using an alternative interrogation approach based on tunable filter is also plotted for comparison, highlighting the benefits of the tunable laser approach. Finally, the tunable laser measurement system has been shown to handle polarization-induced errors that are common to Fiber Bragg Gratings [6].

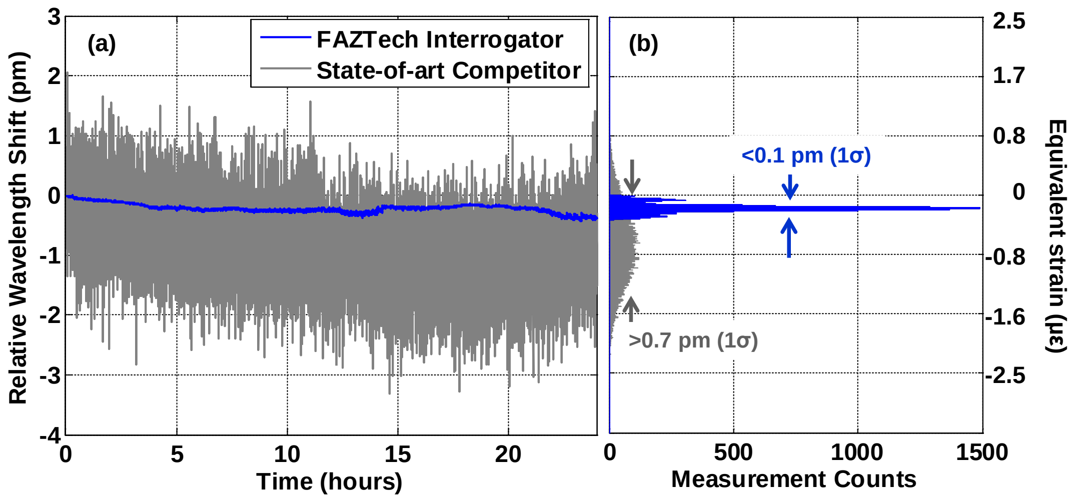

Figure 2 (a) Time trace of a 24 hour differential recording of a pair of Fiber Bragg Gratings whereby both sensing elements are exposed to the same open conditions, and their wavelength difference represents the temperature compensated measurement accuracy achievable, measured with both the FAZ V4 tunable laser unit and previous state-of-art interrogation system based on tunable filter technology. (b) The histogram of the measurements demonstrating the high repeatability of the FAZ interrogation platform, with a 1-sigma resolution as low as <0.1 pm (equivalent to 0.08 με).

3. FIBER BRAGG GRATING SENSORS

The thermal responsivity and the strain sensitivity of Fiber Bragg Gratings have been well established since their early days in operation and it has been used initially for tuning the gratings to required reflection wavelengths, and later to perform highly localized measurements of strain and temperature changes. These properties have already been leveraged in a range of structural health monitoring applications from monitoring of strains in bridges to measurements of temperatures in harsh environments. However, many structural monitoring applications require additional parameters to be monitored, preferably in real-time, to enable more accurate information extraction and correct decision making. The FBGs, with their sensitivity to strain can be employed to detect forces and several different effects can be transduced into forces by use of appropriate transducer elements, as shown in Figure 3. In one example, both static and dynamic pressure can be used to generate a stretching of the FBG by use of pressure flexible sealed sensing elements. In another example, acceleration due to vibration and tilt can be transformed into inertial forces that strain the FBG, as shown in the lower part of Figure 2. With the sub-microstrain level resolutions demonstrated in the preceding section, vibrations down to micro-g level and up to kHz frequencies have been demonstrated. The obtained resolutions have enabled tilt sensing down to 0.01 degree resolution.

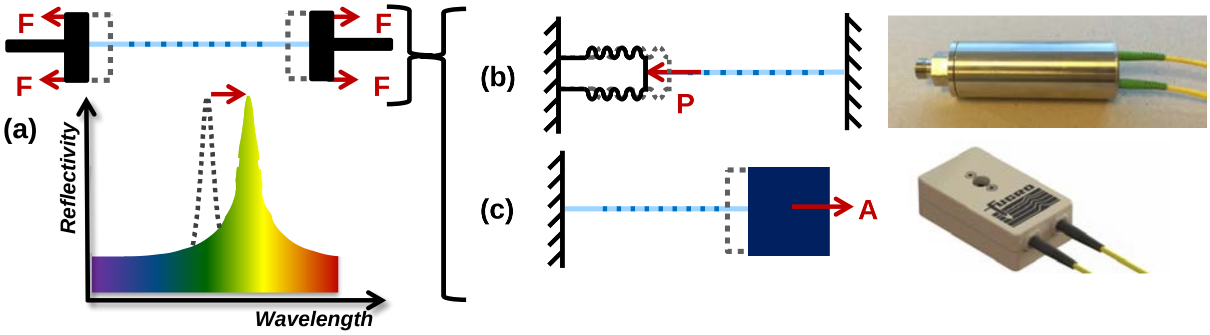

Figure 3 (a) The strain sensitivity of the reflection wavelength of the Fiber Bragg Grating (FBG), also known as the Bragg wavelength, can exploited to manufacture force-based sensing, such as (b) pressure sensors, when the FBG is coupled with a compressible body, or (c) accelerometers by connecting the FBG to a mass where an inertial force due to acceleration with respect to the fixed world can generate strain.

As with any sensing system, thermal effects on the transducer and its packaging have to be carefully considered to be able to maintain the precision and accuracy throughout the operation range of the sensor. Here, the intrinsic sensitivity of the Fiber Bragg gratings provide a considerable advantage as it can be used for compensating the thermal effects using a secondary sensing element on the same fiber integrated into the sensor, and recorded using the tunable laser system as above. Such corrections have enabled, for example, pressure measurement using FBGs with a thermally induced error <0.5% full scale even in exposures to rapid temperature changes [7].

4. MULTIPARAMETER MONITORING SYSTEM FOR OFFSHORE VESSELS

With the fundamental components for fiber optic sensing described above having gone through substantial development in the recent years, and having reached considerable maturity, as described above, time is ripe for field deployments of the technology to demonstrate its potential. Marine vessels, similar to the trend in all offshore structures, are growing in size and complexity. As such, their downtime due to both scheduled and unscheduled maintenance issues, is a growing cost in oil and energy operations. Furthermore, with the ever increasing operation distance to shore, planning of maintenance cycles needs to be very well scheduled. For such high value assets, there is a growing desire to minimize downtimes and perform preventive and even predictive maintenance depending on need as opposed to the current approach of fixed scheduling. However, this requires continuous monitoring of the equipment during operation for a wide range of parameters to enable identification of performance issues, its related causes and decision making on preventive actions to be taken. In such situations, use of electronic sensors often requires a large set of sensors each with their data and power cabling, often using different data acquisition units, in many cases the analog to digital conversion unit being required to be in close proximity to the sensing point to avoid issues related to noise pick-up. Such systems become costly to install, and challenging to ensure the data from the different units are correlated accurately and efficiently.

On the other hand, the Fiber Bragg Grating sensing approach provides a passive set of sensors that are coupled to a generic recording platform such that the wavelength-encoded information is extracted from a central data acquisition and recording unit for all types of sensors, with the system being fully flexible by software configuration to correlate the data to valuable information on temperature, strain, vibration, pressure etc. By sharing of the data acquisition and processing resources across many sensors, the system hardware, installation, data management and overall operation costs are considerably lower and system complexity is greatly reduced.

In one example application, Fugro has outfitted a geotechnical survey vessel, shown in Figure 4(a), with a suite of fiber optic sensors to monitor its engine performance, engine room conditions and hull strain. The entire system is recorded using the tunable laser interrogator platform FAZ I4 described above, with more than 20 FBG-based sensors being wavelength multiplexed to be all connected to an eight fiber channel interrogation system as shown in Figure 4(b), with several pressure and temperature sensors monitoring engine cooling system and engine room conditions, vibration sensors for engine diagnostics and strain gauges for load monitoring on the hull all intermixed on the fiber lines. With a large count of accelerometers connected in designated vibration-based diagnostic points on the generator engine (Caterpillar Marine Generator C18) operating nominally around 1800 rpm, channels 5-8 of the interrogation system with is scanned with 4 kHz to ensure high frequency vibrations are also captured.

The sensors are connected using standard telecommunication fibers to the tunable laser interrogator system located remotely in the engine control room, with the data centrally acquired, processed, and recorded for all sensors, and relayed via satellite communication to fleet management offices on shore every minute. With the data acquired and processed centrally for all sensors, the system allows for overview of the entire vessel as well as detailed analysis. Figure 5 displays an overview of one week sample data demonstrating the correlations between engine load (acquired from vessel control unit), with cooling system activity in pressure and temperature, to engine vibrations which are clearly increasing to several g-levels with strongest tones in the 10-1000 Hz frequency range.

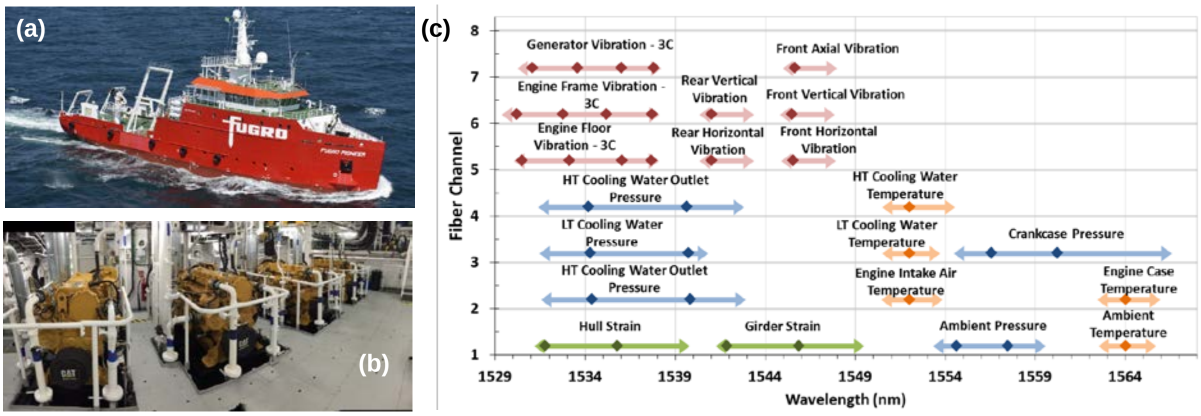

Figure 4 (a) The Fugro Pioneer geotechnical vessel, onto which a fiber optic monitoring system with 8 fiber channels using the FAZ I4 system was installed, with channels 1-4 recorded at 1 kHz and channels 5-8 recorded at 4 kHz, (b) engine room being the primary install area for monitoring of power generator engine monitoring for predictive and preventive maintenance. (c) The wavelength map of the Fiber Bragg Grating sensors, distributed over only eight fibers and 40 nm wavelength map with significant remaining bandwidth for further sensor installations. The dots indicating the nominal wavelengths of each Bragg grating and the arrows indicative of the range of its peak shift within operating conditions. The arrangement demonstrates that with one centralized data acquisition unit, several locations on the engine and generator can be monitored with fiber optic accelerometers (red) described in the preceding section with single and three-axial (3C) configurations, cooling water being monitored for pressure (blue) and temperature (orange) in the high temperature (HT) as well as low temperature (LT) lines for both inlets and outlets, as well engine case and ambient pressure and temperature, and strain (green) on the vessel hull. Fibers 4-8 are scanned at 4 kHz to enable the capture of high frequency dynamic events in the accelerometers while the recordings of Fibers 1-4 are kept to 1 kHz but with polarization mitigation functions of the FAZ I4 interrogator enabled.

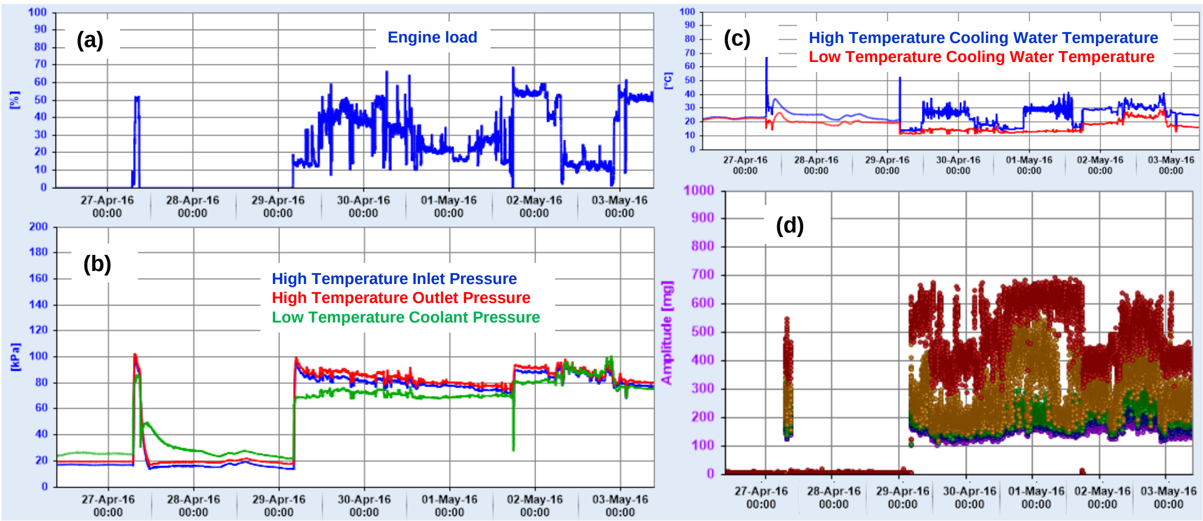

Figure 5 A downsampled sample set of preliminary 1 week data recorded from the fiber optic vessel monitoring system as communicated remotely via satellite link to the vessel, where (a) the engine load (recorded from the vessel computer) can be correlated with (b) the cooling water system pressure and (c) temperature, as well as the (d) vibrations of the 5 strongest tones (different colors) recorded in this case from the generator in its axial direction.

In an effort to establish further confidence in the fiber optic measurement system, an electronic reference accelerometer (Monitran MTN/1100C) recording and the FBG-based accelerometer data is plotted in Figure 6, demonstrating the high fidelity between the two sensors in picking out the strong vibrational tones in the engine. The continuous and precise recording of the individual vibration tones from multiple engine locations identified in collaboration with the engine service experts, is expected to yield much valuable information on the performance of the engine as well as its changes over long periods of operation, especially when the information is well correlated with temperature, crankcase pressure, performance of cooling system and engine and generator loads, as it is for the above described system.

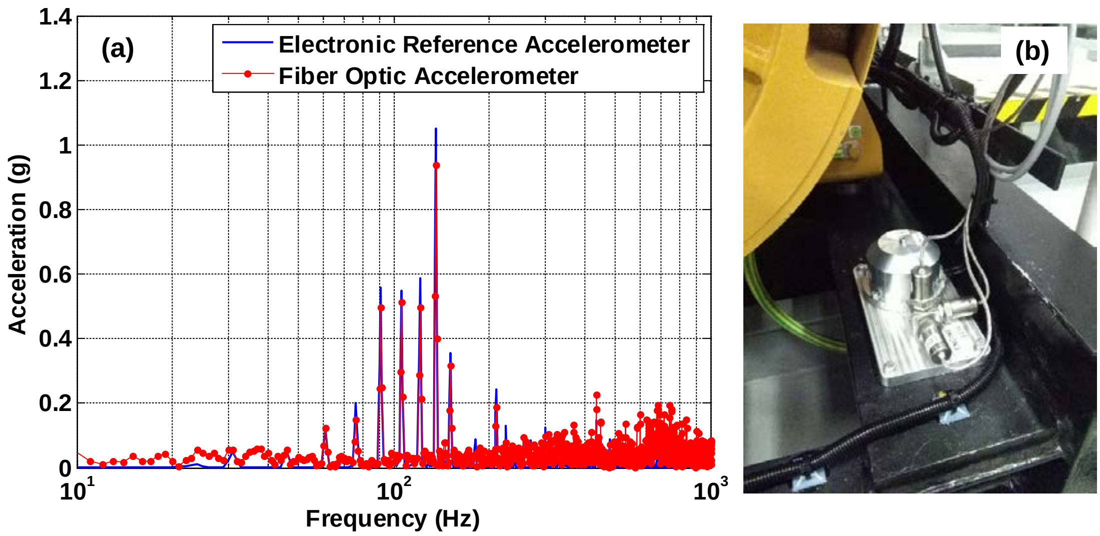

Figure 6 (a) The spectra of engine vibrations recorded in the vertical axis of the (b) engine frame with both electrical and optical 3-component recorder units installed. The result, demonstrating the high fidelity of the optical system with respect to commercial electronic recorders, shows strong tones in the 6-200 Hz spectral band, with vibrations up to g-levels.

5. CONCLUSIONS

With the growing complexity in infrastructure and operational systems, especially in oil and energy markets, real-time and continuous information on the health and operation performance of the assets is becoming increasingly crucial to minimize operational failures as well as maintenance related costs. Here, fiber optics, with its capabilities in remote operation, arrayability, low system cost, and operability in harsh conditions provides a suitable sensing platform. With the latest generation of fiber optic interrogators based on tunable laser system providing the high resolution and high speed recording capability for a large array of diverse sensors, along with the suite of Fiber Bragg Grating-based sensors now reaching maturity, a complete-fiber optic monitoring system becomes highly feasible. Such systems can allow for large scale multiparameter health monitoring installations to be undertaken cost effectively.

To exemplify the potential of fiber optic sensing for structural health monitoring, an FBG-based sensing system was installed and demonstrated for monitoring of a geotechnical survey vessel for preventive and predictive maintenance management application. The system, with recording speed and accuracy required for various measurements, has successfully demonstrated a combination of sensors in one platform, facilitating truly correlated multiparameter continuous monitoring of a complex system.

With the FAZ laser-based system being highly scalable with synchronization capabilities as well as the possibility to measure a larger number of fibers using switching units, very large scale monitoring with passive sensors connected via a low cost fiber grid is definitely leading the way for centralized structural health monitoring systems of the near future.

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