Fiber Optic Sensors for Multiparameter Monitoring Of Large Scale Assets

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Abstract

Determining the operational performance and health of large-scale assets often require the continuous monitoring of a wide range of parameters, from strain, temperature and pressure to vibration and sound. In many situations, it is highly desirable from cost and system robustness point of view to have a centralized data acquisition and analytics for the entire asset. For such applications, fiber optics becomes an ideal option, owing to its inherent characteristics: long distance and lossless data transmission, ability to multiplex and chain multiple sensors, cheaper cabling and passive (electricity-free) sensors.

Here, we present a portfolio of fiber optic sensors, based on Fiber Bragg Grating (FBG) technology, which includes strain, temperature and pressure gauges as well as accelerometers and acoustic detectors. Using novel techniques to leverage the inherent strain and temperature sensitivity of FBGs, for example, drift-free high resolution temperature compensated pressure gauges have been designed and demonstrated. In another example, accelerometers that operate with constant sensitivities from static (0 Hz) to dynamic (kHz) frequency range provide ability to record both tilt and vibration from single sensors, well-suited for machine and structure monitoring.

Keywords: Fiber Bragg Grating, Sensors, Interrogator, Multiparameter

1. INTRODUCTION

Structural health monitoring applications often require various physical parameters to be recorded at multiple locations that are in many cases distributed over large areas. Here, fiber optics can provide significant advantages considering its ability to transmit large amounts of data over long distances with minimal loss. However, until recently, the use of optical fibers in large asset monitoring has been limited to data transmission between communication hubs using electrical sensors, each with their own power supply and digitization circuitry. On the other hand, an increasing number of sensing and interrogation technology building blocks have been developing in recent years to enable passive sensors to be recorded from large distances by use of low cost fiber cables. Recent progress in fiber optic sensors, presented here, allow to overcome these barriers for deployment of fully optical systems in the field.

One important enabling technology for fiber optic sensing is Fiber Bragg Gratings (FBGs), which are essentially wavelength-specific narrow band reflectors formed by refractive index variations in the core of the fiber. In their most simple form, the spacing of the periodic grating with respect to the effective wavelength of the light in the fiber core determines the wavelength of the reflection while the design of the grating along with its refractive index variation allows for adjustment of the reflectivity, the bandwidth and the spectral features of the reflected light. While initially used for telecommunication systems for various filtering applications, FBGs have also attracted attention in recent years for their sensitivity to temperature and strain effects. Essentially, strain-induced increase in the spacing of the gratings results in an increase in the wavelength reflected from the grating, often referred to as the Bragg wavelength, as schematized in Figure 1. Similarly, the FBGs also have well defined thermal response characteristics, where a combination of thermally-induced refractive index change and thermal expansion of the glass fiber resulting in an increase of the Bragg wavelength with increasing temperature. As such, Fiber Bragg Gratings, form an ideal sensing element by allowing manufacturing of very localized sensitive points that do not require electrical power, and by reflecting only a very narrow spectra of light and thus allowing other wavelength multiplexed gratings in the chain to be illuminated by a wide spectra of light and recorded individually, essentially facilitating building of chains of quasi-distributed sensor systems.

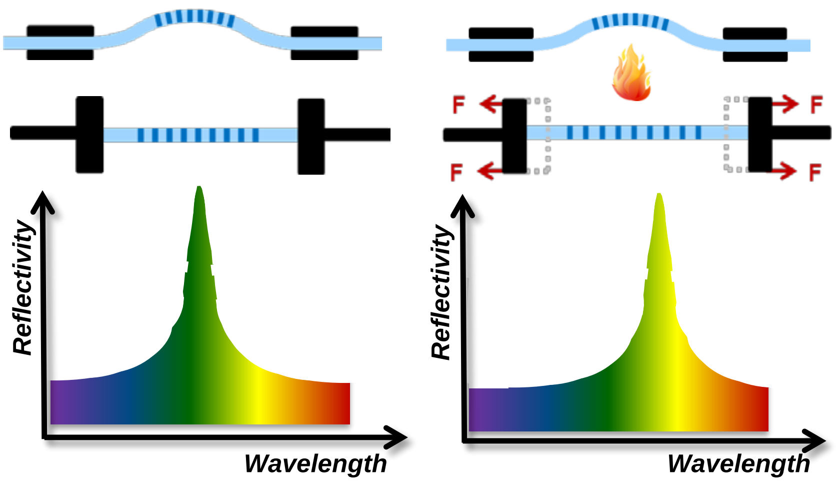

Figure 1: Sensing mechanism of Fiber Bragg Gratings, where changes in the periodicity and amplitude of the refractive index variations results in a shift of the wavelength of the reflected light.

However, despite the inherent advantages of fiber optics and FBGs, the lack of, sensitive, robust and reproducible transducers beyond the strain and temperature sensors and the measurement limitations in cost-effective optical interrogation platforms regarding speed, accuracy and precision have largely limited the use of FBGs to academic environments. Here, a tunable laser based fiber optic interrogation system capable of monitoring up to 120 sensors at 1 kHz and an accompanying set of Fiber Bragg Grating based sensors allowing detection of pressure, sound, acceleration, vibration and tilt are presented.

2. TUNABLE LASER BASED FIBER OPTIC INTERROGATION

Precise and high speed measurements using Fiber Bragg Grating-based sensors requires the tracking of the Bragg wavelengths very accurately to be able to resolve the underlying effects on the fiber, as illustrated in Figure 1. There exists several approaches to FBG interrogation, with the two main ones involving use of broadband source with spectral separation of collected response using a spectrometer or an interferometer, or a narrowband tunable laser source with a broadband photodetector. While each approach has its advantages, it has been shown that for measurement frequency ranges from static (0 Hz) to low kHz range, which covers the needs of many structural health monitoring applications, the use of tunable narrowband laser with broadband detection can achieve Bragg wavelength tracking in the femtometer-level resolutions with cost effective solid state lasers [1]. The detection scheme is based on a wavelength tunable laser with a linewidth of <20 MHz, which is swept across the wavelength measurement range (typically 40 nm) while the source output is continuously calibrated and corrected for thermal and vibration effects using integrated stable gas cells, etalons and interferometers. The system, labeled FAZ Technology I4 and shown in Figure 2(a), can record and track up to 30 FBG sensors in one fiber line with 4 fibers simultenously measured, each illuminated with approximately +3 dBm (2 mW) optical power and with detection capability for Bragg reflections as low as -17 dBm (0.02 mW) while maintaining a resolution of <50 fm (1σ) at 1 kHz sweep frequency.

A typical trace of a pair of FBGs measured differentially is demonstrated in Figure 2, where the demonstrated resolution of 20 fm corresponds to 0.02 με in strain resolution or sub-degree temperature resolution. While the achieved resolution clearly goes beyond the needs of strain and temperature sensing, the precisions achieved allow for accurate and high dynamic range sensing of many other effects such as pressure, vibration and tilt with the careful design of the transducer elements, as described below. Furthermore, with the achieved resolution and ability to multiplex and connect many sensors in a chain of fibers enables many structural health monitoring applications from load and deformation monitoring in large assets such as bridges and buildings, to monitoring of processes or pipelines for temperature conditions.

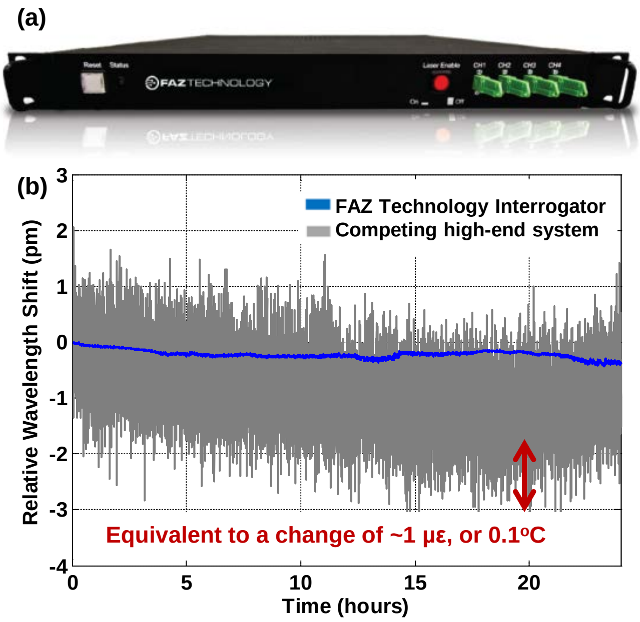

Figure 2(a) The four channel FAZ Technology field-use fiber optic interrogator, based on tunable laser technology with integrated compensation and correction systems that allow it to achieve. (b) Differential measurement of a pair of Fiber Bragg Gratings over 24 hours recorded at 2 Hz with the FAZ Technology V4 interrogation system.

3. FORCE-BASED MEASUREMENTS USING FIBER BRAGG GRATINGS

While Fiber Bragg Gratings are well established in their sensitivity to strain and temperature, there exists a wide range of applications that require measurements of different types of physical effects, such as pressure, sound, vibration and tilt. In most situations, the effects can be transformed into forces using transduction mechanisms which can then be applied on the optical fiber such that they generate strains in the fiber resulting in Bragg wavelength shifts that can be well correlated to the measurand. Here, several challenges emerge to achieve the ideal sensor solution; high sensitivity, large operation range, broad bandwidth sensor with a compact form factor.

Fiber Bragg Gratings provide a very robust sensing element owing to their high strength reaching several percent strain in some fiber types [2], and a high linearity and therefore a large operating (dynamic) range from the resolutions in sub-microstrains, as demonstrated above, to their upper limit of operation (few percents of strain). However, owing to the rigidity of optical fibers, the transduction mechanisms need to be carefully designed to maximize the force generated on the fiber while maintaining the linearity of the response over a large range and fitting the application requirements in terms of size and form factor. Additionally, due to the intrinsic sensitivity of the Fiber Bragg Gratings to temperature, as well as the influence of temperature on the transduction elements, thermal responsivity of the sensor needs to be compensated for, especially for static measurements requiring a high level of accuracy.

3.1 Measuring pressure and sound

There exists many situations where pressure levels and sounds can be highly indicative of the health of the structure being monitored. Safety of storage tanks and pipelines require continuous monitoring of pressure while sounds, which are essentially dynamic pressure waves, can be useful indications of operational or structural issues, especially in underwater environments where long propagation distance of sounds make them suitable for a variety of remote measurements. Fiber optic sensing of pressure, both static and dynamic, can provide significant advantages over traditional electrical counterparts in various situations. In explosive or hazardous environments, such as pressurized tanks of hydrocarbon gases, fiber optics provide an inherently safe sensing scheme for determining tank pressures and monitoring of safety during operations. In subsea, use of long chains of sensors without the need for electrical power and signal lines to record depth as well as acoustic signals can enable applications from localizing equipment to identifying faults and structural failures based on acoustic signatures of machinery. In refineries and production facilities, a large distributed network of pressure gauges can be linked up without the need for expensive electrical power and data cables.

Fiber Bragg Gratings have been previously utilized for pressure sensing in some of these applications [3]. Early attempts to pressure sensing have focused on use of diaphragms or membranes as the transduction elements, whereby the fiber is attached either perpendicular to or on the surface of the flexible membrane such that deformation of the center of the diaphragm results in a stretching of the fiber. Both designs have encountered significant fundamental shortfalls whereby the high sensitivity transducer that can be obtained with large diameter to thickness ratio of the membrane results in highly nonlinear transducer element with very limited linear operation range. Furthermore, the design with the fiber being perpendicular with the membrane results in a construction that is often single fiber port, resulting in loss of one of the fundamental advantages of FBGs for easy chain formation capability with 2 fiber ports. The latter design, where the fiber is attached on the surface of the membrane [4], there exists considerable restrictions in the grating length to ensure uniform strain across the grating for avoiding distortions on the spectral response of the FBG.

Here, the above challenges are overcome by the use of a novel transduction scheme based on pressure-sealed deformable bodies with large linear operation range. Figure 3(a) shows the schematic of the pressure gauge based on bellow configuration whereby the Fiber Bragg Grating is stretched in length in response to the compression of the pressure-sealed transducer elements attached at the either side of the grating. The configuration is symmetric and easy to assemble with the fiber going through the construction for a two-port configuration, as shown in Figure 3(b). The sensor described above allows for various sensitivities to be achieved by changing the effective hydraulic area of the transduction elements and the rigidity of the assembly. Figure 3(c) displays the response of the FBG-based pressure gauge to pressure changes, in comparison to a calibrated reference.

Furthermore, due to the compact form factor, relatively high rigidity of the fiber and the small effective mass of the assembly, very high fundamental modal frequencies can be achieved, typically in the kHz-levels. As such, the transduction mechanism essentially forms an acoustic sensor that can operate with very flat response in frequency levels that are relevant for a range of applications, especially suitable for acoustics for machine monitoring.

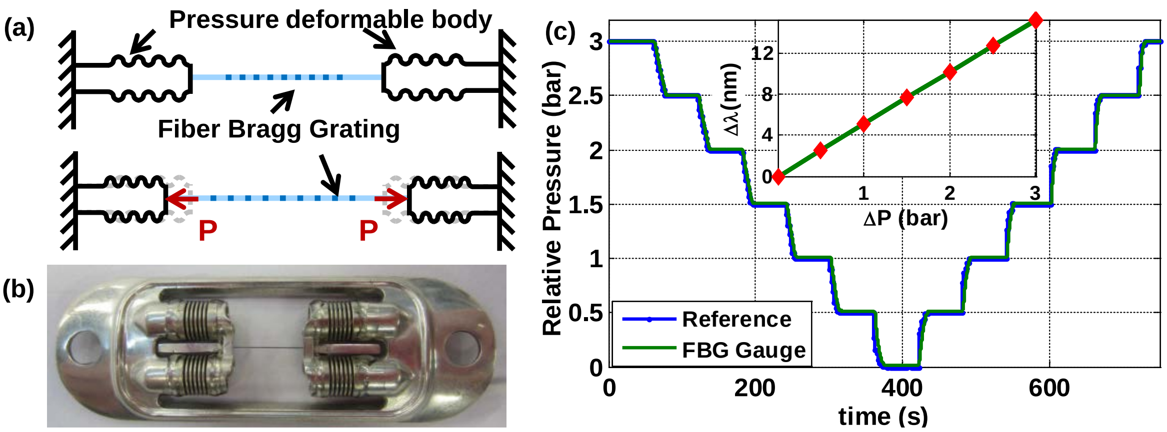

Figure 3.(a) A fiber optic pressure transducer whereby a section of fiber containing the Fiber Bragg Grating (FBG) is strained with increasing pressure as the pressure deformable bodies are decreasing in length. (b) A picture of the FBG-based pressure transducer, and (c) the measurement results with the same gauge to pressure steps of 0.5 bar pressure with a Bragg wavelength sensitivity of 5.1 pm/mbar in comparison to the calibrated reference in the pressure controller (GE PACE6000). Inset shows the linearity of the response of the FBG-based pressure gauge across the measurement range even up to signals that reach 1.3% strain of the grating.

As discussed above, Fiber Bragg Gratings, while being highly sensitive to strain also show thermal sensitivity due to a combined effect of both thermal expansion of the grating and the refractive index change with temperature [5]. As such, it becomes impossible to distinguish temperature and pressure effects with a single FBG sensing element. For accurate measurements of (static) pressure, it is necessary to compensate for thermal effects. One approach for cancelling out the thermal effects is the use of a secondary Bragg grating in the same sensor such that the wavelength shifts $[\Delta\lambda]$ of the two FBGs will contain information on both measurands of temperature change ΔT and pressure change ΔP, as defined by

$$[\Delta\lambda] = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta P \end{bmatrix}, \quad (1)$$

where the pressure and temperature sensitivity coefficients, c_{i1} and c_{i2} respectively, of are substantially different to each other and need to be empirically determined during calibration cycling of the pressure gauge with a series of temperature and pressure exposure combinations. Here, FBG sensing elements provide the advantage that two sensing elements can easily be placed in one fiber with slightly offset Bragg wavelengths, such that they can both be recorded remotely using the same fiber and interrogator unit, without any significant complexity in the read-out or data analysis. Figure 4 displays the residual temperature change induced error in a set of temperature corrected FBG-based pressure gauge with dual Gratings according to equation (1), where even at relatively high temperature shifts of >30^{o}C/hour temperature increase the error remains well below 0.5% full scale.

The above described balancing also allows for very high stability sensors such that drifts and creep effects in the sensor are also balanced out. Figure 5 displays the month-long recording of the same type of pressure gauge as in Figure 4**,** whereby the error remains <+/- 0.1% FS even at elevated temperatures where drifts and resultant errors are expected to be accelerated.

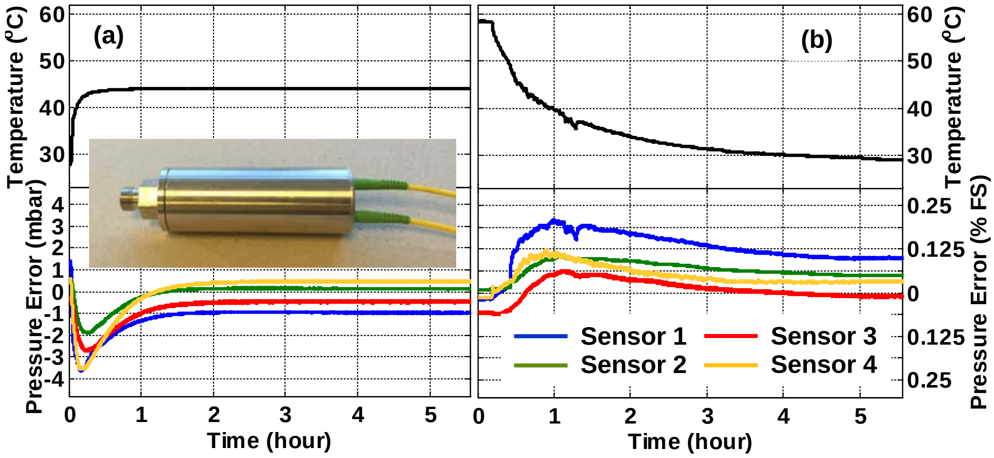

Figure 4 Pressure measurement error generated in 4 FBG-based 2-fiber port relative pressure gauges with 1 bar measurement range (shown in the inset) of due to (a) rapid heating with >30°C/hour, and (b) a cooling from 60°C to 30°C whereby a maximum transient error of <4 mbar (<0.4% full scale) is observed briefly while thermal equilibrium is reached and error is reduced below <0.1 % full scale.

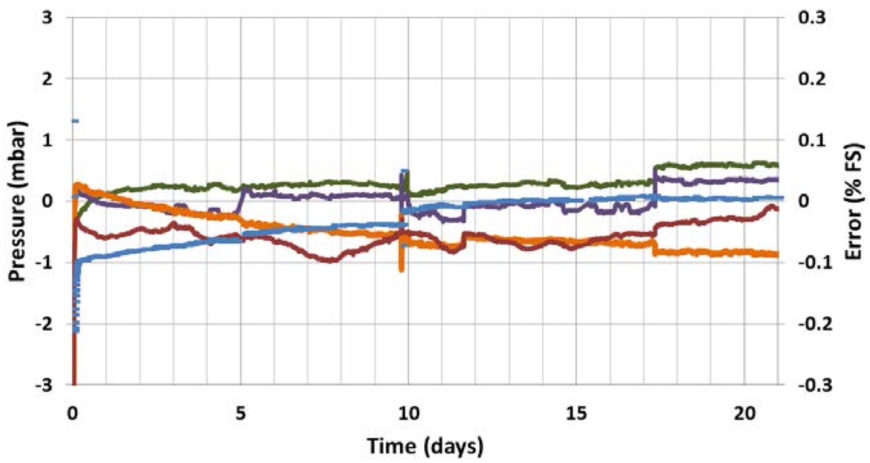

Figure 5 Month long recording of 5 FBG-based 2-fiber port relative pressure gauges with 1 bar measurement range and 5 pm/mbar sensitivity, kept at elevated temperature of 60°C for acceleration of drift, whereby the zero point drift of the sensor is continuously recorded using an FAZ I4 interrogator, demonstrating a peak-to-peak error of less than 1 mbar 0.1% full scale. All sensors yielded a standard deviation of <0.04 mbar (1σ).

3.2 Measuring vibrations and tilt

Another measurand that is important for structural health monitoring applications is vibrations. From decision making in preventive and predictive maintenance for machines, especially for rotary elements [6], to monitoring of bridges and railroads, continuous recording of vibrations can provide significant data regarding the health of the asset being monitored. Typically, however, vibrations on machinery and structures are low in amplitude of motion with high frequency content. As such, accelerometers, whereby the signal amplitude is proportional to f^2x, where x is the displacement amplitude and f is the frequency of vibration, are suitable devices for recording vibrations in structural health monitoring applications.

Accelerometers are simply mass-spring mechanisms where a mass, often referred to as the inertial mass, is connected to a reference frame through a spring element such that inertial forces due to accelerations coupled into the frame result in a motion of the inertial mass with respect to the frame. In the simplest design, Fiber Bragg Gratings can be used as the spring element between the frame of reference and the inertial mass, as schematized in Figure 6 such that the inertial force generates strain on the FBG which can be remotely measured.

Furthermore, the use of transmission mechanisms, such as that shown in Figure 6(b) can provide significant flexibility in design and the trade-off between the sensitivity and resonance frequency of the accelerometers, where the sensitivity is amplified by decreasing the transducer rigidity while the resonance frequency is proportional to $\sqrt{\text{stiffness}/\text{mass}}$ Ideally, it is desirable to operate the accelerometers substantially below the resonance frequency, in the region where the sensitivity of Bragg grating wavelength to acceleration is constant with frequency. By introduction of transmission ratio, a significant enhancement can be achieved in sensitivity for a given operation frequency band. Furthermore, the use of transmission arms allows for more compact form factor for a given frequency range accelerometer as well as a range of different accelerometers to be built on the same architecture. The response of the FBG-based accelerometer with transmission mechanism that results in a Bragg wavelength sensitivity of 3.8 pm/(m/s^2) is plotted in Figure 7, in response to a single tone frequency shaker signal is demonstrated with a signal at 0.2 pm/(m/s^2) at 100 Hz. The spectral response plot of Figure 7(b) demonstrates the very high signal to noise achieved in the measurement when using the tunable laser interrogator platform from FAZ Technology.

Finally, it is important to note that the fiber optic accelerometers, much like the pressure sensors described in the preceding section, provide the additional advantage of providing a constant sensitivity to 0 Hz, which can be a challenge in (piezo)electrical sensing systems which are influenced by capacitive effects. The measurement capability to static conditions allows for measurements of static acceleration, such as gravity vector and its direction and thus facilitating accurate recordings of orientation and tilt.

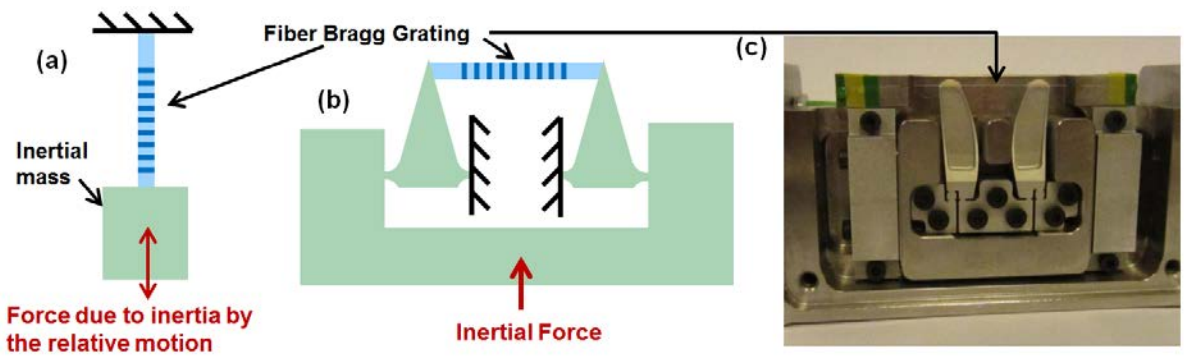

Figure 6 (a) The simplest accelerometer with the Fiber Bragg Grating forming the spring attachment between the frame of reference and the inertial mass, such that the FBG is strained in response to acceleration induced inertial forces. (b) Schematic and (c) photograph of a novel force transmission system that enables enhanced sensitivity for a given frequency band of operation.

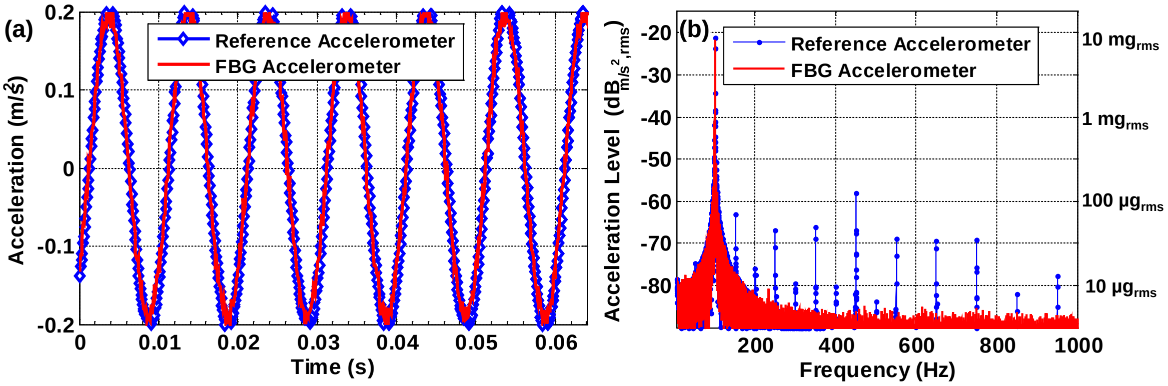

Figure 7 (a) Time trace recording of a 3.8 pm/(m/s^2) sensitivity FBG-based accelerometer measured with a FAZ Technology V4 interrogator recording at 10 kHz in response to a vibration of 0.2 m/s^2 amplitude generated on a shaker table, in comparison to a certified electronic accelerometer (Bruel&Kjaer 4506B), and (b) the spectral plot of the response demonstrating the high signal to noise ratio of the sensor, even at relatively weak vibrations of approximately 0.1 m/s^2, with noise floors in the low-μg levels as shown. The peaks in the spectra of the reference accelerometer are determined to be electronic noise at harmonics of 50 Hz, not affecting the optical accelerometer.

In Figure 8, the combined tilt and vibration capability of the accelerometer is demonstrated whereby the low frequency tilting of the sensor back and forth is recorded alongside the higher frequency vibrations on the unit. With Bragg wavelength sensitivities reaching >20 pm/degree of tilt as demonstrated in Figure 8, using the tunable laser interrogator FAZ I4 resolutions in the 0.01^o to 0.1^o become achievable using compact tilt sensors. This capability provides several opportunities in structural monitoring of large structures, especially in marine vessels and offshore platforms for motion and deformation monitoring in challenging sea conditions.

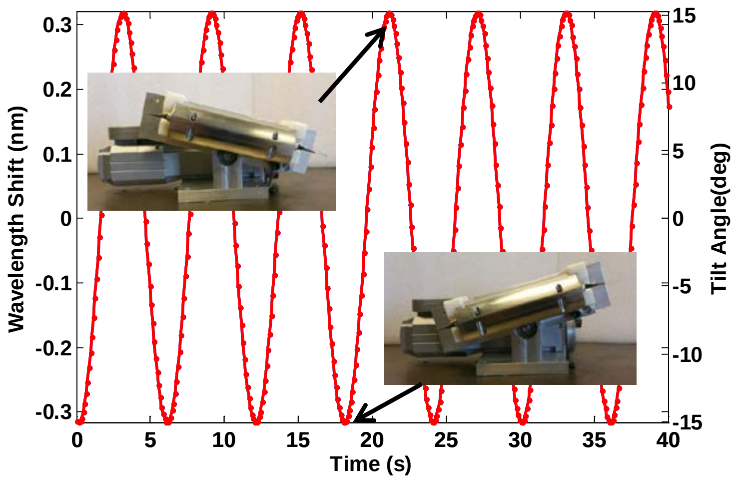

Figure 8 The response of a tilt sensor, built on the same concept of the very high sensitivity accelerometer, demonstrating an FBG reflection wavelength sensitivity of 21 pm/degree and tilt measurement capability up to reaching 0.1^o resolution and an operation range up to 200 Hz.

5. CONCLUSIONS

Structural health monitoring applications often require a large distribution of sensing points with a range of quantities to be recorded. In many applications of such nature, fiber optics is known to be inherently advantageous owing to its ability to cost-effectively transmit optical signals over large distances with minimal loss, with high bandwidth and without interference. Furthermore, Fiber Bragg Gratings have established themselves as potential sensing elements for temperature and strain without requiring coupling of light between free space and optical fiber. However, adaptation of FBG-based sensing in the applications has been limited due to the limitations in high precision recording equipment in performance and cost, as well as the lack of robust and reliable sensors for different physical parameters.

Here, a range of sensors recording pressure, sound, vibration and tilt are presented, where by leveraging the combined strain and temperature sensitivity of Fiber Bragg Gratings a set of thermally isolated and highly stable sensors are manufactured. Furthermore, in combination with a tunable laser based interrogation system, high resolution and broadband sensing performance is demonstrated. The above described technologies clearly provide a set of measurement tools that can be used in measuring a wide range of physical quantities all based on Fiber Bragg Grating sensing elements. Clearly, the wavelength multiplexing capability of FBGs along with the generic technique for interrogation of their spectral characteristics allows for chains of various sensors to be intermixed for multiparameter quasi-distributed sensing systems to be installed. With a potential to record up to 120 sensors over 4 fibers using one system, clearly the system installation and maintenance costs for large scale structural health monitoring applications using FBG-based sensing can be significantly lower than their counterparts in electronic sensing. Additionally, it is important to highlight that since static applications such temperature and pressure monitoring may not require recording speeds in milliseconds, the standard measurement speed of the FAZ tunable laser platform can be leveraged to even further increase accuracy by averaging or enable a substantially higher number of sensors to be recorded per interrogation unit by use of a synchronized high speed optical switch unit to alternate the signal between many more fiber lines, further reducing the cost-per-sensor for large scale monitoring systems.

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