Review of Fiber Optic Accelerometers

Chris Baldwin, Jack Niemczuk, Jason Kiddy, and Toni Salter
Systems Planning & Analysis, Inc.
Advanced Engineering Development Program
4865 Walden Lane, Lanham, MD 20706
cbaldwin@spa.com; www.spa.com/aedp.htm

λ	Wavelength	K	Spring constant
n	Refractive index	L	Length
Λ	Grating pitch	a	Acceleration
p	Strain optic coefficients	M	Mass
ν	Poisson's ratio	E	Elastic modulus
ε	Strain	A	Area

ABSTRACT

Over the past decade, the proliferation of fiber optic sensors and sensing systems has been ever increasing, especially the use of fiber Bragg grating (FBG) based sensors. These sensors have been mainly relegated to research applications with a few noted large-scale structural tests. The main sensing parameters for these tests have been strain and/or temperature. This paper discusses the development of accelerometers with FBG sensors as the measurement medium. The discussion includes a brief overview of FBG sensors, the functionality of FBG sensors as accelerometers, aspects of commercially available instrumentation for monitoring the accelerometers, and experimental data from three commercially available accelerometer designs. The purpose of this paper is to provide the modal analysis community with an understanding of the current state-of-the-art in fiber Bragg grating sensors for dynamic and vibration testing.

INTRODUCTION

Traditional accelerometers used in modal analysis are either piezoelectric, piezoresistive or capacitive based sensors that measure the motion of a structure via the current induced by the inertia forces acting on the material. The response of these sensors is typically processed by a signal amplifier and converted to a voltage change for detection and acquisition. This technology has proven useful in many applications. In recent years, the development of fiber optic-based sensors has seen fiber optic sensors for the measurement of strain, temperature, and pressure that have performance characteristics meeting and/or exceeding those of traditional sensors [1]. The development of fiber optic accelerometers and their use in existing markets has been slow to materialize due to the general unfamiliarity of fiber optic sensors in these markets. Applications with severe operating environments, such as oil and gas drilling, where the advantages of fiber optics sensors allow them to function, where traditional sensors cannot, have been the only areas to see marginal use of these devices. This paper aims to provide a brief introduction to a particular fiber optic sensor, the Fiber Bragg Grating (FBG), and its use as an accelerometer.

A key issue facing the proliferation of FBG sensors and instrumentation systems is the lack of acceptance in the market place. Part of the lack of acceptance is due to a lack of an industry standard by which the products can be produced. Currently, each manufacturer has their own means of fabricating the FBG sensor designs and instrumentation systems that lead to a wide variety of capabilities and the potential for incompatibility between instrumentation systems and sensors. By gaining a basic understanding of the functionality of FBG sensors and the different types of instrumentation, an informed consumer can begin to make decisions regarding what is the best sensor and instrument for their particular application needs.

FBG SENSOR OVERVIEW

The commercial interest in FBG sensors continues to grow due to their inherent optical advantages and multiplexibility. FBGs have become an integral part of modern telecommunications hardware, used in applications such as add/drop filters, fiber lasers, and data multiplexing [2]. Since the discovery of the photosensitive effect in optical fiber [3], by which UV light can be used to induce a permanent change in the refractive index of optical fiber, researchers have been discovering new applications for this unique optical phenomena. Photosensitivity causes an essentially permanent change in the refractive index or opacity of glass induced by exposure to light [2]. In the case of Bragg grating formation, the change of the refractive index of an optical fiber is induced by exposure to intense UV radiation (typical UV wavelengths are approximately in a range from 150 nm to 248 nm). To create a periodic change in the refractive index, an interference pattern of UV radiation is typically produced such that it is focused onto the core (light guiding) region of the optical fiber. The refractive index of the optical fiber core changes where the intensity is brightest in the interference pattern to produce the periodic refractive index profile [2]. The length of a single period for the grating structure is called the grating pitch, Λ, as shown in Figure 1. The pitch of the grating is controlled during the manufacturing process, and this pitch is typically ~0.5 μm, while the amplitude of the index variation is only on the order of 0.1 to 0.01 percent of the original refractive index [2]. Each FBG reflects a unique wavelength based on the effective refractive index and pitch of the grating as:

$$\lambda_B = 2\, n_{eff}\, \Lambda \tag{1}$$

where n_{eff} is the average refractive index and the subscript 'B' defines the wavelength as the Bragg wavelength.

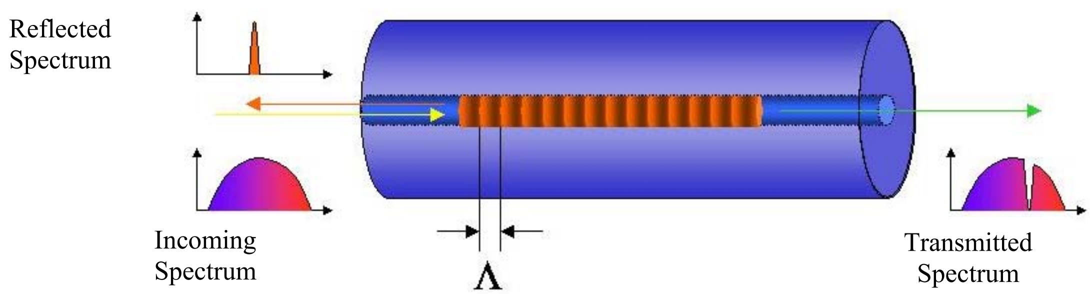

Figure 1: Schematic of FBG sensor with reflected and transmitted spectra

Both the effective refractive index of the core and the grating pitch vary with changes in strain (ε) and temperature, so that the Bragg wavelength shifts to higher or lower wavelengths in response to applied thermal-mechanical fields. For most applications, the shift in the Bragg wavelength is considered a linear function of the thermal-mechanical load. The treatment of FBG sensors here will ignore the thermal effects, because the thermal effects can be modeled as an independent response of the Bragg grating. The following equation demonstrates the Bragg wavelength shift of the FBG sensor on the refractive index, strain-optic coefficients, and Poisson's ratio for the optical fiber.

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(1 - \frac{n_{eff}^2}{2}\left[p_{12} - \nu\left(p_{11} + p_{12}\right)\right]\right)\varepsilon_z \tag{2}$$

The terms multiplying the strain in Equation 2.12 are constant over the strain range of the Bragg grating, and Equation 2.12 is often written in simplified form as

$$\frac{\Delta\lambda_B}{\lambda_B} = P_e \varepsilon \tag{3}$$

Multiplexing is one of the most critical advantages offered by Bragg grating sensor technology. Serial multiplexing involves using the wavelength selectivity of FBG sensors to multiplex many FBG sensors within a given wavelength space following the illumination with broadband or white light. As shown in Figure 2, serial multiplexing is accomplished by producing an optical fiber with a sequence of physically separated Bragg gratings, each with different grating pitches, $\Lambda_i,\ i = 1,\ 2,\ 3, \ldots,$ n. The reflected spectrum contains a series of peaks, each associated with a different Bragg wavelength given by $\lambda_{Bi} = 2n\Lambda_i$, where λ_{Bi} and Λ_i are the Bragg wavelength and pitch of the ith grating, respectively. For example, the measurement field at grating 2 in Figure 2 is uniquely encoded as a perturbation of the corresponding Bragg wavelength, λ_{B2}.

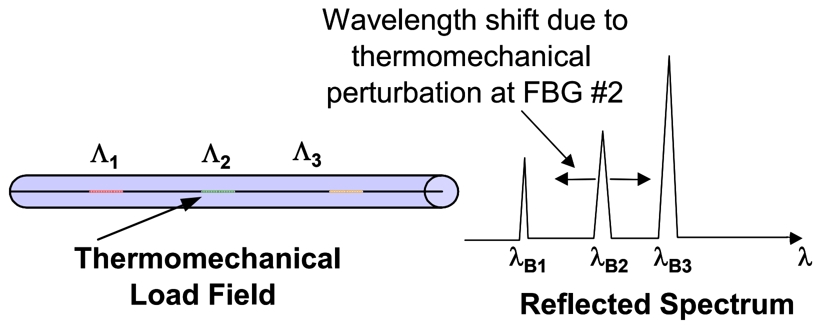

Figure 2: FBG sensor serial multiplexing

FBG-BASED ACCELEROMETERS

In order for an FBG sensor to function as an accelerometer, the acceleration must be coupled to a mechanical load on the FBG. The resulting wavelength shift is then calibrated to the level of acceleration. One can envision multiple schemes to construct such a devices, and multiple vendors are offering these types of sensors as commercial products. The opto-mechanical design of the accelerometer determines the characteristics of the sensor from linear frequency response range, maximum acceleration, and sensor sensitivity (in terms of wavelength shift to acceleration). In order to gain an understanding of these influences, a simple linear spring accelerometer model is examined with the FBG sensor acting as the spring attached to a mass (M), as shown in Figure 3. In this case, the optical fiber acts as a mechanical rod with a spring constant K=EA/L. The FBG sensor is optically inscribed into the glass structure of the optical fiber, and the mechanical properties can be assumed to be similar to that of the original optical fiber. Optical fiber possesses a modulus of elasticity of 69 GPa, and typical singlemode optical fiber has a diameter of 125 μm (diameter of the glass structure). If the fiber length is set to 2 cm and the mass is set to 0.5 Kg, then the natural frequency of the accelerometer design is found to be 46.3 Hz. Variations in the length of the optical fiber section and mass will shift the natural frequency, thus changing the accelerometers frequency response range. Issues of maximum load on the optical fiber and buckling of the optical fiber need to be addressed to determine realistic limits for this sensor design.

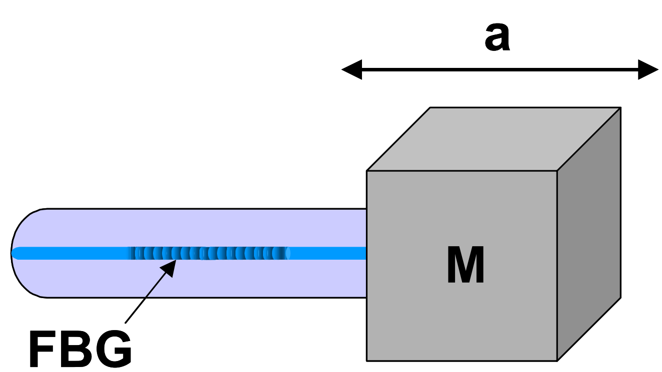

Figure 3: Schematic of simple FBG accelerometer design

The acceleration is measured by the FBG sensor as the mass applies a resultant force to the optical fiber (and hence strains the fiber) due to the change of inertia. For this simple linear system, the strain experienced by the FBG sensor with respect to the acceleration is given by:

$$\varepsilon = \left(M/_{EA} \right) * a \tag{4}$$

As discussed above, the FBG sensor experiences a wavelength shift that is linearly proportional to the applied strain. The ability to measure a wavelength shift of an FBG sensor is analogous to measuring voltage change in a standard accelerometer sensor system. The instrumentation employed to monitor the FBG senor response also dictates the measurement sensitivity of the accelerometer, as is discussed in the next section.

INSTRUMENTATION

Development of instrumentation systems to monitor fiber optic sensors has expanded with the growth in interest in this sensing technology. For most sensor types there are multiple instrumentation systems available that provide different attributes. For FBG sensors alone, there are a number of manufacturers of FBG instrumentation on the market today. In general, these instruments are based on three primary technologies, 1) swept laser or tunable filter, 2) optical filter, or 3) spectrometer. These instrument technologies provide different attributes to sensing with FBG sensors. Table 1 displays a comparison of typical instrumentation values between the three instrumentation types. The key differences between the instrumentation systems are in the sampling rate and number of optical channels/sensors. These differences dictate the selection of the appropriate FBG sensor system for any given application.

	Swept Laser [4]	Optical Filter [5]	Spectrometer [6]
Sampling Rate	250 Hz	10 kHz	3kHz / 100 Hz
Strain Resolution	1 $\mu\varepsilon$	Variable	1 $\mu\varepsilon$
Maximum Number of Sensors*	40	1	8 / 200
Wavelength Ranges	1520-1570 nm	~1310, ~1550 nm	815-860 nm
Cost	~$40,000	~$10,000	~$50,000

Contact manufacturers/vendors for current specifications and pricing
*at listed sampling rate

Table 1: Specifications of three types of FBG instrumentation systems

When choosing an instrumentation system to monitor the FBG accelerometer one must consider the specifics of the application. Are multiple accelerometers to be interrogated simultaneously? What the sampling rate is required? Sensor resolution (wavelength/strain)? Each of these issues drives the selection of the instrumentation system. For example, if multiple low frequency accelerometers are to be interrogated, such as in a seismic monitoring system, then the swept laser system is probably the best choice. The swept laser provides adequate sampling frequency and the ability to multiplex/interrogate many sensors with a single instrumentation system. Another example is the case of a single sensor at high sampling rate. For this case, the optical filter design is the most likely the best choice. The spectrometer-based system provides a good combination of the other two systems in that it allows for multiple sensors to be interrogated at a relatively high sampling frequency. Other considerations are system costs and sensor wavelength range. The most popular wavelength range for FBG sensors is 1520 – 1570 nm, which is commonly utilized in telecommunication applications. Sensors outside of this range will generally incur a slightly higher cost per sensor due to the non standard wavelength. The final consideration of instrumentation is the use of other sensor types in the overall sensing system. Ideally, a single FBG instrumentation system can be employed to meet all of a particular application's needs. The selection of the instrumentation system is ultimately up to the engineer in charge of selecting the sensing solution. Hopefully this section has provided some insight into the issues that need to be considered when choosing an instrumentation system for your FBG sensor system.

RESULTS FROM COMMERCIALLY AVAILABLE ACCELEROMETERS

Disclaimer: The product and vendor names for the accelerometers have been withheld from publication. The purpose of presenting this data is to provide an indication of the differences in FBG-based accelerometers that are commercially available. It is recommended that the purchaser discuss issues of sensor sensitivity, frequency range, and maximum acceleration with specific vendor.

SPA has tested three commercially available FBG-based accelerometers. Each accelerometer was mounted to a Ling Dynamic Systems Inc., LDS V408 shaker using double-sided tape. An electronic signal generator and power amplifier were used to actuate the shaker with a single-frequency sine wave signal. An Entran model EGA-250 accelerometer was mounted to the FBG accelerometer case using double-sided tape and cellophane tape to provide a reference acceleration measurement. The Entran EGA-250 is a miniature accelerometer weighing just 0.5 grams with a nominal acceleration range of 250 g's. The natural frequency of this unit is 2000 Hz and has a flat response from DC to 50 percent of the natural frequency. In these series of tests, the frequency was held constant while the peak-to-peak acceleration level was varied. The peak-to-peak acceleration in these tests did not exceed the stated maximum acceleration level for the given accelerometer. During these tests the shaker excitation frequency was set at frequencies between 5 and 50 Hz, and the acceleration was varied by changing the level of the power amplifier. The wavelength shift of the FBG sensor was monitored and recorded during the tests using the swept laser instrumentation system discussed in the previous section.

The results from the first accelerometer are shown in Figure 4. As the excitation frequency is increased, the ratio of the measured peak-to-peak wavelength change of the accelerometer to the peak-to-peak voltage of the Entran EGA-250 accelerometer increases meaning the sensitivity of the accelerometer increases with increasing excitation frequency. The sensitivity values are listed in Table 2. The large increase in sensitivity at the 50 Hz excitation is in part due to the higher accelerations achieved during this test. For the 50 Hz excitation, the acceleration achieved was 10.5 g (not shown in figure), whereas, the other excitation frequency levels were restricted to less than 3 g. For lower excitation frequencies it is difficult to create higher accelerations.

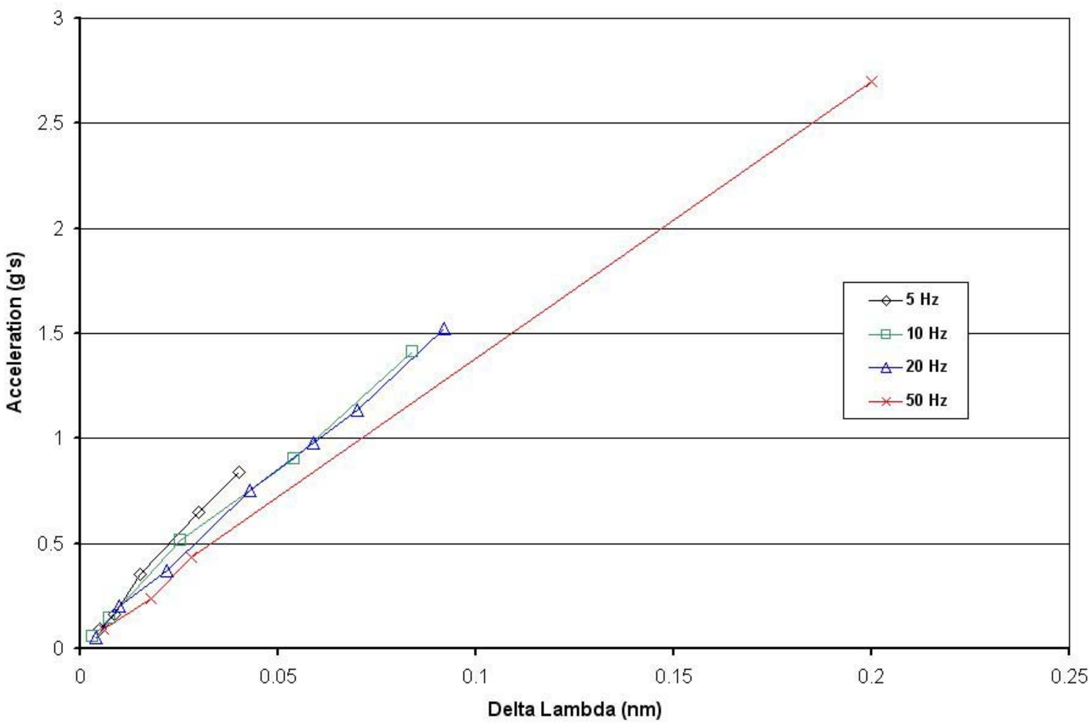

Figure 4: First Accelerometer Sensitivity Based on Fixed-Frequency Excitation

The second FBG accelerometer tested displayed an opposite effect to sensitivity where the peak-to-peak wavelength change decreased with an increasing frequency. To confirm the result, a second series of tests with a second EGA-250 accelerometer were run. Both sets of data are displayed in Figure 5. The acceleration level was restricted to less than 3 g for this test based on the maximum rated acceleration for this particular FBG sensor design. This second FBG accelerometer appears to be designed for a seismic application with low g loads and low frequency response. The sensitivity values for the accelerometer are listed in Table 2. This accelerometer design had the highest sensitivity of the three tested, but was limited in terms of the maximum allowable acceleration and frequency range.

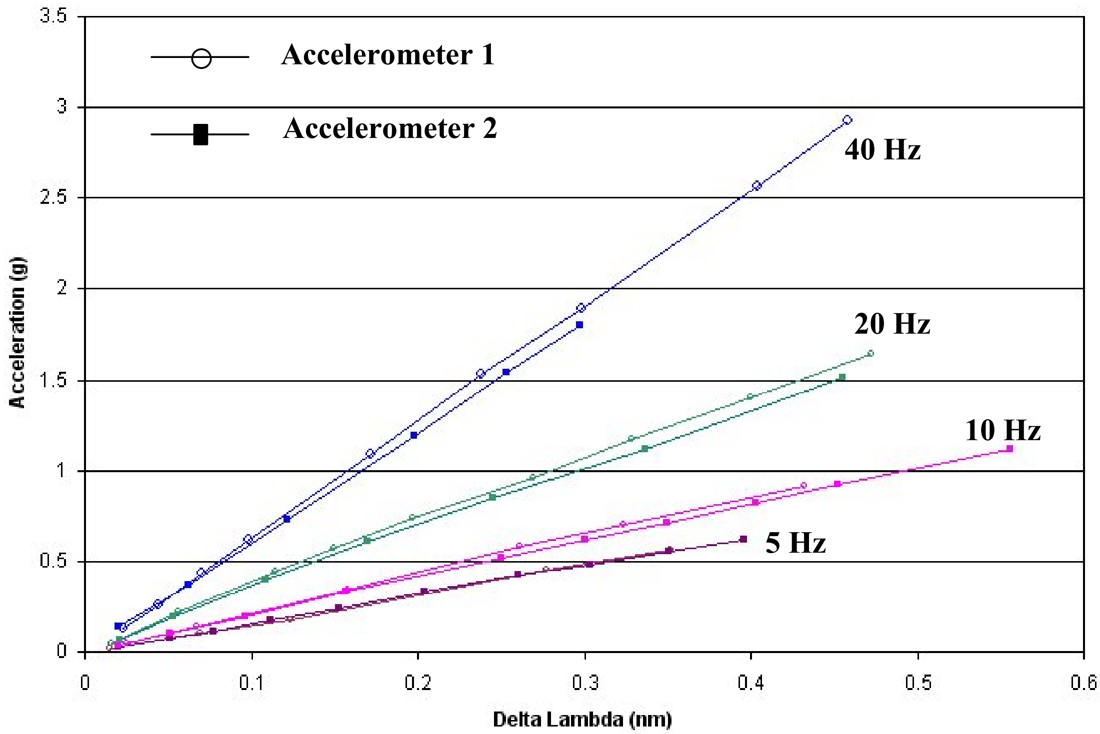

Figure 5: Second Accelerometer Sensitivity Based on Fixed-Frequency Excitation

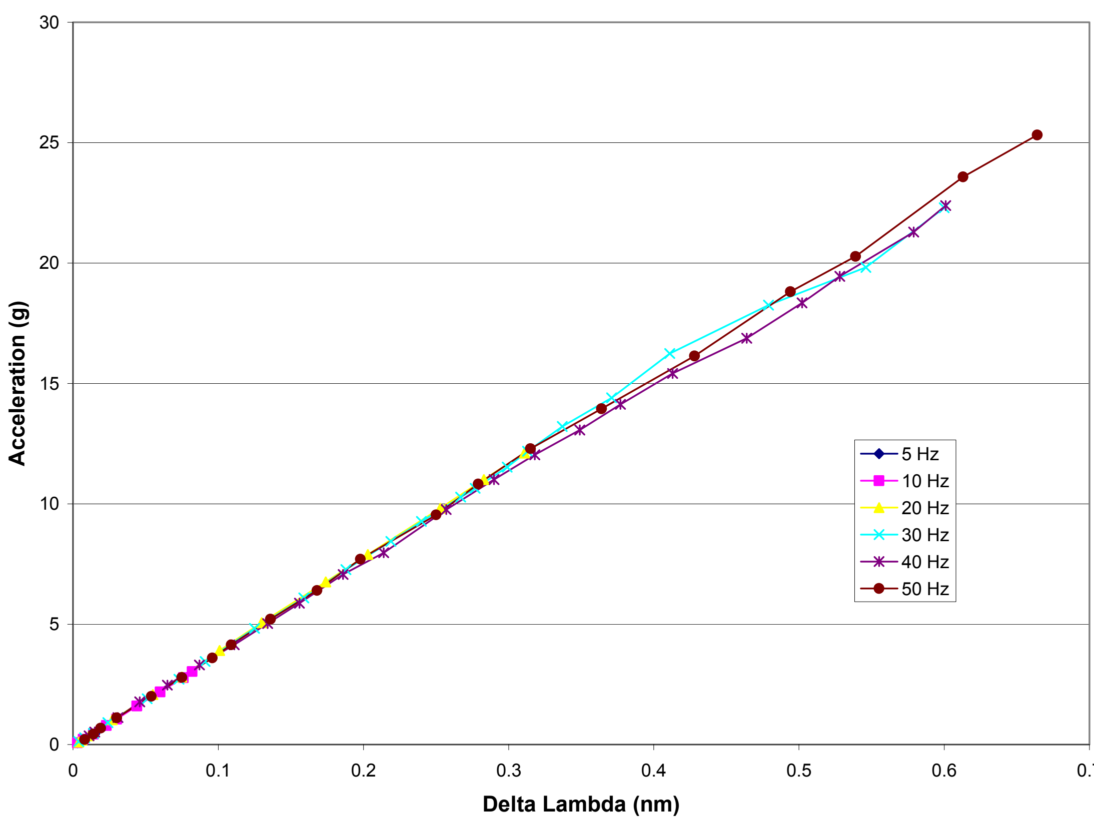

Figure 6: Third Accelerometer Sensitivity Based on Fixed-Frequency Excitation

The third, and final, FBG accelerometer design was tested in a similar manner as the previous two FBG accelerometers, but the maximum acceleration was increased to approximately 25 g, which was half the rated full-scale input. This FBG accelerometer design did not experience a shift in sensitivity as the excitation frequency was varied, as shown in Figure 6, but was the least sensitive unit. The sensitivity values are listed in Table 2. These values do indicate a slight decrease in sensitivity as the excitation frequency is increased, but this effect is minimal compared to the other two accelerometers.

Frequency (Hz)	Accelerometer #1	Accelerometer #2	Accelerometer #3
5	0.046	0.618	0.035
10	0.060	0.477	0.030
20	0.061	0.295	0.028
30	n/a	n/a	0.027
40	n/a	0.160	0.027
50	0.081	n/a	0.027

Table 2: List of FBG Accelerometer Sensitivity versus Excitation Frequency (nm/g)

Based on the FBG accelerometer test results, a variety of FBG-based accelerometer designs exist that provide different characteristics in terms of sensitivity, frequency range, and maximum allowable acceleration. Selection of the appropriate FBG accelerometer design will depend on the specific requirements of the sensing application. Selection of an FBG accelerometer must also consider the response versus excitation frequency to the overall system.

SIZE AND COST

The size of FBG accelerometers is typically larger than that of typical conventional accelerometers. Typical FBG sensor lengths are approximately 1 cm (0.4 inches). Mechanically coupling the acceleration loads to the grating requires additional volume. The volume of the FBG accelerometers tested for this paper varied from 1.6 cubic inches to 5.1 cubic inches. The cost of these accelerometers varied from $1,700 to $2,300 for a single unit.

CONCLUSION

This paper has discussed various aspects of fiber optic-based accelerometers. Determining the applicability of a fiber optic accelerometer for a given application requires knowledge of not only the dynamic response of the particular sensor, but also knowledge of the capabilities of the instrumentation system used to interrogate the accelerometer. The end user needs to verify the performance characteristics of the fiber optic accelerometer to ensure quality performance during operation. The end user must also verify that the performance of the accelerometer is achievable with the selected instrumentation system. In most cases, the accelerometer vendor should be able to provide detailed information on their calibration studies and the instrumentation used for these calibration studies.

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