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High-g Accelerometer Based on an In-Fiber Bragg Grating Sensor

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An accelerometer based on an in-fiber Bragg grating sensor has been fabricated and demonstrated. The grating sensor operates linearly up to accelerations of 170,000g_n. The design, testing and performance of the accelerometer are discussed.

Key words: fiber Bragg gratings, fiber optic sensors, accelerometer, photosensitivity

1. Introduction

Photosensitivity[1] in optical fibers is a useful phenomena for writing Bragg gratings in the core of optical fibers. The resonant frequency of the photoimprinted Bragg grating shifts when strain is applied to the fiber thus providing basis for making optical fiber sensors. In-fiber Bragg grating sensors have been made that detect measurands such as temperature and/or strain.[2]

In this paper, we describe a novel application of in-fiber Bragg gratings to sense the high levels of accelerations typical of impact dynamics. Such a sensor has applications for example in instrumentation for monitoring the acceleration pulse generated in crashes, drop tests, pyroshocks and hard target munitions.[3] The objective is to measure an acceleration pulse with a nominal duration of 100 μs and an amplitude of 100,000g_n where g_n is the free fall acceleration (9.8 m/s^2). There is a limited number of high-g sensors able to measure such an acceleration and each type has some drawbacks, for example undamped resonance modes in piezoresistive accelerometers can produce permanent damage and cross-axis sensitivity is sometimes important.

2. Sensor Operating Principles

The operating principles of a Bragg grating based accelerometer are as follows. The sensing element consists of a Bragg grating in a short length monomode optical fiber that is clamped in a mount so that the protruding piece of optical fiber ($\leq$1 cm) is free to stretch or compress (see Fig. 1). The Bragg grating is located near the clamping point. Under acceleration, the free length of the fiber elongates (or compresses) changing the grating period and consequently its reflection response. The nature of the change in the reflection response depends on the strain distribution produced along the length of the grating. In general, the strain distribution will be nonuniform, however, by choosing a grating whose length is small with respect to the length of the free fiber, the strain induced by acceleration is approximately uniform over the length of the grating. This condition has the advantage that acceleration results in a simple wavelength shift in the peak of the grating reflection response without changing its spectral shape (see Fig. 1).

3. Calculations

We have carried finite element calculations of the strain induced in the fiber sensor by high-g acceleration. The calculations showed that a 10 mm long fiber has a low mechanical resonance frequency (150 kHz) with a large damping coefficient. The mechanically induced oscillations on the sensor output signal are only a few percent of the signal maximum amplitude. Consequently, it is not necessary to filter the sensor signal as for piezoresistive sensors. Furthermore the large natural damping in the sensor makes it resistant to catastrophic damage from resonant coupling of shock wave.

4. Detection

The scheme used for detecting the acceleration through a shift in the grating resonant wavelength is shown in Fig. 2. A laser diode operating at a fixed wavelength (in this case 826 nm) is coupled into a 3 dB fused coupler splitter whose output arm is connected to the Bragg grating sensor. Light that is back reflected by the sensor grating enters the splitter which redirects it to a photodetector. A Faraday isolator is used to block that back reflected light which is incident on the laser diode. Acceleration changes the Bragg grating resonant wavelength and thus the amount of light that is reflected back to the photodetector. In order to detect either acceleration or deceleration, the wavelength of the laser diode is set at one of the 3 dB points of the reflection response curve of the Bragg grating.

5. Sensor Design

The design of the sensor we used in the high-g tests is shown schematically in Fig. 3. The sensor is formed out of a piece of Corning 800 Flexcor fiber with the fiber buffer coating stripped off one end. The fiber is singlemode at the wavelength of operation of 826 nm. A Bragg grating (length=1 mm, reflectivity=65% and spectral width=0.3 nm FWHM) is photoimprinted in the bare fiber close (~1 to 2 mm) to the coated section of the fiber. The bare fiber is cut so that the fiber containing the Bragg grating protrudes only 5 to 6 mm out of the coated section. The

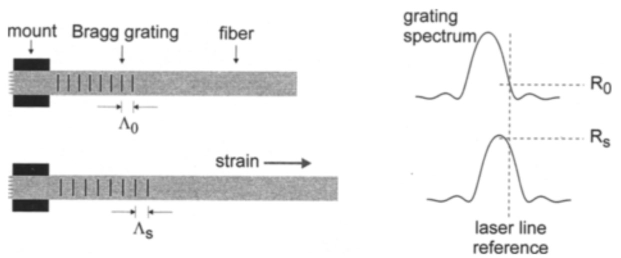

Fig. 1. The measurement principle is based on the fiber elongating with strain, changing the grating period and resulting in a shift of the spectral response toward the long-wavelength region.

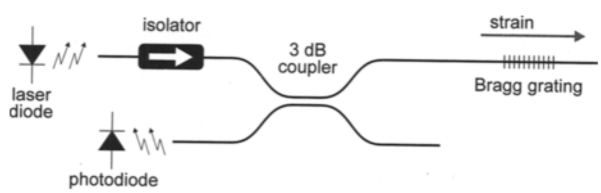

Fig. 2. The light from a single mode laser diode is reflected back to a photodiode for the detection of a shift in the spectral response of the Bragg grating.

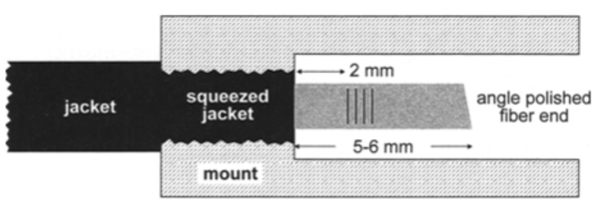

Fig. 3. Illustration of the sensor mount with the protective jacket squeezed between both halves of the mount.

cut is made at an angle to minimize back reflections into the detection system. The mount for the fiber sensor is constructed by cutting V-grooves in two aluminum blocks. The jacketed portion of the sensor fiber is then placed in the V-grooves and clamped between the two blocks. The sensor fiber is positioned between the blocks such that the end of the fiber is recessed in the hole formed by the two V-grooves of the clamping block. This hole has a diameter of 150 μm which is larger than the 125 μm diameter of the fiber. Thus as shown in Fig. 3, the protruding bare fiber containing the Bragg grating is free to move laterally but its motion is limited by the V-groove hole. This method for mounting the fiber sensor is used to reduce the sensitivity of the accelerometer to transverse accelerations, i.e., accelerations perpendicular to the sensor fiber's axis.

6. Tests of Bragg Grating Accelerometer

There is no accepted standard to characterize completely an accelerometer in the very high-g regime. A Hopkinson bar is among the most commonly used to test and evaluate the performance of an accelerometer for this regime.[4] High-g tests on this novel sensor were carried out on the Defense Research Establishment Valcartier's Hopkinson bar which is capable of generating an acceleration pulse in excess of $100{,}000 g_n$. In these tests, it is only the Bragg grating sensor that is subject to the high acceleration; the detection system electronics and laser diode are connected to the sensor by means of a shortlength of optical fiber.

The principle of an Hopkinson bar is simple; when a projectile strikes the front end of the bar, an elastic wave propagates along the bar and at the instant of its reflection at the other end of the bar (where the sensor is mounted) the compressive wave generates an acceleration given by: $a(t)=2C\ d\varepsilon(t)/dt$ where C is the velocity of the longitudinal wave in the bar and $d\varepsilon/dt$ the time derivative of the strain measured at the end of the bar. However, it is not possible to measure the strain at the end of the bar. It is usually measured at the center of the bar and corrections are made for dispersion effects.

Figure 4 shows a response (solid line) of the Bragg grating sensor to a high acceleration pulse. For comparison the acceleration obtained from the strain gage measurement (neglecting dispersion effect) is also shown (dotted line) in the figure. Note the Hopkinson bar generates many acceleration pulses and because of its location in the center of the bar, the strain gage sensor detects twice as many pulses as the Bragg grating sensor located on the end

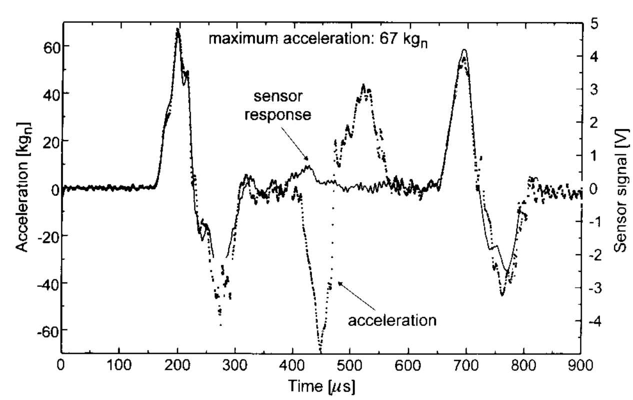

Fig. 4. Typical response of the Bragg sensor at an acceleration of 67 kg_n. The acceleration (dots) and sensor (thin line) responses are plotted.

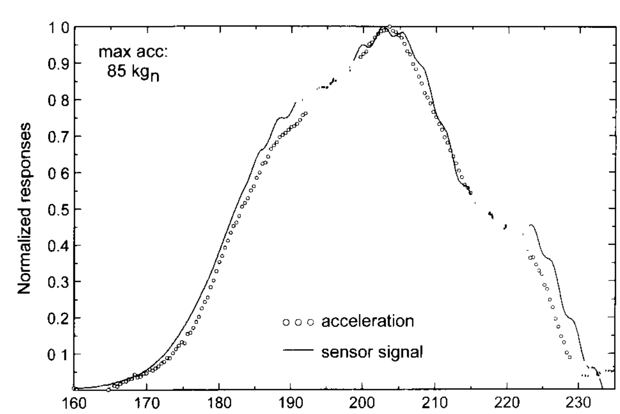

Fig. 5. Comparison between the first acceleration pulse and the resulting sensor signal.

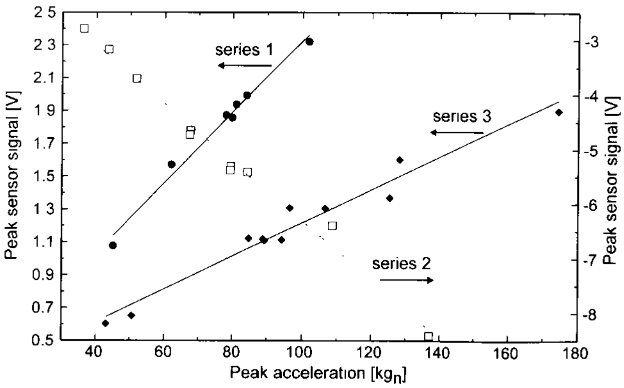

Fig. 6. Plot of peak sensor output as function of peak acceleration impulse for three different sensor designs denoted as series 1, 2 and 3 respectively. The solid and dash lines are least square fits to the data for each sensor design. The results show the linearity of the sensor responses.

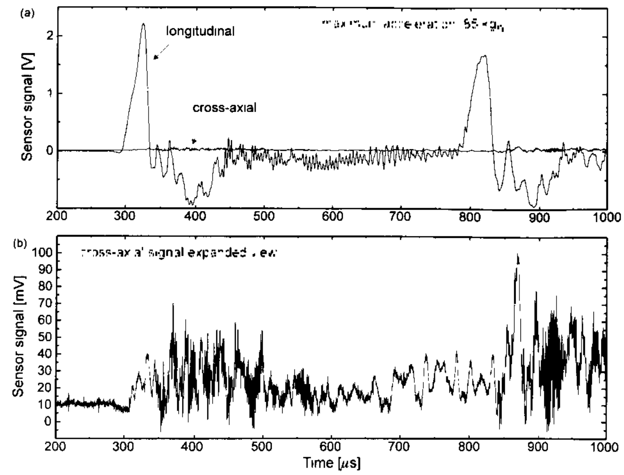

Fig. 7. Cross-axial sensitivity measurement of the fiber Bragg sensor. The curves labeled cross-axial and longitudinal in Fig. 7(a) show respectively the sensor response when a 85 kg_n acceleration is applied perpendicular (cross-axial) to the axis of the sensor fiber and same acceleration is applied along (longitudinal) the sensor fiber axis. Figure 7(b) is the same signal redrawn with a higher amplitude sensitivity.

of the bar. Figure 5 shows a comparison between the signals from the two sensors for the first acceleration pulse; the Bragg grating and the strain gage (signal derivative) sensors are in close agreement.

We have carried out tests on the linearity of the Bragg grating sensor by monitoring the peak sensor output obtained as the sensor is subjected to different magnitude acceleration pulses ranging between 0 and 170 kg_n. The results of the measurements are shown in Fig. 6 for three different sensor designs designated as series 1, 2 and 3 respectively in the figure. The straight lines in Fig. 6 are a least square fits to the experimental data. The results show that the Bragg grating sensor operates linearly up to accelerations of 170 kg_n which is a much higher value than our design goal of 100 kg_n. For two the of sensor designs, series 1 and 3, the sensor sensitivity is positive with slopes of 0.0217 V/kg_n and 0.0101 V/kg_n respectively. The reduced sensitivity of the series 3 sensor design is accounted for by the fact that the sensor fiber in comparison to the series 1 sensor fiber, has a shorter length and the Bragg grating is located closer by 2 mm to the end of the free fiber. The series 2 sensor has a negative slope of -0.0536 V/Kg_n; this type response is obtained by setting the wavelength of the monitoring laser diode on the other 3 dB reflection point of the Bragg grating spectral response curve. The results show that the accelerometer sensitivity can be controlled by the length of fiber protruding from the mount and by the location of the Bragg grating in the free fiber.

The sensitivity of the Bragg grating sensor to accelerations perpendicular to the fiber grating axis was also measured. These measurements were carried out on a sensor design in which the free fiber (see Fig. 3) is mounted within a V-groove hole in order to restrict lateral movement, i.e. bending of the fiber as a result of accelerations perpendicular to the fiber's longitudinal axis. Figure 7(a) shows respectively, the sensor signal outputs when a 85 k g_n acceleration is applied longitudinally and transversely to the sensor fiber axis. Since for the amplitude scale used in Fig. 7(a) the cross-axial signal is effectively zero, the same cross-axial signal is redrawn again with an expanded amplitude scale and is shown in Fig. 7(b). The figures show the first acceleration pulse followed by a reflected pulse. During the acceleration pulses, the sensor signal is relatively free of noise, but between pulses the sensor signal is noisy. We attribute this noise to mechanical resonances which depend on the sensor mounting configuration. In any case, it can be seen that the sensitivity of the accelerometer to transverse accelerations is lower by a factor of 40. We have found that the cross-axial sensitivity of the Bragg grating sensor depends strongly on the hole diameter of the tube. In the present case, the hole diameter is 150 μm; larger hole diameters resulted in increased sensitivity to cross-axial accelerations.

7. Conclusions

The feasibility of the fiber Bragg grating based accelerometer has been demonstrated. It promises a damped response at resonance and little cross-axial sensitivity. It would offer an interesting alternative to the cantilever and diaphragm types of accelerometers.

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