Temperature, Displacement and Acceleration Fiber Optic Sensor for Large Machinery Monitoring

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ABSTRACT

In this paper, a multi-parameter optical sensor system for vibration, temperature and strain monitoring is presented. It is based on a hybrid singlemode-multimode fiber optic transducer, where the vibration is detected by means of a fiber cantilever beam and extrinsic coupling of light, while two fiber Bragg gratings measure the temperature and strain. Experimental results show good performance for the monitoring of large electric machines.

Keywords: Optical sensors, fiber optic sensors, optical transducers, vibration monitoring, strain monitoring, non-destructive testing, optical sensing, temperature monitoring, intensity modulation sensors.

1. INTRODUCTION

Optical fiber sensor systems have proved to be a very successful technique for the non-destructive testing of smart materials and structures[1]. Particularly, large electric machines require real-time monitoring in order to assure a long operative life and to plan maintenance periods. The primary magnitude to be monitored in this particular application is the vibration, but another variables such as temperature and strain, measured at key points of the structure, should also be known[2], not only as an extra parameter of the behavior of the structure, but also as additional information that is able to improve the accuracy and compensation capabilities of the multi-parameter transducer[3].

Many sensing techniques has been proposed and used, but optical sensing provides the advantage of its immunity to electromagnetic interferences, among others. For temperature and strain measurement, fiber Bragg gratings (FBGs) have emerged as a very successful technique, due to their EMI immunity, accuracy, low cost per sensing point, and multiplexing capabilities for multipoint measurements[4]. Regarding vibration monitoring, several schemes of optical sensing have been proposed for this application, including the technique of laser doppler velocimetry (LDV), that provides non-contact high-accurate measurements but it is very expensive, specially if multiple points are to be sensed in large structures. Vibration sensors with contact to the structure (i.e., accelerometers) based on optical fiber technology include those based on interferometry, polarimetry, or intensity modulation, being the later more suitable for this applications due to its simplicity, low cost, and performance[5].

With this aim, a novel multi-parameter sensor system for temperature, strain and acceleration measurement is proposed in this paper. The vibration signal is obtained from a intensity-modulated transducers based on extrinsic coupling between single-mode and multi-mode optical fibers, by means of a simple differential detection scheme. Fiber Bragg grating (FBGs) embedded within one of the fibers of the sensor head are used for both strain and temperature measurement, using a simple interrogation technique based on differential responsivity of photodiodes. Both methods lead to cost-effective sensor systems while maintaining great performance.

2. TRANSDUCER'S ARQUITECTURE

The transducer's architecture is shown in Figure 1. The vibration detection mechanism consist of a singlemode optical fiber in cantilever beam configuration, whose light spot at the beam's end is projected on to two multimode receiving fibers. It has been demonstrated that the displacement of the beam's end is directly proportional to the applied acceleration at low and medium frequencies, so the mechanical behavior of this structure is similar to an accelerometer. Provided that the optical power coupled to both multimode receiving fibers changes in a linear way with the movement of beam, a simple optical accelerometer is obtained, being the differential detection of the light at the receiving fibers a mechanism to compensate the

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measurement against unwanted perturbations (for example, changes in the losses at the optical channel).

Regarding the temperature sensing, it is accomplished by an embedded uniform FBG in the emitting single-mode fiber. Theoretical and experimental studies have shown that the strain at some points of the cantilever beam is negligible, so the shift of the Bragg wavelength is only due to temperature changes. In the same way, a FBG firmly attached to the transducer's body is able to detect the strain applied to the structure. Thus, the transducer works in transmissive mode for vibration information, and in reflective mode for strain an temperature measurement.

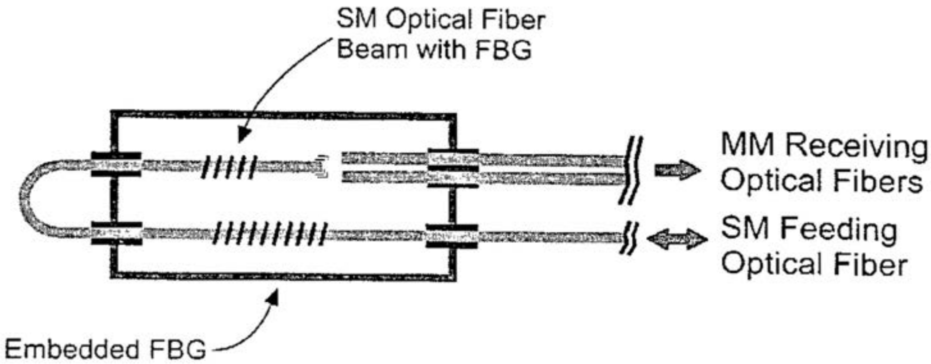

Fig. 1. Transducer's architecture.

3. TRANSDUCER DESIGN

The design process of the transducers involves several aspects. For strain and temperature measurement, the parameters, position, and fixing of the FBGs must be considered. Two uniform FBG, with different Bragg wavelength, and several centimeters apart, have been chosen. The FBG interrogation subsystem within the optoelectronic unit is able to resolve the Bragg wavelength shift for each FBG with a simple method based on lateral filtering[6].

Regarding the vibration sensing, two key issues must be taken into account: the mechanical behavior of the fiber beam, and the coupling of light to the receiving fiber. Firstly, a study of the mechanical properties of the fiber beam in a cantilever configuration must be done. If the singlemode fiber beam must behaves as an ideal accelerometer, the relative displacement of its end must be proportional to the applied acceleration. This can be easily accomplished with a concentrated mass at is end, but this technique introduces severe technological difficulties. We have proposed a mass-less fiber cantilever beam as the sensing element of fiber optic accelerometers, that has been proved to match an ideal accelerometer, at low frequencies, with little error [7]. If a standard singlemode optical fiber is going to be used, the material and cladding diameter are fixed, and the beam's length should be calculated according to the expected frequency range of vibration to be detected. A 7 mm long beam is able to measure acceleration up to 1 KHz with less than 10% of error.

Secondly, the light coupling characteristics between fibers should also be studied. The parameters of the emitting and receiving fibers, along with the relative position between them must be carefully chosen with the following aims:

- The collected optical power must be maximized to improve the signal-to-noise ratio, i.e., the resolution of the sensor system.
- The collected optical power should change in a linear way with the transverse displacement of the emitting fiber (related to the applied acceleration) to avoid distortion of the vibration information.
- The variation of the collected power with the transverse displacement must also be noticeable, that is, with high slope, to improve the sensitivity of the sensor.

Clearly, not all the above described requirement can be satisfied simultaneously, and the design process must be guided by the amplitude and frequency ranges of the acceleration to be measured. Although a preliminary analysis of the coupling problem strongly suggest multimode receiving fibers with a large core-to-cladding diameters ratio (for example, 50/55 multimode fibers), we have chosen 100/140 fibers due to their availability. The emitting fiber has chosen to be standard singlemode fiber, mainly to facilitate the writing process of the FBGs and their interrogation.

Once the parameters of both emitting and receiving fibers are known, only one design variable remains: the axial separation between them. For this task, an accurate model for the coupling between fibers is desirable. Many of them have been proposed in the literature[8], but they are usually intended to predict the coupling losses in optical connectors, and tends to fail for large misalignments typically found in those coupling-based sensors. In a previous work, we have developed a model based on geometric optic, and it has shown an accurate prediction of the coupling between multimode fibers[9], and it has also shown a good behavior with the architecture proposed in this paper: singlemode to multimode coupling. Figure 2 show a simulation of the light coupling between a standard telecommunications singlemode fiber and 100/140 multimode fiber, against the axial gap between them. The transverse misalignment has chosen to be 70 microns, that is, the radius of each receiving fiber. In order to validate the model, the coupling has been measured in the laboratory, and although the matching is not perfect, specially for small axial gaps, both curves show an optimum zone around 400..500 microns of axial separation where the coupling of light is greater.

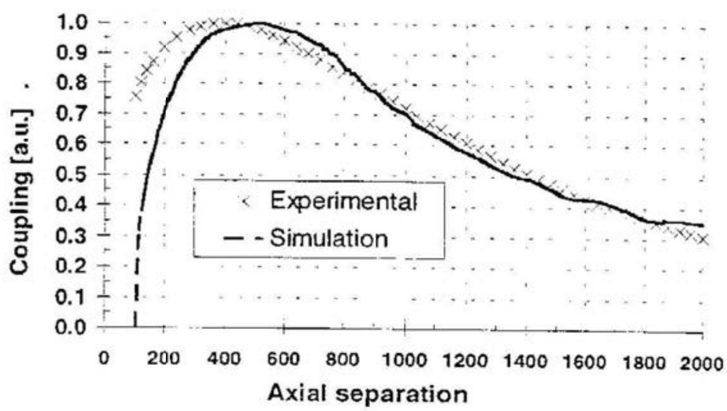

Fig. 2. Simulation of the optical power coupled between the fibers, obtained from both simulation and experiments.

But although the gap (axial separation) required for maximum coupling could be clearly identified using the above shown figure, the linearity and sensitivity must also be known. To do that, the so-called coupling curves, obtained at different gaps, must be used. Figure 3 shows the coupling curves obtained experimentally in the lab, using a computer-controlled setup and micro-positioners, with a LED light source emitting at 1550 nm. The transverse offset of 70 microns has been highlighted, as it is the operation point when two 100/140 multimode fibers are used to collect the projected light. Once the variation of the coupled power is known around this point, the sensitivity and linearity at any axial gap can be calculated. A gap of 700 microns has been chosen for the prototypes of the transducer as a compromise between both magnitudes.

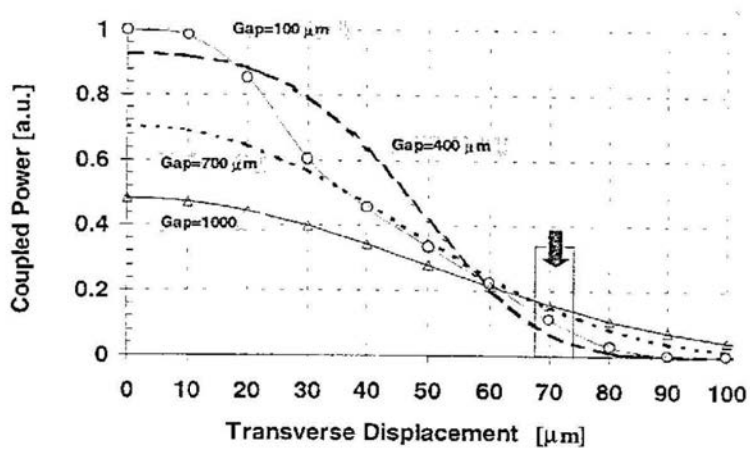

Fig. 3. Coupling curves.

One major concern with this kind of transducer is the cross-talk between the different measurands. The sensor system must be able to extract the correct information from the optical signal provided by the transducers, with the proper isolation between magnitudes. For instance, it must be demonstrated that the Bragg-wavelength shift of the two FBGs is independent of the magnitude of the applied vibration, so a stable and repeatable measurement can be achieved. For the embedded FBG for strain measurement, firmly attached to the transducer's body, it is clear that the effect of the vibration is negligible. In a similar way, other works have confirmed that the strain induced by the beam's movement on the other FBG can also be neglected[10]. The mechanical model of the fiber beam, previously mentioned in this paper, has been used to predict the maximum amount of strain induced by the vibration. Considering a singlemode fiber beam with a length of 7 mm, the strain could reach the value of 0.005 $\mu\varepsilon$ per G of acceleration, so it can be neglected. In order to confirm that, an experiment has been carried out in which the Bragg-wavelength shift of a FBG in a fiber beam has been dynamically monitored. A vibration with frequency 15 Hz (within the bandwidth of the interrogation system, 25 Hz) and amplitude of 2 G has been applied to a fiber beam of length 7 mm. Figure 4 shows the time-resolved Bragg-wavelength shift under vibration (upper chart) and in rest (lower chart). In both cases, the Bragg wavelength is the same, with an stability of +/- 2 pm.

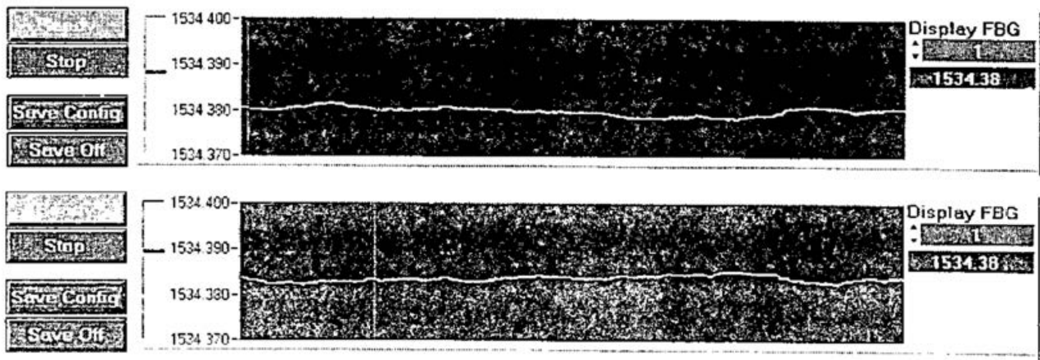

Fig. 4. Time-resolved Bragg wavelength shift of the FBG inside de fiber beam, with (upper) and without applied vibration (lower chart).

On the other hand, it is expected that the FBGs written very close to the emitting fiber's end don't affect to the intensity coupling characteristics between the fibers. In order to prove that, several coupling curves have been measured with and without a gratings close to its end. Figure 5 shows some of the curves at different axial gap, and a little difference can be seen, so it can be concluded that the FBG does not affect, in a measurable amount, the modal field size and distribution of the emitting fiber.

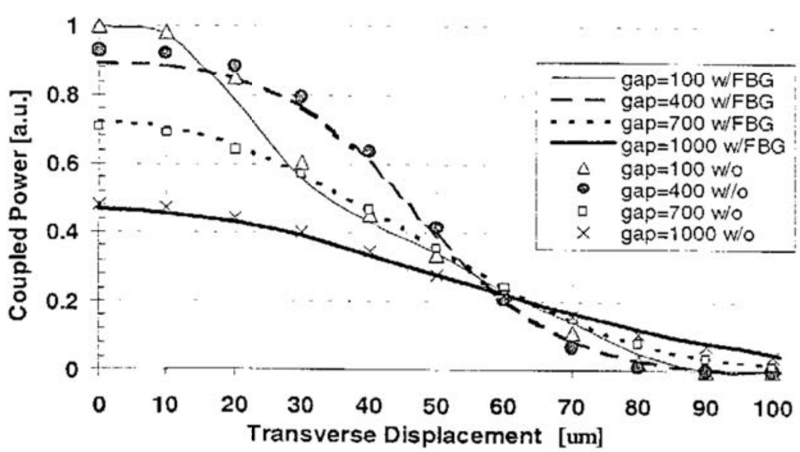

Fig. 5. Coupling curves obtained with and without a FBG close to the fiber's end.

4. SYSTEM'S ARQUITECTURE

The complete system comprise the above described transducer, plus an optical channel with three fibers and the optoelectronic unit, as is shown in Figure 6.

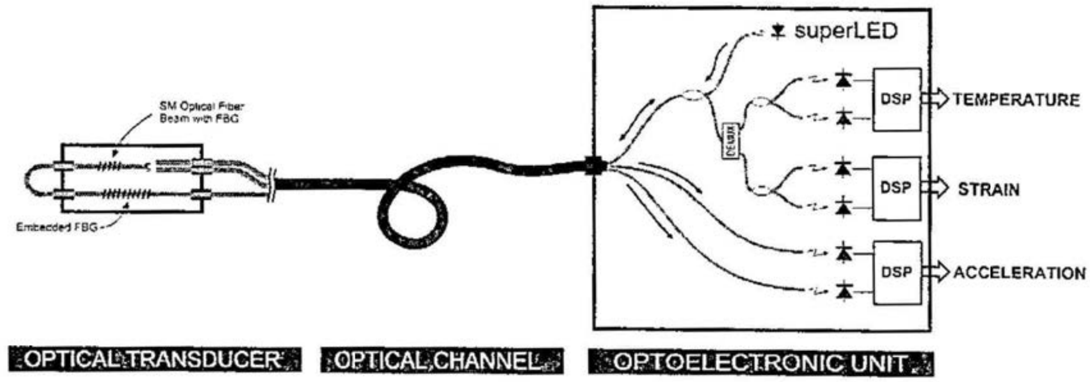

Fig. 6. Architecture of the sensor system.

A single broadband superluminiscent LED light source centered in the third window is used to feed the transducer. The light reflected by the two FBGs is firstly de-multiplexed in order to identify each Bragg wavelength in a separated way, and each signal sent to two photodiodes. In one of them is carefully chosen so its stop wavelength matches the Bragg wavelength of the FBG, a simple interrogation scheme can be implemented. Using the signal from this photodiode as a measure of the Bragg wavelength, and the signal from the other photodiode as a reference, the temperature and strain measurements can be easily obtained through differential digital processing.

Regarding the vibration detection, a similar differential processing is performed to the signals coming from the two receiving multimode fibers. Due to the particular position of the receiving fibers with respect to the emitting one, it is expected a linear and opposite variation of the received optical power with the transverse position of the beam, that is, with the applied acceleration, as is shown in Figure 7. Therefore, a simple differential processing of both signal provides the applied acceleration. This differential technique allows two additional advantages[5]:

- The vibration measurement is independent of the overall optical power involved in the system: power of the light source, losses of the optical channel, ..., being as a result a compensated sensor system.
- Only the applied acceleration along one axis is detected, resulting in a uniaxial accelerometer with good transverse sensitivity (only about 4% of transverse sensitivity has been measured in the laboratory).

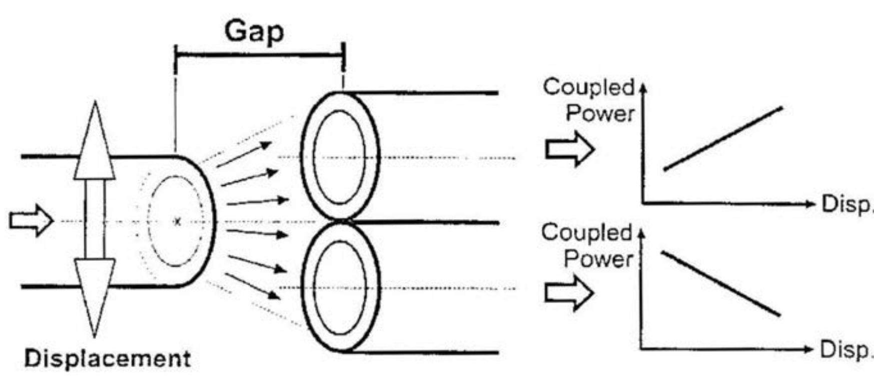

Fig. 7. The inverse variation of the collected optical power.

5. SYSTEM PERFORMANCE: EXPERIMENTS

A prototype of the proposed multi-parameter sensor system has been built and its performance has been checked in the lab. A photograph of a very early transducer can be seen in the Figure 8.

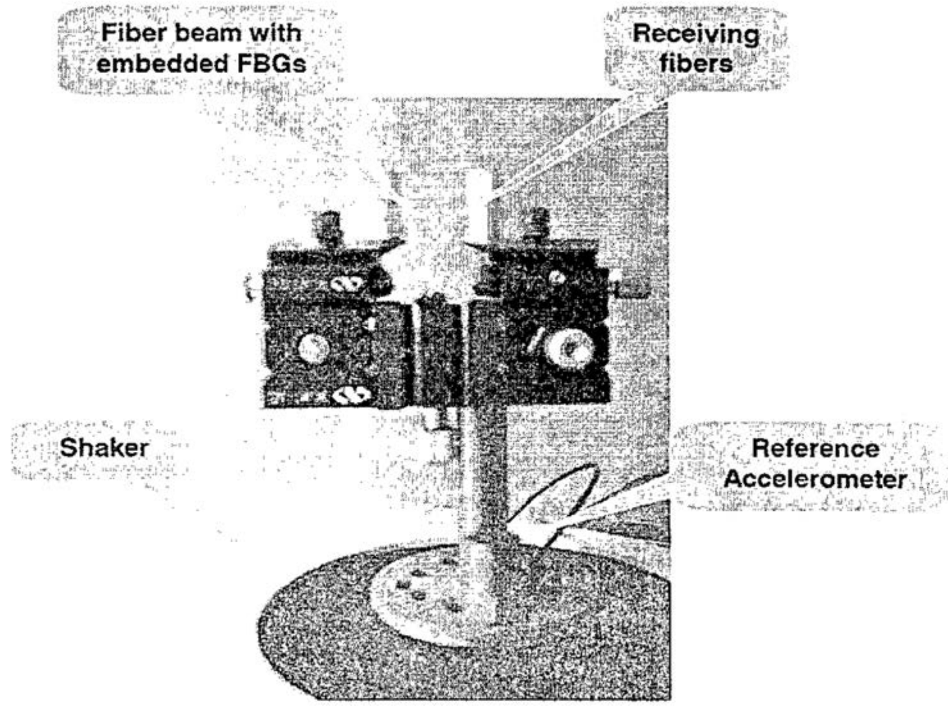

Fig. 8. Photograph of an early prototype of the transducer head.

It is made of a feeding singlemode fiber with two uniform fiber Bragg gratings, one embedded within the fiber beam, and the other several centimeters apart. The wavelength of both FBG are 1525.8 and 1536.0 nm, respectively, and the length of the beam is 7 mm, allowing, theoretically, vibration measurements up to 500 Hz with +/- 5% of error, or up to 1 KHz with +/-10%. Two 100/140 multimode fibers have been used as the receiving fibers for the vibration sensing, while the axial separation between the emitting and the receiving fibers has been set to 700 microns. With these conditions, the insertion losses of the vibration transducer has found to be 8 dB, that is, 8 percent of the emitted optical power is coupled to each receiving fibers.

The performance of the system for the sensing of vibration, temperature and strain have been measured. Figure 9 shows the amplitude response of the sensor system to the applied acceleration, in the range from 0 to 50 m/s^2 ($\approx$ 5 G).

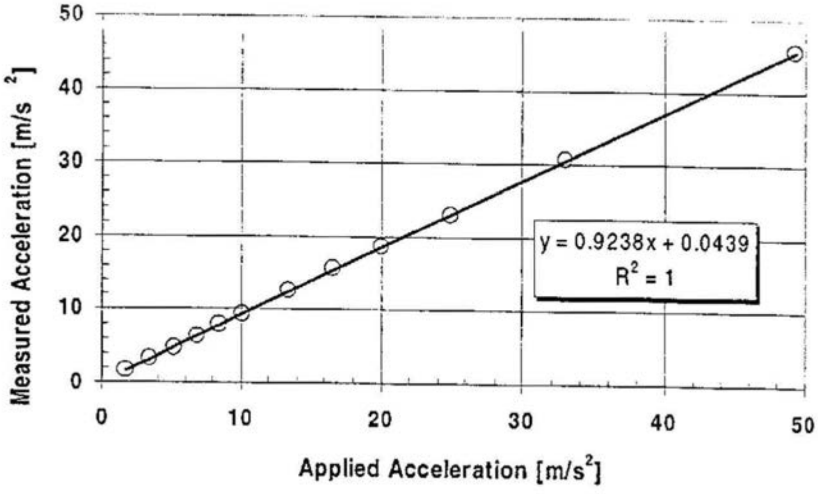

Fig. 9. Amplitude response to the acceleration.

Another important issue regarding the vibration measurement is the frequency response. Figure 10 shows the frequency response of the proposed vibration sensor at a fixed amplitude of 1 G. It can be seen that the response is constant with a maximum deviation of +/- 20% in the range from 0 to about 400 Hz, where a strong resonant peak has been detected (exactly, at 420 Hz). It is owned to the construction of the body of this first prototype, and this limit should be easily eliminated. In fact, the expected resonant frequency of a 7 mm-long fiber beam is about 2.2 KHz, resulting in a maximum deviation of +/- 5% up to 500 Hz.

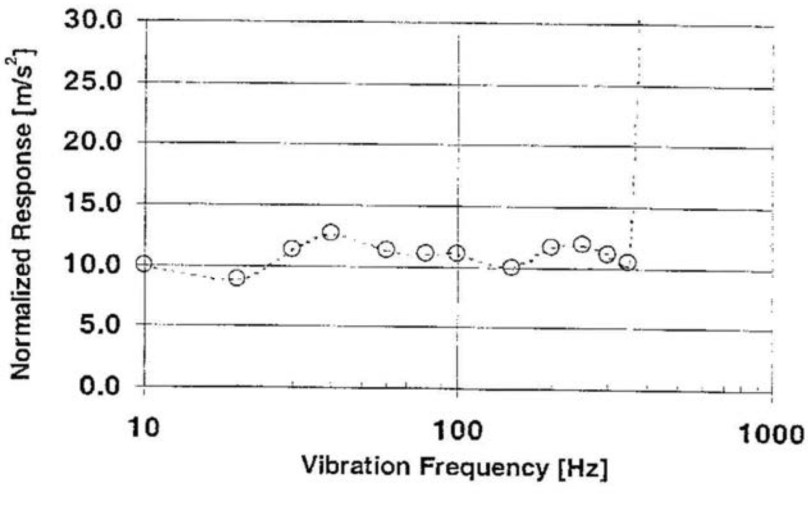

Fig. 10. Frequency response to the acceleration.

Finally, the temperature and strain response have also been measured. Figure 11 shows the measurement of temperature in a range from -40 to +40 °C, while Figure 12 shows the strain measurement within a range from 0 to 2000 με. In both cases, the linearity is very good.

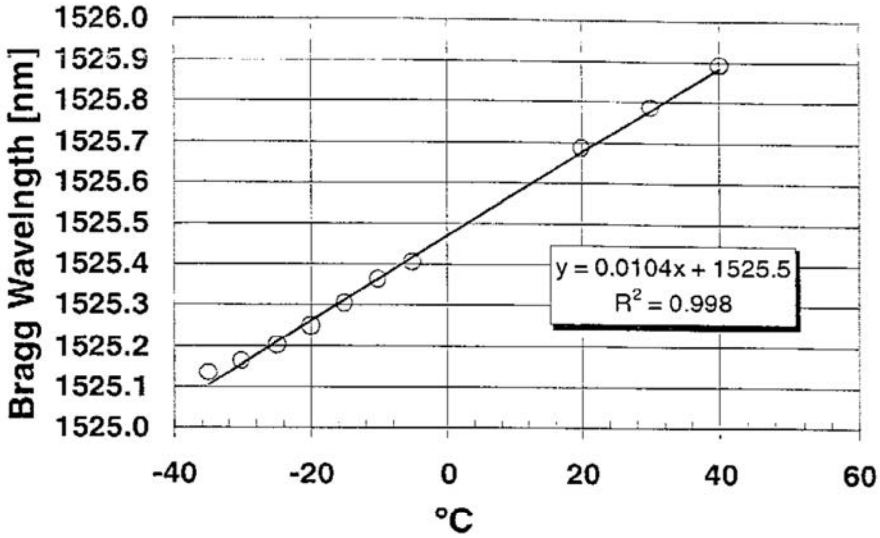

Fig. 11. Response of the transducer to the temperature.

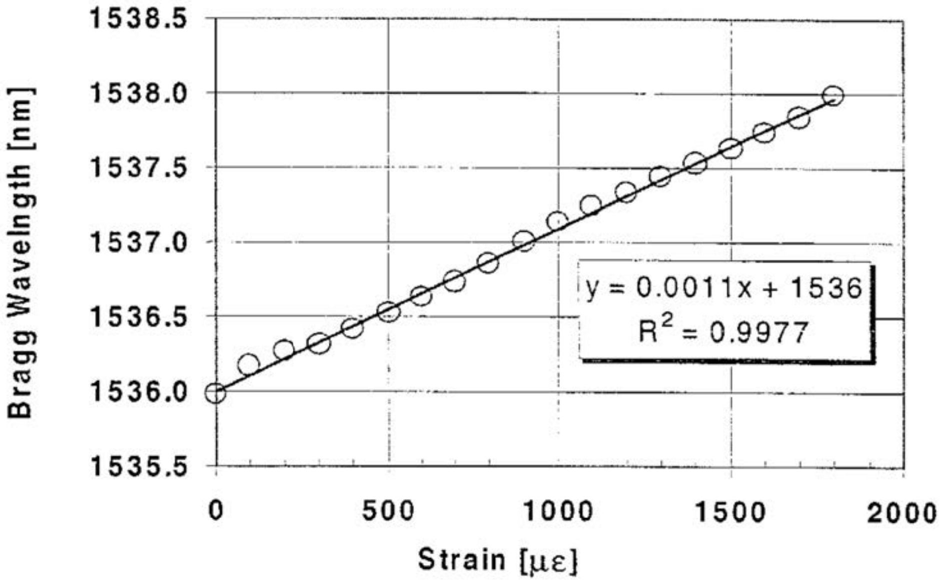

Fig. 12. Response of the transducer to the applied strain.

6. SUMMARY

The feasibility of a simple and robust sensor system for the simultaneous measurement of vibration, temperature and strain has been shown. It is based on extrinsic coupling between a single-mode and two multi-mode optical fibers for the acceleration sensing, and of two FBGs embedded in the former fiber for the measurement of the temperature and strain. The experimental results, and the use of simple differential techniques in the opto-electronic unit, confers to this sensor system good technical behavior and make it cost-effective.

7. ACKNOWLEDGEMENTS

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