Multi-parameter force sensing with fiber Bragg grating sensors

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Today many niche applications demand the use of multi-parameter force sensing. Two distinct examples hereof are the force feedback control of robots operating in electromagnetically noisy industrial environments and the stress build-up of dental resin cements during their curing. Instead of conventional measurement tools we propose fiber Bragg gratings (FBGs) written in polarization maintaining fibers to perform these strain measurements, taking advantage of their multiplexing capabilities and their immunity to electromagnetic interference. In this paper, we introduce a fully automated set-up to calibrate the multi-parameter FBG force sensors and we present our first calibration results.

Introduction

Assembly, surface machining and cutting operations require multi-component force sensing schemes to control the force exerted by the robot end-effector or the manipulators on an object. Since such remote-handled tools have to operate in electromagnetically noisy environments, classical force sensors based on electrical strain gages require a complex design and need a large amount of shielded connections. The control of robots in noisy environments may therefore benefit from the use of EMI-insensitive multi-component force sensors. Multi-component force sensing is usually done with local strain measurements on a force-uncoupling elastic transducer. We have demonstrated that fibre Bragg grating (FBG) strain sensors [1] can be used to perform these local strain measurements [2]. Their multiplexing capabilities allow to construct very compact sensors, with a reduced number of connections to the instrumentation. The complexity of these sensors could be drastically reduced by having fiber optic gages able to perform multi-axial strain measurements.

In the other hand, polarimetric optical fiber sensors have shown promising application in dentistry for the monitoring of the dental cement shrinkage. These sensors measure an external perturbation as a phase difference between two orthogonal modes propagating inside a polarization-maintaining fiber [3, 4]. Although the well known advantages of such sensors, such as small size, light weight and bio-compatibility, the use of the polarimetric sensor is currently limited by the complexity, the price of the optical measurement set-up and its intrinsic lack of selectivity when subjected to multiple solicitations, like temperature, axial strain and transverse strain. The characterisation of dental cements and its curing process optimisation could also benefit from the measurement of the temperature and the complete state-of-stress between the dentine and the porcelain facing.

In this paper, we discuss the operation of the multi-parameter fibre Bragg grating sensor. Then, we describe the fully-automated measurement calibration set-up for FBG sensors. Finally, we present some preliminary calibration results on polarimetric sensors.

The multi-parameter fibre Bragg grating sensor

Lawrence [5, 6] showed that multi-component force sensing could be achieved by using a single Bragg grating written into a high-birefringent, polarisation-maintaining (PM) fibre, that supports two linear polarisation eigenmodes. When a grating is written in a hydrogen-loaded PM fibre, the physical periodicity of the grating Λ is identical for both modes. However, the effective index of refraction is distinct for each mode. We may state that the refractive indices are n_1 and n_2. Therefore, the Bragg wavelength is different for each mode and two peaks are reflected by the FBG:

$$\lambda_B^2 = 2n_1\Lambda \qquad \text{and} \qquad \lambda_B^1 = 2n_2\Lambda \tag{1}$$

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The peak separation depends mainly on the birefringence of the fibre $B = n_1 - n_2$, while the position of the peaks depends on the effective refractive index of both modes n_1 and n_2. Contrary to the intensity-encoding of the sensing information in classical polarimetric sensors, the sensing information is now spectrally encoded making this sensor more suitable for an industrial application. The birefringence in PM fibres arises from the anisotropy of the state of stress freezed in the during its manufacturing process. The birefringence depends on any externally-applied transverse strain.
Moreover, Lawrence showed that, in principle, it is possible to measure the axial stress σ_z, the two principal transverse stresses σ_x, σ_y and the temperature T, with two superimposed gratings at 1300 nm and 1500 nm written into a PM fibre[6]. Each grating has a different grating periodicity and two refractive indices, making four reflected peaks in total. This would allow to perform multi-axis force measurements and compensate for temperature variations at the same time. To achieve this, the multi-parameter FBG sensor need to be selective enough to measure at the same time isotropic solicitations, such as temperature, and anisotropic solicitations such as transverse forces.
In what follows, the FBG sensor selectivity is qualitatively shown. The gratings are supposed to be ideal and written into a Fibercore HB1500 PM fiber. The fiber mechanical parameters are supposed to remain unaffected by UV irradiation. For the grating period, We take Λ equals to 530 nm. The hypothesis of linear elasticity is assumed, which means that the stress contribution from each solicitation can be calculated separately and then superimposed.
The refractive indices n_1 and n$_2$, can be written as [7]:

$$n_1 \approx n_0 + \frac{B_i}{2} \qquad \text{and} \qquad n_2 \approx n_0 - \frac{B_i}{2}$$

where B_i is the intrinsic birefringence of the PM fiber. For the Fibercore HB 1500 PM fiber, the refractive index of the core n_0=1.465 and B_i = 5.34 10^{-4}. This leads to $n_1 \approx 1,4653$ and $n_2 \approx 1,4647$
When an external perturbation (temperature T, axial strain ε_z or transverse force F) is applied to the fiber, the birefringence B and the refractive index of the core n_0 of the fiber are modified. Therefore, the Bragg peaks shift not only due to the refractive index changes (elasto-optic effect and the thermo-optic effect), but also due to grating period changes.

$$\Delta\lambda_B^i = 2\Delta n_i \Lambda + 2 n_i \Delta\Lambda \quad \text{with} \quad i = 1, 2.$$

The resulting birefringence B in the fiber core can be written as follows, [8, 9, 10]

$$B = B_i + B_T + B_s + B_F = B_i - CA_T\Delta T - CA_s\varepsilon_z + CA_F F \qquad (2)$$

The sensitivities of the birefringence due to a change of temperature, a longitudinal strain, a hydrostatic pressure and a transverse applied force are, respectively [8, 9, 10]:

$$A_T = -\frac{E\Delta\alpha B^*}{2(1-\nu)}, \quad A_s = \frac{E\Delta\nu B^*}{2(1-\nu)}, \quad A_F = \frac{8}{\pi h d} \qquad (3)$$

where ν is the Poisson's ration, E is the Young's modulus, d is the diameter of the fiber, h is the length over which the force F is applied and B^* is the average geometrical factor of the PM fiber.
Considering a bow tie fiber Fibercore HB 1500, a stress-optic coefficient C of about $3.810^{-12} Pa^{-1}$[11] and a solicitation length h of 15 mm, we can estimate the order of magnitude of A$_T$, A$_s$ and A$_F$, at:

$$A_T = -4.6\ 10^4 Pa/^\circ C, \quad A_s = 1.1\ 10^3 Pa/\mu\varepsilon, \quad A_F = 1.4\ 10^6/m^2$$

For the Fibercore HB1500, the birefringence dependence therefore equals to:

$$B \approx 5.3\ 10^{-4} + 3.4\ 10^{-7}\Delta T - 4.1\ 10^{-9}\varepsilon_z + 5.1\ 10^{-6} F \qquad (4)$$

where T is expressed in C, ε_z in $\mu\varepsilon$ and F in N. From Equation 4, we see that the contribution of transverse solicitation is predominant. In other hand, the temperature and axial strain effect are small in comparison with the thermo-optic effect and the elasto-optic effect respectively (see Eq. 1). We can therefore consider that the Bragg peak separation is a direct measurement of transverse applied, while the mean position of the Bragg peaks is a measurement of both the temperature and the axial strain.

In first approximation, we can estimate the peak separation of a FBG written in PM fiber subjected to purely transversal force F, if the fiber is supposed elastically homogenous. Under this assumption, it results a plane state of stress in the fiber and the principal stresses are given by: [10]

$$\sigma_1 = \frac{2F}{\pi hd} \qquad \sigma_1 = -\frac{6F}{\pi hd} \tag{5}$$

In the case of isotropic and homogenous media it can be shown that [11]

$$n_1 = n_0 + \Delta n_1 = n_1 - \frac{1}{2}n_1^3\left(p_{11}\varepsilon_1 + p_{12}\varepsilon_2\right), \qquad n_2 = n_0 + \Delta n_2 = n_2 - \frac{1}{2}n_2^3\left(p_{12}\varepsilon_1 + p_{11}\varepsilon_2\right)$$

The Bragg peak positions are therefore:

$$\Delta\lambda_1 = -\lambda_1 \frac{n_1^2}{2}\left(\frac{1+\nu}{E}\right)\left[p_{11}(1+2\nu) - p_{12}(3-2\nu)\right]\frac{2F}{\pi hd} \quad > 0$$

$$\Delta\lambda_2 = -\lambda_2 \frac{n_2^2}{2}\left(\frac{1+\nu}{E}\right)\left[p_{12}(1+2\nu) - p_{11}(3-2\nu)\right]\frac{2F}{\pi hd} \quad < 0$$

where d is the fiber diameter, h the length of the fiber over which the force is applied, p_{11} and p_{12} are the elements of the stress-optic tensor. The peak separation increases linearly with the transverse applied force.

Experimental set-up and results

A fully PC-controlled calibration set-up has been developed to test multi-parameters FBG force sensors. This set-up can apply axial and transverse forces, rotate the fiber sensor and control the temperature next to the fiber. The optical sensor is attached to two mounting brackets. One of the bracket is fixed to the optical table while the other is mounted on translation table. The axial strain is produced by a NEWPORT-850 actuator, which is steered and controlled using the Newport M4005 movement controller. The axial force applied to the fiber is measured by a load cell ENTRAN ELPM, sited between the mobile mounting bracket where the fiber is fixed, and the mounting bracket on the stage. We feed back the axial force measurement to the motion controller to increase the displacement linearity and to reduce hysteris.

The transversal force is applied to the fiber by means of a step motor, driven by a McLENNAN PM170 motion controller. This actuator rotates along an axis. This rotation movement is converted into a linear movement that originates the transverse force. A rectangular pressure head applies the force to the fiber sensor. A load cell ENTRAN ELPM, mounted between the step motor and the pressure head, measure the transversal force applied to the fiber and send it also back to the controller. The angle between the applied force and the fiber is controlled using two NEWPORT precision rotation motors that hold the fiber. To avoid twisting and damaging the fiber, the motors work in master-slave mode, in this way the fiber is rotated under the same angle on both sides. The rotation motors are driven using the NEWPORT M4005 movement controller. A thermoelectric cooler, located directly under the fiber, deals with the temperature control of the fiber sensor.

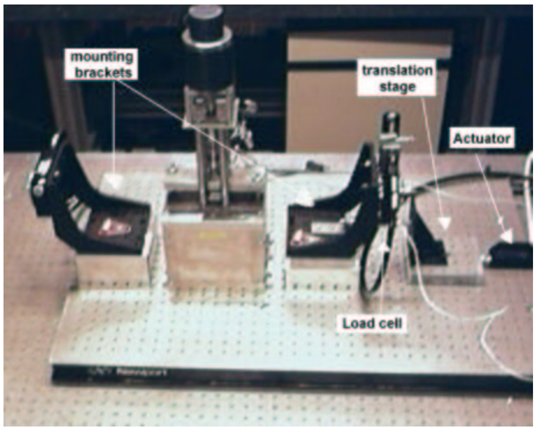

Figure 1: Multi-axial calibration set-up for multi-parameter FBG sensors

We determined the axial and the transverse sensitivities of a polarimetric sensor made of Fibercore HB 1500 PM fiber. The sensor length was 788 mm. At 1550 nm, we measured an axial strain sensitivity of 90 rad mm^{-1} and a transverse strain sensitivity of 14 rad $(MPa/m)^{-1}$. These values are in accordance with the values found in the literature [12, 13].

Conclusions

Multi-axial fiber optic force sensing could bring interesting alternatives to classical force sensors in robotic application and help the understanding of cement curing process in dentistry applications. Fibre Bragg grating written in polarisation maintaining fibres reflects two peaks corresponding to the two orthogonal polarisation modes of the PM fiber. The sensing information is encoded both in the absolute Bragg peak position and in the Bragg peak separation. The absolute peak position is selectively sensitive to isotropic solicitations (temperature and axial force) whereas the Bragg peak separation is sensitive to anisotropic solicitations (transverse force). We presented a fully PC-controlled set-up engineered to evaluate multi-parameter FBG sensors. Preliminary results on polarimetric sensors have been presented. The characterisation of FBGs written in PM fiber is currently on going. Future work will include the evaluation superimposed FBGs written in PM fibers.

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