Experimental analysis of the dynamic behaviour of FBG temperature sensors

T. Carlesi, [1,2,3] D. Laboureur,[1] P. Planquart, [1] J. Pacio, [3] K. van Tichelen, [3] P. Mégret,[2]

[1] von Karman Institute for Fluid Dynamics, Environmental and Applied Fluid Dynamics Department, Waterloosesteenweg 72, 1640 Sint-Genesius-Rode, Belgium

[2] University of Mons, Electromagnetism and Telecommunication Department, Boulevard Dolez 31, B – 7000 Mons, Belgium

[3] Belgian Nuclear Research Centre (SCK CEN), Institute for Advanced Nuclear Systems, Boeretang 200, 2400 Mol, Belgium

Abstract

This work investigates theoretically and experimentally the thermal dynamic behaviour of fibre Bragg grating (FBG) temperature sensors. The bare fiber used is modeled as a first order system and its time response under a temperature step simulation is calculated according to well-known mathematical models. The same procedure is carried out for a type K thermocouple (TC) to compare the performance of the two sensors under the same conditions. Comparisons with previous literature works and theoretical calculations are also carried out, showing a general good agreement among them. Characteristic response times of FBGs in water are in the order of 7–20 ms. The results are relevant for any application involving temperature measurements with FBG sensors.

Introduction

Fiber Bragg gratings (FBG) have been used for almost forty years in many applications for telecommunication or as strain and temperature sensors [1]. Generally, temperature measurements are performed in static or quasi-static conditions since the temporal variations of the measured quantity are very low. However, sensors with a rapid response are required by dynamic temperature measurements in specific fields like ocean and aerospace applications [2], medical applications [3, 4] and turbulent measurements in fluids. Despite of that, the dynamic behaviour of FBG temperature sensors is not well-known. In 2016, Pan *et al.* characterized the response time to a temperature step in water of three different sensors (bare, gold-coated, and ceramics packaged FBG) obtaining respectively averaged values of 8.9 ms, 12.3 ms and 336 ms [5]. Most of the studies present in literature focusing on FBG temperature measurements consider regenerated and packaged FBGs for high temperature applications [6, 7, 8, 9]. Therefore, the time responses obtained swipe a wide range between 4.8 ms [6] up to 9 s [7] according to the type of the fiber and the methodology applied for its calculation. In most of these cases, the response times are still not small enough for many of the forementioned applications. A further investigation on temperature response time of FBG sensors is therefore beneficial for the research field. In this article, the time response of an FBG in water is evaluated and compared with the one of a standard K-type thermocouple (TC) tested in the same conditions. Different experimental solutions are discussed and a new analysis of processing methods and their accuracy is presented aiming at finding a standardization for the calculation of this parameter.

Theoretical background

FBGs are sensitive to both strain and temperature variation, and under fixed strain conditions, the Bragg wavelength shift is linearly related to temperature with a sensitivity coefficient around 10 pm/°C. For any temperature sensors, the temperature variation depends on the energy transfer between the sensor and the external environment, following the Fourier thermal equation and the Newton's law in Eq. (1):

$$\rho c_P V \frac{\mathrm{d}T_s}{\mathrm{d}t} = hA(T_f - T_s) \tag{1}$$

where ρ is the density, c_p is the specific heat, V is the volume of the sensor, T_s is the temperature of the sensor, T_f is the temperature of the fluid where the sensor is immersed, h is the convective heat transfer coefficient, and A is the surface of the sensor. Therefore, the sensor can be modeled as a first order system with time constant τ, and with a temperature evolution given by Eq. (2):

$$T_s(t) = T_f - (T_f - T_{s0})e^{-\frac{t}{\tau}} \quad \text{with } \tau = \rho c_P V/(hA). \tag{2}$$

From Eq. (2), τ is the time needed for the sensor output signal to reach 63.2 % of the steady value after a step input. During the experiments, a step in temperature has been applied and the sensor response has been recorded. Four different methods have been used to estimate the time constant: (1) measure the time (5τ) to reach the steady state; (2) find τ as the time corresponding to the 63.2 % of the difference between the steady state and the initial value of the temperature; (3) use a fitting function of the form of Eq. (2) on the measured data and compute τ by the least-square method; and (4) use the so-called log-incomplete method that consists in rewriting Eq. (2) in the form of Eq. (3):

$$Z(t) = \ln\left(\frac{T_s(t) - T_f}{T_{s0} - T_f}\right) = -\frac{t}{\tau}. \tag{3}$$

It follows from Eq. (3) that the time constant is the negative inverse of the slope of $Z(t)$.

Experimental setup

The experiment depicted in Fig. 1 is carried out on a bare FBG with a diameter of 125 µm and a sensitive length of 10 mm and a standard type K thermocouple with a wire dimension of 0.3 mm. Hot water at a temperature of 40–60 °C is held in a container, therefore

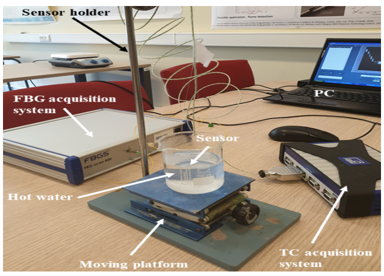


Figure 1 - *Experimental set-up*

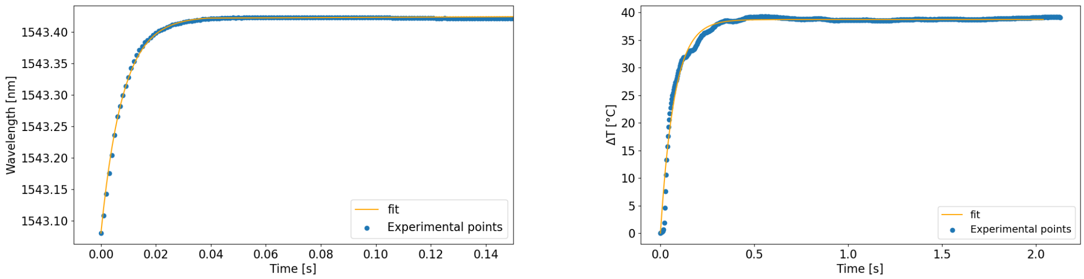
Parameter	FBG		TC
ρ [kg/m^3]	2196		7975
c_P [J/(kg K)]	966	[5]	444
h [W/(m^2 K)]	5000		5000
τ [ms]	9		66

Table 1 - *Physical parameters*

providing temperature steps in the order of 20–40 °C from ambient temperature. Assuming the water as a natural convection cooled body in the environment, the time constant of the cooling process has been estimated to be around 7.5 min. Since the duration of a single experiment is in the order of seconds, the water temperature can be assumed to vary no more than 5% during a whole run. Moreover, the temperature in the water is assumed to be homogeneous due to the small dimension of the container. The FBG and the TC are tested separately in the same conditions. They are plunged in hot water keeping the sensors still and moving the container by hand. The main problem with this procedure is that the sensors start to feel a temperature variation even before being plunged because of convection and radiation phenomena reducing the accuracy of the step input. An FBG-Scan 800 device and a HBM MX440B are used as acquisition systems for the FBG and the TC respectively, allowing to acquire data at a frequency of 1000 Hz for the FBG and 4800 Hz for the TC. In both cases, the acquisition frequency is at least 10 times higher than the expected sensor response.

Results and discussion

Theoretical calculations of the expected response time for the sensors are carried out using the values reported in Table 1. The fiber is considered as an homogeneous cylinder made of amorphous silica while for the TC, average properties of nickel and chromium are considered. The experimental signals obtained are reported in Fig. 2 and the results (Table 2) indicate that the time response of the TC is higher than the one of the FBG.



(a) *FBG step in temperature* **(b)** *TC step in temperature*

Figure 2 - *Measured step in temperature experienced by the two sensors with the fitting function (method 3) in orange. The wavelength shift read by the FBG has not been converted to temperature since the linear relationship between the two does not change the dynamic behaviour of the sensor.*

Test	FBG				TC			
	5τ	63.2 %	fit	log	5τ	63.2 %	fit	log
1	10	11	8	12	100	63	66	108
2	8	7	6	7	120	60	75	119
3	14	20	16	20	60	62	68	139
4	10	8	13	8	60	49	51	115
Average	10.5	11.5	10.8	11.8	85	58.5	65.0	120.3
Type A uncert.	1.1	2.6	2.0	2.6	13.0	2.8	4.4	5.8
Type B uncert.	0.0006	0.0006	0.0006	0.0006	0.0001	0.0001	0.0001	0.0001
Total uncert.	1.1	2.6	2.0	2.6	13.0	2.8	4.4	5.8

Table 2 - *Response time in ms for FBG and TC sensors*

The uncertainty has been calculated following the procedure by Li *et al.* [10] evaluating separately type A and type B uncertainty and combining them together. Type B uncertainty reveals to be negligible in respect of type A. For both sensors, the different methods are in general in good agreement and consistent with theory. Despite its simplicity, the 5τ method has many drawbacks in terms of accuracy and cannot be considered very reliable since it is only based on an estimation of the operator. This fact is well represented by the high uncertainty shown in the case of the TC tests. The 63.2 % method can be considered more reliable, even though the definition of the initial and steady state values is not trivial to find accurately in practice. The log-incomplete method often gives values higher than the other methods. Since the fit is made in a logarithmic scale, it is not always easy to set the boundaries of the fitting function. The most accurate method among the proposed ones is the fit made through the least square method, as it is possible to see from the low uncertainty shown for both sensors. Overall, the methods show that the time response of the TC is almost six times higher than the one of the FBG.

Conclusions

The dynamic performances for temperature measurements of an FBG and a TC have been compared through a total of eight tests, applying four different processing methodologies for the response time calculation. It has been proved that bare FBGs have lower response time than standard TC and can be used in applications where temperature varies fast and where standard TCs do not give the required performances. Further tests can be performed with different experimental techniques to overcome some practical difficulties encountered here. To build a more precise temperature step, a continuous laser regularly shaded by a rotating element could be used to illuminate the sensor. Moreover, with more details about the environmental conditions in which the experiment is performed, type B uncertainty can be estimated more precisely [10].

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