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# Aluminum coated fiber optic sensor for enhancing flow rate measurement

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**ABSTRACT**

A water flow and velocity aluminum-coated Fiber Bragg Grating sensor system for open channels was designed, simulated and tested. The sensing head was designed, ruggedized and customized to measure velocities at different depths, in order to calculate the discharge in open channels. This paper shows, for the first time to our knowledge, the simulation of such kind of fiber sensors in open channels.

**Keywords:** Velocity gradient, open channel, ANSYS, Fiber Bragg Grating, strain.

## 1. INTRODUCTION

Optical fiber sensors are especially appealing for applications that need to measure elastic deformations or use the measurement of deformations to induce the variation of another parameter. They have interesting advantages such as their small dimensions and their electromagnetic immunity because they are fabricated using dielectric materials. Also, they are chemically passive and mechanically compatible with many materials. Among these sensors, Fiber Bragg Gratings (FBGs) are well suited point transducers [1]. These sensors have been previously used to measure flow inside pipes [2]. FBGs can be coated with different materials for the suitable application. In this paper we show an enhanced FBG based sensing configuration to measure the velocity profile and, therefore, the flow rate in open channels, improving sensibility and the hysteresis from an exhaustive computational analysis and modelling of water flow.

## 2. COMPUTATIONAL METHOD FOR OPEN CHANNEL SIMULATIONS

The computational method is based on two calculations: the fluid dynamics calculation for the determination of the velocity and force profiles on the photonic wire and then the mechanical strength calculation for the determination of the wire deformation. After both calculations, the calculated deformation is compared with the deformation measured "in situ" in the channel using photonics.

**1.- Computational simulation: Fluid Dynamics.**

Simulations have been carried out with the ANSYS-CFX V2020 R2[3] program, that is a finite volumes program, with one simulation for each of the eight flow rates tested [4]. The three-dimensional mesh consists of 2,805,888 elements (2,804,224 hexahedrons and 1,664 prisms) and 3,013,233 nodes. This case is a free surface model with some simplified steps: fluid buoyancy model considers density difference, without interphase transfer model, without a surface tension model.

Isothermal and the turbulence model is the standard $k$-$\varepsilon$. Given the symmetry of the problem, only half of the domain has been considered, from a sidewall to the central plane or plane of symmetry. The number of iterations for solving the mass and momentum equations varies from 1,023 for the 1.5 $m^3$/h flow rate to 325 for the 8.5 $m^3$/h flow rate. The largest error is mass water normalized imbalance 2.79%, showing a good convergence with measured data.

Figure 1 shows the fraction of water (in red) in the center plane and Figure 2 shows the free surface (green), both analysis in the vicinity of the obstacle.

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### 2.- Computational Simulation: Structural Mechanics

The previously mentioned program has been used to calculate the strain on the sensor. However, the fiber deformations have also been calculated by computational simulation with ANSYS Mechanical APDL V2020 R2, which is a finite element program that can be used to perform static and dynamic structural analysis. The element type LINK180 from the ANSYS library was used. LINK180 is a three-dimensional element that is useful in a variety of engineering applications. The element can be used to model cables and wires. The element is a uniaxial tension-compression element with three degrees of freedom at each node: translations in the *x*, *y*, and *z* nodal directions. Only tension (cable) is supported.

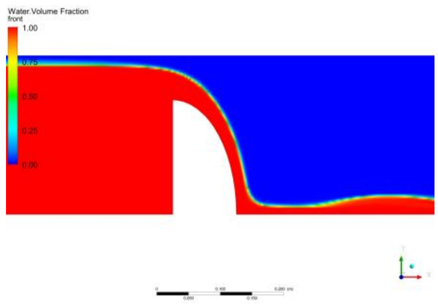


Figure 1. Water volume fraction simulation.

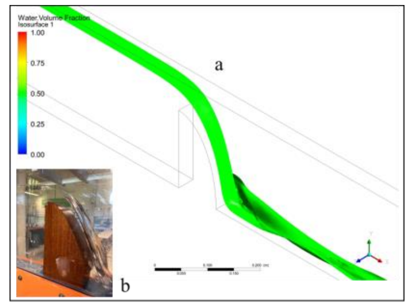


Figure 2. a) Free surface in obstacle vicinity b) Spillway placed in experimental channel.

## 3. EXPERIMENTAL SETUP

### 3.1 Fabrication process

The device used for open channel flow measurement has been designed to meet the mechanical conditions of the experimental channel. It has been modified from the work previously done by [5] to correct some technical details. First of all, the horizontally placed sensors have been made independent. Fig. 3 describes the shape of the element with its dimensions. It consists of a stainless-steel part adapted with two screws at mid-height that serve as fasteners to the fiber thread containing the FBG. The maximum bending radius of the fiber is 17 mm in accordance with the manufacturer's recommendation.

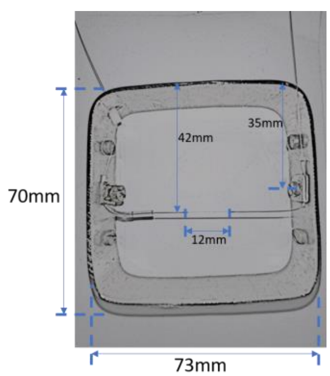


Figure 3. Sensor holder for aluminum coated FBGs.

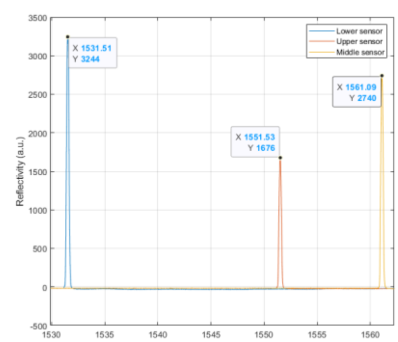


Figure 4. Reflected spectra of the three independent aluminum-coated FBG sensors.

Moreover, aluminum-coated optical fibers have been chosen, which makes the sensor more rigid. Notably, the sensitive area is not covered with metal, marking 12 mm of length of interest and placed in the center of the metallic structure. This eliminates the use of plastic or acrylate-based materials which have been shown to have plasticity and therefore a delay in recovery of the initial conditions once the fiber has been under stress. Finally, the structure has four mounting screws, two on each side, whose purpose is to facilitate the fastening of the metal frame to the channel walls. The FBGs used come from Technica. S.A. and have been chosen with different wavelengths in order to ensure adequate spectral separation and to facilitate peak detection and further processing of the collected data. Fig. 4 shows the spectrum of the three sensors. All sensors were pre-stressed, as a reference measurement, by hanging a mass at one end. The resulting (initial) strain was calculated considering the Young's modulus of aluminum and silica, and the dimensions of the optical fiber.

### 3.2 Experimental setup and working principle

Figure 5 shows a schematic diagram of the experimental setup for the strain sensors multiplexing. The setup is formed by a commercial FBG sensors interrogator (Micron Optics® SM-130), an experimental channel with a transversal section of 230 x 75 mm, the three-level sensing head and a computer were a custom-made data acquire software is running. Several sensors have been placed at certain heights using the structure described above. In our final design, we decided to place the sensors horizontally, in different fibers. In this way the channel section is covered with the possibility of measuring the influence of the water level at different heights as shown in Fig. 6.

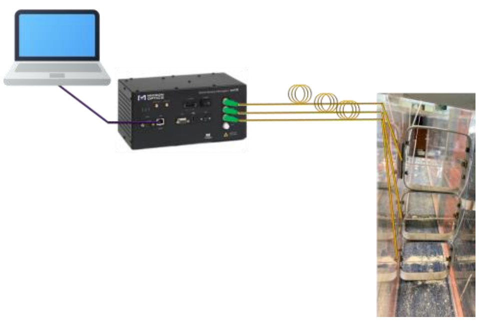

Figure 5. Schematic diagram of the experimental setup. Figure 6. Sensor holders placed in experimental channel.

The measurement procedure was carried out by driving a stream of water through the channel by means of a pump and controlling the flow with a control valve. The flow readings were taken from a flow meter present in the experimental installation. The flow rate was increased at 0.5 $m^3$/h intervals, from 1 $m^3$/h to 8.5 $m^3$/h, the maximum possible flow rate at the pump. Different pieces of wood can be placed to raise the water level and appreciate the effect of dragging currents. In Fig. 2b is depicted the one that was used in the validation and the computational simulation. Once the maximum flow rate is reached, it is decreased with a similar interval until the valve is completely closed. the objective is to evaluate the behavior of the sensor to variations and the repeatability of the proposed system. All experimental procedure was performed under constant temperature conditions.

## 4. RESULTS AND DISCUSSION

The water velocity at the midplane at the position of the sensors was also simulated as a function of flow rate (see Fig. 8). Later on, the velocity gradient in direct relation with the thickness *z*, this time for the maximum flow rate possible (8.5 $m^3$/h) is described in Fig. 9. Figure 10, analogous to previous one, is dedicated to the dynamic pressure force, function of the thickness *z*, also for the top flow rate.

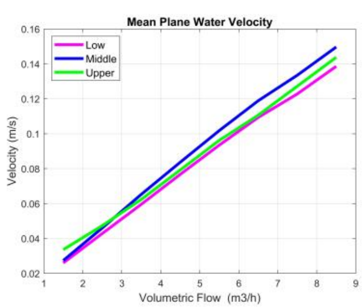


Figure 8. Simulated water velocity at sensors location.

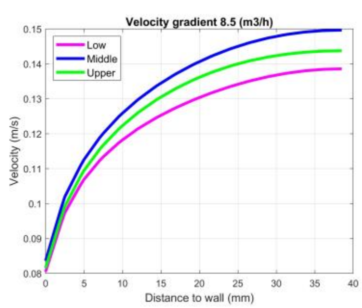


Figure 9. Simulated velocity gradient.

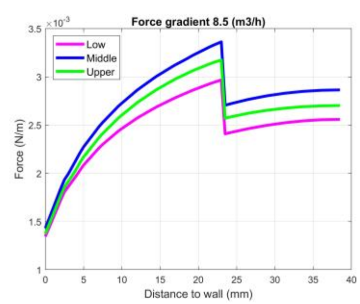


Figure 10. Simulated dynamic force gradient.

The water force $p$ on the sensor is the input and the sensor elastic strain is the output. A simulation for each water flow has been performed. This figure clearly shows a jump in the forces, which is due to the sudden change in diameter of the sensor when there is no aluminum protection. Since the force on the sensor is not uniform, 78 nodes have been taken, for each half sensor, where the corresponding force has been applied. Figure 11 shows the theoretical deformation of the three sensors under water pressure in *microstrains* ($\mu\varepsilon$), as a function of the flow rate considered. Figure 12 shows the experimental records corresponding to the MIDDLE sensor (in red) together with its theoretical deformation curve calculated by the computational methods presented. A good approximation is seen for this higher flow rate. The approximation for the rest of the flow rates is even better, since the lower the flow rate, the lower the deformation.

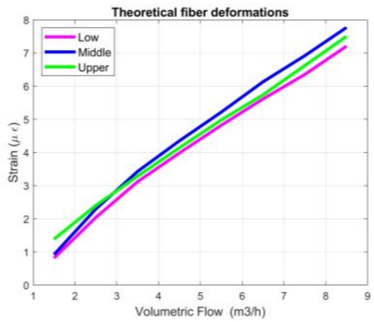


Figure 11. Strain calculation.

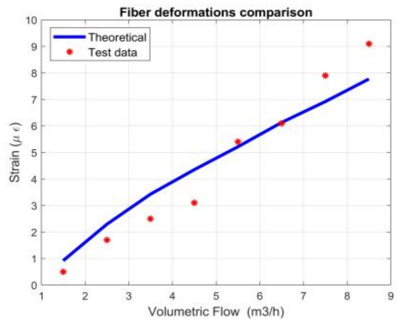


Figure 12. Middle sensor strain comparison.

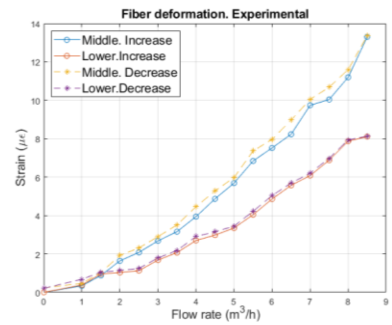


Figure 13. Experimental strain data obtained.

The experimental data obtained for the middle and upper sensors show a linear trend similar to the theoretical estimation, both for the rise and fall of the flow rate (Fig. 13). There are differences in the initial and final points of the measurement, in the order of 0.2 $\mu\varepsilon$, which has improved the hysteresis of the sensor. In the case of the upper sensor, a maximum deformation of 68.6 $\mu\varepsilon$ has been obtained, which is consistent with the non-uniform distribution [6] of water stream velocities in open channel and, therefore, higher values are observed at greater heights.

## 5. CONCLUSIONS

In this work, an aluminum coated FBG sensor was improved for measuring of water velocity in open channels. A computational simulation was performed in order to analyze the physical processes that occur in the fiber optic sensor. A mechanical strength estimation was calculated for the comprehension of FBG strain under maximum flow rate conditions. Compared with [5], where a difference of 5.76 $\mu\varepsilon$ was achieved, the obtained system hysteresis is been reduced and higher resistance and independence of the sensor, thus, a better sensing area.

## ACKNOWLEDGMENT

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