Development of a water flow and velocity optical fiber sensor for field testing

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Abstract: A water flow and velocity fiber optic sensor system was developed and tested. The sensing head was especially developed and ruggedized to measure velocities at different depths, in order to calculate the discharge in channels.

1. Introduction

Continuous streamflow records are necessary to plan water supply systems, for the correct operation of water management and distribution systems. This requires systematic and continuous streamflow recording. A hydrograph is the representation of discharge values with respect to time at a point in a river or channel. To obtain it, it is necessary to take measurements of the water surface height (stage) that is transformed into flow through the stage-discharge curve. Discharge is measured at stream gaging stations using the velocity-area rate of a channel. Usual devices to measure velocity in channels are fabricated using electronic or mechanical components [1].

Optical fiber sensors are especially appealing for this application due to 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 [2]. These sensors have been previously used to measure flow inside pipes [3]. In this paper we show a new FBG based sensing configuration suitable to measure flow and speed of the water in open water channels.

2. FBGs characterization for water velocity measurements in water pipes

Mechanical simulations and experimental validations have been carried out in order to check the behavior of the FBGs to know the structural deformation of the sensor, mainly the elastic strain. We have utilized two different software tools to simulate the mechanical behavior of FBGs on different supporting materials. We consider in our first simulations that the acrylate coating of the FBGs fabricated in standard SMFs has been removed along 67,8 mm, as we experimentally did.

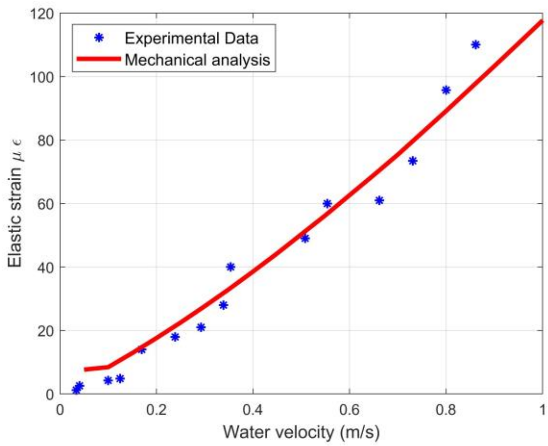
The first software tool has been ANSYS CFX, that is a general-purpose Computational Fluid Dynamics (CFD) software. This program has been used to calculate the water force on the sensor from a hexahedric mesh with 82040 finite volumes. The mean water velocity into the pipe is the input. The other tool was ANSYS Mechanical APDL, that is a finite element program, which may be used to carry out static and dynamic structural analyses [4]. This program has been used to calculate the strain on the sensor. The water force on the sensor is the input and the sensor elastic strain is the output. The LINK180 type element, for 3-D spar simulations from ANSYS library has been used. This element can be used to model wires as a uniaxial tension element. The Young module of 70GPa for the fiber has been considered in calculations. Figure 1.a shows the achieved results of the simulations versus the experimental measurements in the pipe.

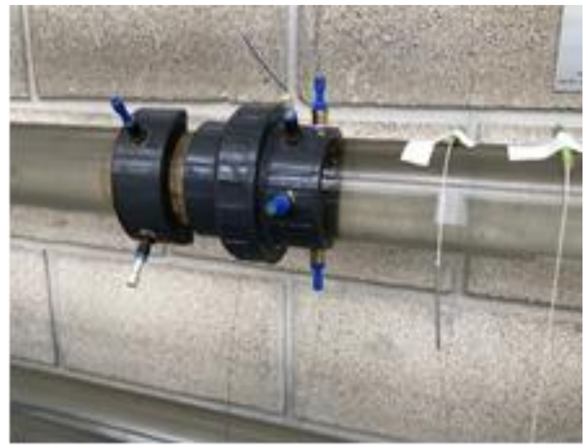
For these measurements, a couple of FBGs were placed in a pipe of 67,8 mm of diameter. Water flow measurements were carried out by using a flow meter to take readings and do the proper calibration of the FBGs. In order to describe the water flow behavior inside the pipe, we have placed a FBG in vertical position and another one in horizontal way. Fig. 1.b depicts the setup. A distance of 50 mm between both sensors was considered because the turbulences caused by the fiber itself when the stream goes thru could affect the last sensor. The maximum flow rates the pump can achieve is 43,5 m^3/h.

FBGs sensors placed inside the pipe suffer a strain proportional to the applied water flow, as shown in Fig. 1.a. The strain is translated to a wavelength reflected shift when the FBGs are interrogated with and optical FBGs interrogator (SM-130 from Micron Optics Inc.) FBGs behavior in vertical or horizontal position were very similar. However, FBGs without coating or even with the primary acrylate coating were broken periodically because of turbulences inside the pipe, besides, the impurities dragged by the water accumulated on the fiber creating long threads that alter the measurements.

Thus, in order to develop a sensing head suitable to work in real conditions in open channels, different combinations of fastenings and protections were tried. Finally, each of the gratings has been attached to a nylon thread and covered with a heat-shrinkable Polyvinyl Chloride (PVC) jacket to protect them. This combination protects correctly the FBGs sensors while the resulting sensitivity is higher enough to correctly measure even low flow rates. This is due the resulting wire-liquid contact area is increased because the protection arrangement, partially compensates the use of a more rigid structure. The final diameter of our sensing wire was 1 mm.

Evolution of the design of different supports and protections of FBGs for water flow measurements will be published elsewhere.





a) **b)**

Fig. 1.a) Water velocity strain response simulation vs measurements b) Experimental set-up where two FBGs were placed orthogonally into a pipe

3. Sensors Experimental setup in a water channel

The velocity in open channel flows follows a non-uniform distribution on a cross section. The highest values are taken at distances close to the water surface; meanwhile the lowest can be found at bed level. So is highly convenient to locate several sensors at different heights along the waterway. The measurement of different flow values and respective correlation allow to calculate the distribution along the section.

In order to study the behavior of the water flow in open structures and the suitability of FBG based sensors for this task, an experimental channel (Fig. 2a) was employed as testing field. The transversal section of the channel (230 x 75mm) is suitable to design an affordable sensor. It has a pump with a controllable flow rate and an intermediate faucet to modify the amount of water along the channel. Different pieces of wood can be placed to raise the water level and appreciate the effect of dragging currents. The proposed sensing head was developed taking a metallic frame as support. The sensor holder is made of an aluminum alloy, with a spring-loaded screw to adjust the width of the holder, so that it can be adapted to the width of the experimental channel.

Before placing the sensors, it is necessary to tighten the fiber optic thread to achieve its correct elongation. In the upper part of the aluminum frame there is also a spring-loaded wheel through which the optical fiber passes and is held with a plastic washer so as not to damage the material. It is gradually tightened by turning it clockwise and its tension is monitored through the interrogator. When the optimum point is reached, each grating reflected wavelength is taken as the starting point of the measurement.

The importance of studying the flow distribution in the channel cross section was previously discussed. That is why it has been proposed to place several sensors 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. 2.c.

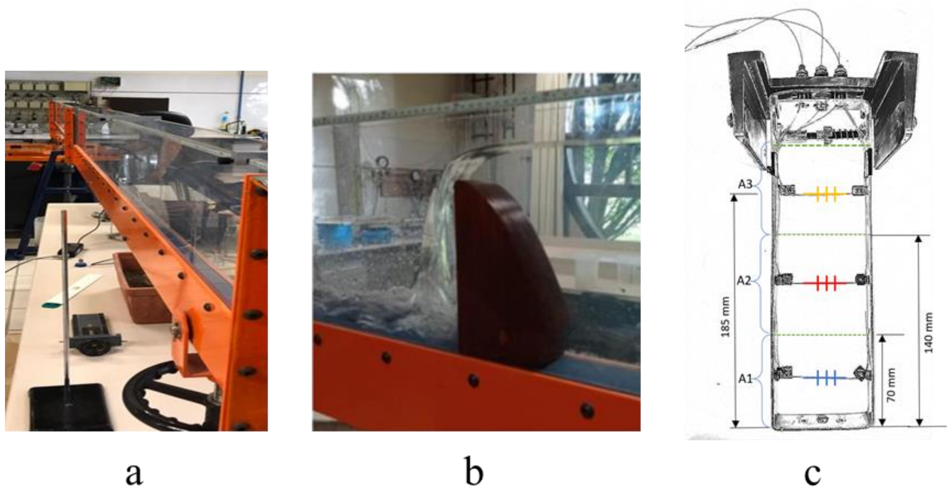


Fig.2. a) Experimental channel used in experiments b) Spillway placed in the channel c) Sensor holder with horizontally-placed FBGs.

The wavelengths of each sensor were chosen so that they are spectrally separated, resulting in the lower sensor (blue) at 1561 nm, the intermediate sensor (red) at 1549 nm and the upper sensor (yellow) reflecting at 1536 nm. The SM-130 FBGs interrogator was configured with a sampling rate of 1 kHz. The choice of this sample rate, as the maximum the interrogator can afford, is used to calculate and perform proper statistical analysis in order to correctly stablish relation between water flow rate and the strain applied to the fiber.

4. Results and discussion

In order to get reliable information from the proposed sensor for water velocity characterization is mandatory to perform a calibration. It is necessary to get the higher Bragg wavelength range for each grating and the noise limits at each flow rate applied to the channel. The performance of the sensor has been assessed by manually incrementing the flow rate through the channel from 0.5 to 8.5 m^3/h. The initial inclination of the channel was 1% and the height of the water level was also recorded. This task was repeated several times for statistical error analysis.

It can be observed in Fig. 3 that as the flow increases the strain in the FBGs changes. There is a remarkable strain change when the water suddenly covers each sensor, as expected. So, our system is also suitable to carry out water level measurements. Maximum strain variations of 1315 με have been achieved at flow rates of 8.5 m^3/h. All measurements were carried out at constant temperature as the FBG is also sensitive to this magnitude. The estimated sensitivity of each grating is shown in Table 1. The highest value is reached in the intermediate zone, which corresponds to the highest drag velocities, as is described in the model of velocity distributions for open channels.

The calculation of the average water velocity is performed by applying the continuity equation [5].

$$Q = V_m * A \quad (1)$$

Where: $\boldsymbol{Q}$ is the flow rate in m^3/s; $\boldsymbol{V_m}$, the average water velocity, in m/s and $\boldsymbol{A}$, the area of the section in m^2.

In order to analyze the velocity distribution, the sensor head area was divided in three sections, wherein each grating is placed in the center. The total average velocity will be the contribution of the velocities calculated in each section. Once performed the analysis, a velocity distribution curve is obtained as shown in Fig. 4. The trend is closely related to the theoretical aspects described above, highlighting that the highest velocity values are obtained in the central section of the channel.

The process was repeated for a channel slope of 1.7% in order to verify the previous results and to study the effect of the slope on the water velocity. Now, the upper sensor records the highest value, confirming that the surface currents increase with channel tilting. Table 1 also includes this new sensitivity study.

Table 1. Sensor sensitivity at 1% and 1.7% slopes.

Sensor	Sensitivity at 1 %	Sensitivity at 1.7 %
Lower	8.6 με/(m^3/h)	13.7 με/(m^3/h)
Middle	21.4 με/(m^3/h)	25.7 με/(m^3/h)
Upper	10.9 με/(m^3/h)	56.4 με/(m^3/h)

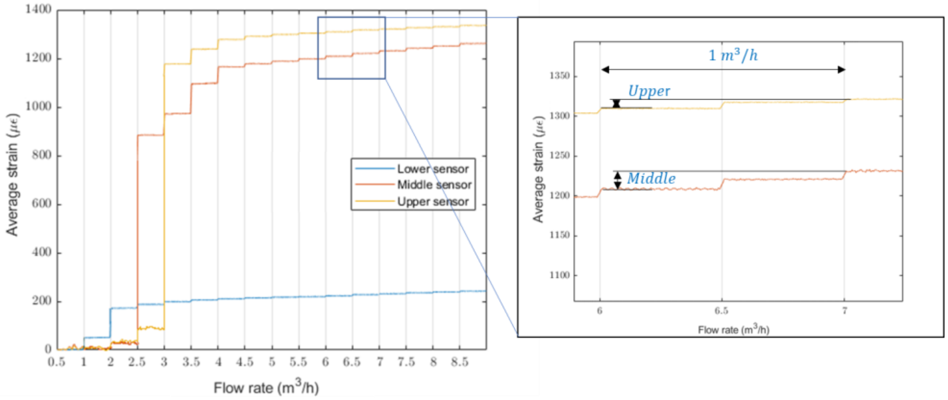


Fig 3. Average sensor response for 1% channel slope.

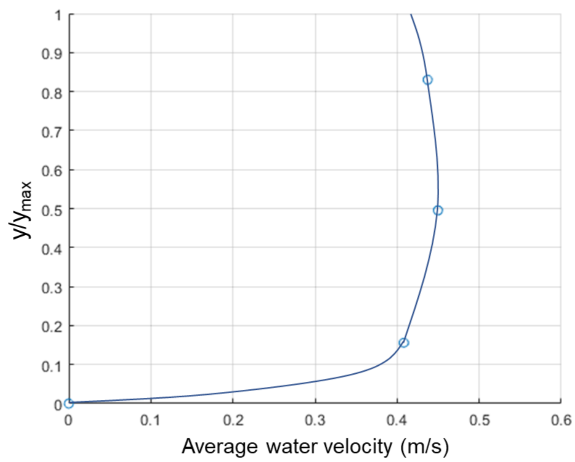


Fig. 4. Velocity distribution depending on the measuring height into the channel, when a 1% channel slope is applied.

5. Conclusions

A fiber optic sensor system has been specifically developed to measure water flow or velocity in real open channels. It can discriminate simultaneously the velocities of water flows at different heights, with high sensitivity and reliability against environmental disturbances. The developed sensing head used specially protected FBGs in a horizontal distribution with independent optical fibers. The protection (a PVC coating) increases the contact surface of the water with the sensor, enhancing the sensitivity. With this arrangement, it is possible to distinguish and measure different areas of interest inside the channel, as needed for the correct calculation of the average speed of water. The measured spatial distribution of velocities fits the theoretical model, with slight variations depending on the inclination of the channel, making the proposed sensor an effective alternative to detect such changes.

6. Acknowledgements

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7. References

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