MORE THAN DEPTH: DEVELOPING PRESSURE SENSING SYSTEMS FOR AQUATIC ENVIRONMENTS

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SUMMARY

Natural flows are a complex amalgamation of velocity, vorticity and pressure. Water rapidly attenuates light and electromagnetic fields but due to its high density provides an excellent medium for the transmission of pressure field fluctuations, both hydrodynamic (mechanical fluid motion) and hydroacoustic (energy transmission). Aquatic vertebrates such as fish use a variety of pressure sensitive systems including their inner ear, lateral line and in some species their swim bladder to localize, communicate and create hydrodynamic images of the aquatic environment. Inspired by the ubiquitous use of pressure-based systems of fishes, we have developed two pressure sensing systems which can aid in studies of the aquatic environment. First, we show how a differential hydrodynamic pitot system can provide estimates of spatially distributed turbulence in conjunction with ADCP measurements in front of a hydropower intake. Second, we provide preliminary results from a prototype barotrauma detection system for downstream passage through hydropower turbines can be created with neutrally-buoyant pressure sensors. Our objective is to show that pressure sensors can offer much more information than just the water depth, and are an excellent source of new data by collecting hydrodynamic metrics in aquatic environments. Future applications in pressure sensing devices for aquatic ecosystems can benefit from the new information won using the high-frequency measurements in the 100-500 Hz range, which corresponds to the hydrodynamic bandwidth sensed by most aquatic vertebrates. Thus pressure-based measurements will allow researchers to investigate ecologically-relevant flows from a physical point of view closer to that of the indicator organism.

Keywords: pressure, aquatic ecosystem, turbulence, ADCP, barotrauma

1. INTRODUCTION

Downstream migration (migration descending in a river towards lower reaches or the sea) became an important research topic in European surface waters, as hydraulic structures can effect downstream migration. Technologies and structures to study and promote down-stream migration are less advanced than those employed in upstream migration due to the fact that the topic of downstream migration came in the focus just recently. Downstream migration is species and life stage dependent, and occurs over a wide range of spatial and temporal scales, making its study and remediation particularly challenging. For example, cyprinids move both up and downstream during their life cycle on annual, seasonal or daily cycles for spawning, dispersion, feeding, shelter and colonization (Larinier and Travade 2002).

It is common practice to install physical barriers, mostly metal mechanical screens (trash racks), directly upstream of the hydropower intake in order to prevent debris as well as fish from entering the turbine during operation or to guide the fish into a downstream bypass. Most commonly, trash rack barriers are arranged as a series of vertical metal elements, with an angle to the flow of 20˚ to 45˚. Thus it is important to understand the flow conditions upstream of physical barriers in order to improve the knowledge on fish behavior in front of a physical barrier, in order to reveal options for downstream passage (i.e. positioning of a bypass channel).

The FIDET project (Schmidt and Schletterer 2017) was initiated in order to provide an innatura investigation regarding the presence of fish as well as of local hydrodynamic conditions upstream of hydropower intakes, making an important step in developing repeatable, scientifically-based measurement methods to study down-stream migration. Such data is needed in order to understand the underlying mechanisms which control fish migration in terms of the timing, direction and distances associated with underwater stimuli (Smith 2012, Langford et al. 2011, Böttcher et al. 2015). Specifically, FIDET developed a new field probe for flow turbulence measurement, which when combined time-averaged velocity fields obtained with state-of-the-art acoustic Doppler current profiler (ADCP) can provide new insight into the types of hydrodynamic stimuli fish experience near trash racks.

Although the presence and intensity of flow turbulence is well-established to affect fish swimming and hydraulic preference, there is currently not any suitable measuring methodology capable of providing turbulence metrics for innatura studies (Strokina et al. 2016). Within the FIDET project a novel, bioinspired flow sensing device based on the pressure sensitive fish lateral line (Figure 1 + Figure 2), i.e. on differential pressure which could deliver estimates of flow turbulence in the field, was developed. The “Druck Box” (Dbox) was tested at two different sites in Austria on the river Inn at Kirchbichl and Runserau and compared with state-of-the-art ADCP measurements. The combination of spatially explicit, time-averaged flow velocities recovered from ADCP and DBox pressure turbulence measurements form the first dynamic picture of the complex flow field experienced by fish in front of hydropower intakes. Furthermore, pressure sensors with dataloggers were fitted into a compact waterproof body and sent through a turbine at the HPP Kirchbichl (Figure 6) to gather information on the rapid pressure changes during downstream passage.

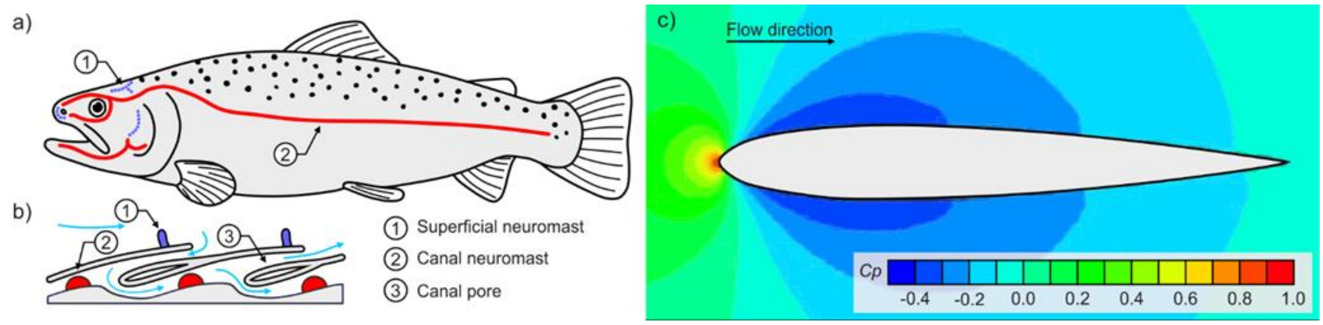

Figure 1: (a) Illustration of the distribution of superficial and canal neuromasts on a rainbow trout (*Oncorhynchus mykiss*) (distribution based on (Montgomery et al. 2003)). (b) Cross-section of lateral line system on and beneath the scales, showing positions and flow-wise orientation of superficial and canal neuromasts (diagram not to scale, after (McHenry and Liao 2013)). (c) Contour plots of the coefficient of pressure ($Cp = P/0.5\rho V^2$) over NACA 0013 aerofoil in open water (Windsor et al. 2010). Pressure distribution about the body is the highest at the nose, rapidly decreases and reverses along the body. The DBox probe developed in this work is based on a simplified lateral line design.

2. THE "DBox" HYDRODYNAMIC PITOT

Estimation of the flow velocity can be achieved easily using a careful arrangement of the pressure sensors, making use of a symmetrical pressure transducer configuration on a circular cylinder. The relationship (Eq. 1) between the pressure difference for both sides of the prototype (ΔDP1 and ΔDP2) and the time-averaged flow velocity (V) is the Pitot equation for 0º of angle of attack, where ΔDP1 = ΔDP2. Note that with two transducers the equation can be applied including angular deviations of up to 45º:

$$V = \sqrt[4]{a(\Delta \mathrm{DP}_1^2 1 \ + \Delta \mathrm{DP}_2^2)} \qquad [1]$$

where a is an empirical coefficient to be fitted according to the prototype geometry and chosen sensors. The calculation of the flow-induced turbulence was performed using the pressure-velocity uniformity coefficient, K_{pv} which describes the ratio between the fluctuating pressure field and the time-averaged velocity magnitude at each measurement point.

In a recent study on the 3D hydrodynamics of a trash rack, with different bar element angles to assess the turbulence in the local flow (Zhang et al. 2014). The relationship between the fluctuations of the pressure and the mean velocity K_{pv} is:

$$K_{pv} = \frac{\sqrt{\sum[\Delta P(t) - \overline{\Delta P}]^2}}{\frac{1}{2}\rho\bar{v}^2} \qquad [2]$$

where $\Delta P(t)$ is the data recorded at each time, t of the differential pressure sensor, $\overline{\Delta P}$ is the time-averaged differential pressure calculated over a single point measurement, ρ is the density of water (here taken as a constant value of 1000 kg/m³) and $\bar{v}$ is the time-averaged bulk flow velocity at the measurement location.

The DBox is a compact field-ready turbulent flow measurement device, which was designed within the FIDET project in order to record the difference between the dynamic and static pressure. The maximum dimensions are 15 x 9 x 7 cm (length x width x height). First, detailed hydrodynamic studies were performed using computational fluid dynamics (CFD) with OpenFOAM and subsequently the prototype was physically tested in the turbulent flow tunnel at the Centre for Biorobotics. The result was a multimodal sensor platform with two differential (DP1 and DP2) and one total pressure (TP) transducers capable of high frequency (200 Hz) flow measurement.

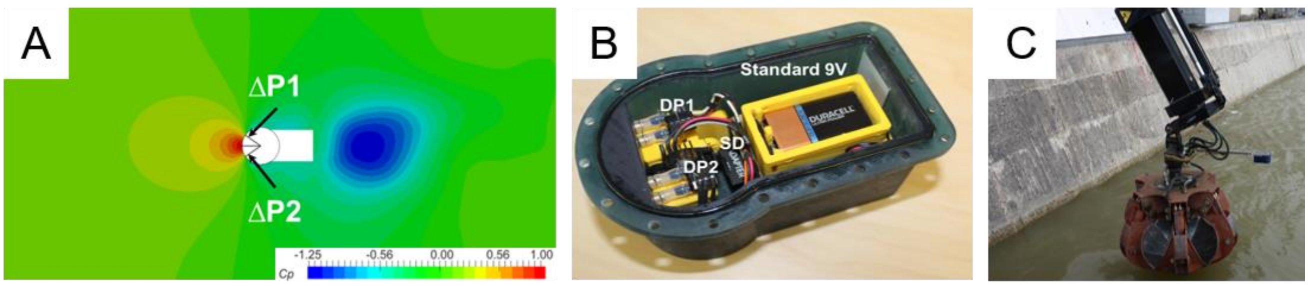

Figure 2. (A) CFD results showing the locations of the differential ports and distribution of the pressure coefficient, C_p for a freestream velocity of 10 cm/s. (B) Photograph of the device including the two differential pressure sensors, DP1 and DP2 as well as the power supply and data storage card. (C) Image of the prototype in the field at the HPP Kirchbichl, mounted on the large debris removal arm.

The data from the DP sensors are used to assess the turbulent fluctuations in the flow field, and the TP sensor outputs the local water depth with 1 cm resolution. The device logs the pressure data as a standard ASCII text file to a SD card, and is capable of continuous recording for 2.5 hours using a single standard 9V battery. The device is activated once the lid has been sealed, by use of an external magnetic key. Once the key has been attached to the back of the device, the DBox records until the user removes the key. Turning the device "on" and "off" using the magnetic key simply results in the DBox saving a series of sequentially named log files (e.g. "Da-ta001.txt, Data002.txt etc.").

The CFD simulations were performed using the open source software OpenFOAM. The resolution of transient flow of incompressible fluid can be achieved with the prebuilt solver pimpleFoam using the PIMPLE algorithm for the pressure-velocity coupling. The model was simplified to 2D domain and a laminar flow approximation was used. Due to the complex geometry an unstructured mesh was used. First, blockMesh utility was used to create a simple fully structured hexahedral square mesh of the environment, defining cubic element of size Δx. Afterwards using as a base the structured mesh, the snappyHexMesh utility was used to create a high quality hex-dominant mesh based on the prototype shape. The time discretization was dynamically controlled using the Courant number (Cr) as threshold. In this sense, OpenFOAM uses a semi-implicit variant of the Multidimensional Limiter for Explicit Solution (MULES) with al-lows the convergence with larger Cr than usual (usually Cr ≤ 1) (Mooney et al. 2014). Thus, a Cr threshold of 3 was used to control the time steps.

Table 1. Technical specifications of the DBox hydrostatic pitot.

DEVICE	PART ID	MANUFACTURER	SPECIFICATION
Microcontroller	ATmega328P	Atmel	20 MHz @ 4,5 – 5,5 V
Differential pressure transducer	MPXV7002DP	Honeywell	-2 bis 2 kPa pressure range, 0.4 mm H20 sensitivity
Total pressure transducer	MPX5100GP	Freescale semiconductor	0 bis 10.2 m H2O, 10 mm H2O sensitivity

Based on the velocity field measurements from the ADCP and pressure fluctuations from the hydrostatic pitot, a regression relation was derived at each site. Using the ADCP data as input, spatial maps of the turbulence parameter were generated based on the regression model. Within the FIDET project, Didson sonar arrays are used to investigate fish behavior (Schmidt & Schletterer 2017) and as a next step observed fish locations will be compared with the ADCP and K_{pv} maps in order to determine if hydrodynamic relations exist between the local flow metrics and fish behavior in front of a hydropower intake.

A site-specific linear relation between the time-averaged velocity and measured turbulence parameter (Figure 3) was observed and used to generate spatial maps based on the ADCP data. The figures below show that the regions with the highest expected usage are not necessarily those with the lowest turbulence parameter values, but rather slower flowing areas where the presence of large, coherent eddies could attract larger fish. Based on the hypothesis set out in the previous sections, it could be the case that adult fish are observed on the leftmost 10 m of the hydropower intake and are less likely to be present in high-velocity regions with overall lower turbulence parameter. Future observations using Didson sonar or echolots which partition fish observations in 10 m intervals can be carried out in order to determine the suitability of the proposed turbulence parameter for predicting fish behavior in front of hydropower intakes.

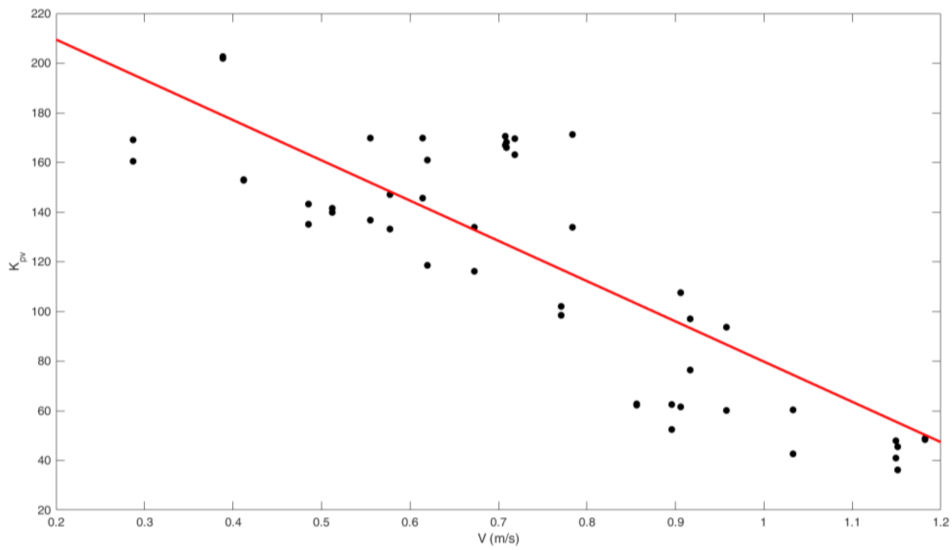

Figure 3. Correlation plot between the time-averaged velocity as measured by the ADCP and the corresponding K_{pv}, based on the measurements from HPP Kirchbichl (18.04.2016). The fit was made using linear least-squares regression (K_{pv} = -162,1 * V + 241,9 (n = 48, R^2 = 0,73).

Generating a turbulent map from the ADCP data requires a calibrated linear relationship between the pressure fluctuations and the time-averaged velocity. Here we showed in the previous section that it can be accomplished by a series of DBox point measurements in the same planar field as an ADCP measurement transect. Afterwards, it is necessary to derive the empirical calibration function for each site as the background turbulence level is not only a function of the time-averaged velocity, but also of the particular flow geometry and upstream turbulence levels. For instance, it was observed that a linear relation exists between K_{pv} and V for both sites, however due to the large differences in background turbulence, the calibration relation is one order of magnitude higher between the two test sites at Kirchbichl and Runserau. As the total number of measurements in this study was limited to 48 for Kirchbichl (Figure 3), future field work will concentrate on increasing the total number of DBox measurements to establish a statistically significant calibration relation.

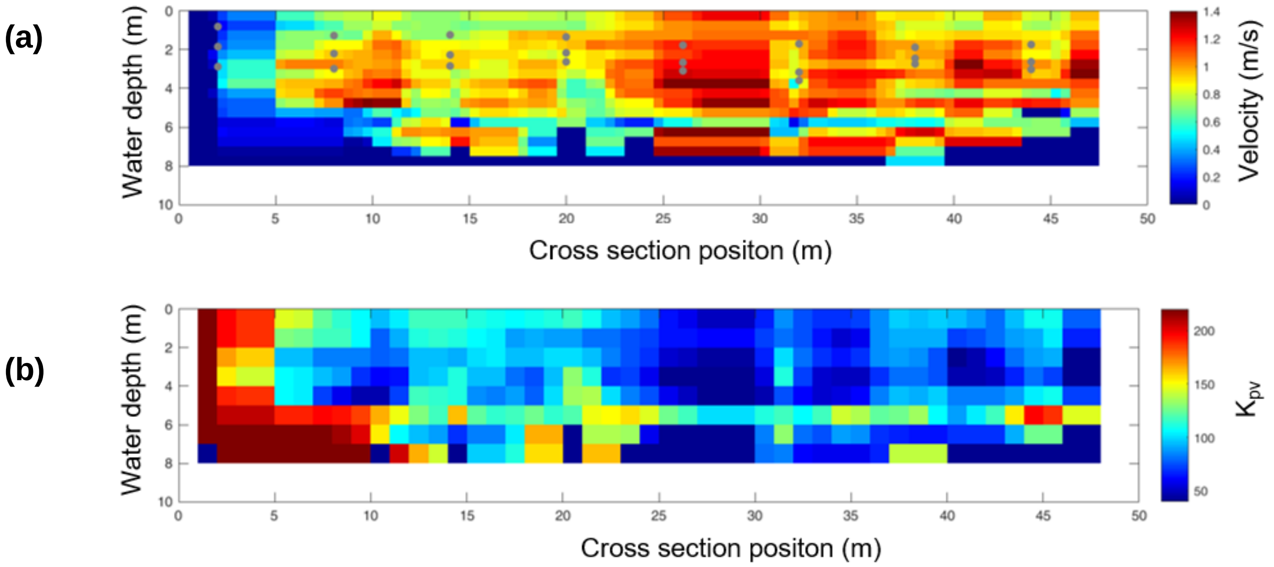

Figure 4. (a) ADCP 50 cm raster of the flow velocity in front of the Kirchbichl hydropower intake at 250 m³/s, positions of the pitot measurements are shown in grey. (b) Map of the turbulence parameter K_{pv} based on the regression model fit from the measured locations.

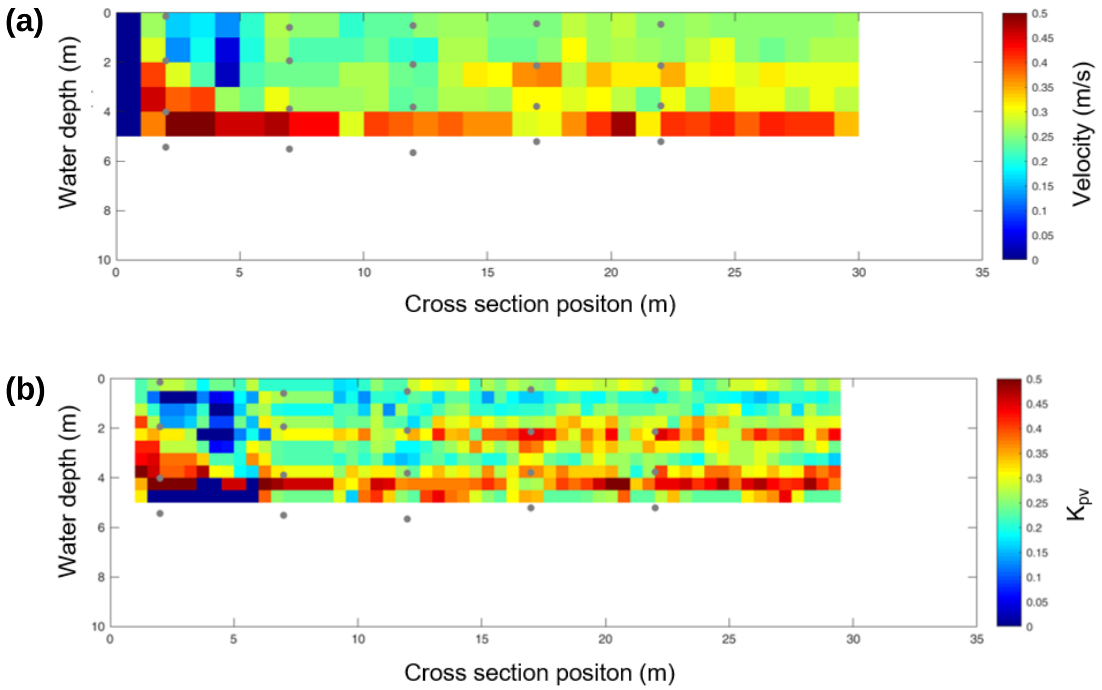

Figure 5. (a) ADCP 50 cm raster of the flow velocity in front of the Runserau intake at 30 m³/s, positions of the pitot measurements are shown in grey. (b) Map of the turbulence parameter K_{pv} based on the regression model fit from the measured locations.

We have shown that the use of a new field turbulence measurement device, the DBox can be correlated to ADCP measurements of the time-averaged flow field (Figure 3) to deliver spatial mappings of the pressure-velocity uniformity coefficient, $\boldsymbol{K_{pv}}$ (Figure 4 + Figure 5). This measure was chosen based on literature studies of fish sensory capabilities, where it was experimentally determined that fish respond to local fluctuations in the pressure field. In a turbulent flow field, the fish experience these fluctuations at a rate directly proportional to the local flow speed, and thus the ratio of the fluctuations to the local flow speed may provide to be a useful indictor of fish behavior in an open flow environment. Future studies should compare $\boldsymbol{K_{pv}}$ maps using the proposed methodology with in-natura observations.

3. BAROTRAUMA DETECTION SYSTEM (BDS)

Downstream migrating fish may experience adverse impacts due to the abrupt physical changes in the flow as they pass through the turbine. In order to quantify the hydraulic conditions which can lead to barotrauma mortality, waterproof sensing arrays can be inserted into the hydropower plant to collect information on the pressure and inertial changes that fish experience (Deng et al. 2014). Using repeated measurements with identical arrays provides the "average experience" (AE) which can then be fed into a barochamber and recreated to test damage and mortality on live specimens.

Thus the key to improve our understanding of downstream migration and fish passage through turbines lies in the development and implementation of accurate measurement systems capable of recording insitu conditions. Single pressure sensors (BDS) recording at 50 Hz were outfitted in a waterproof housing and sent – via an injection tube in the stop log slot (after the trash rack) – through the turbine at the full capacity conditions of 130 m³/s at the Kirchbichl hydropower plant in order to obtain the changes in the pressure experienced by aquatic organisms during downstream passage. Balloon tags (Carlson & Duncan 2003) were used to recover the BDS downstream the HPP.

Data from our pilot study at the HPP Kirchbichl revealed that the BDS sensors successfully passed through the turbine and recorded the total pressure (static + dynamic) including the large pressure differential experienced during passage. Future sensors will also be outfitted with additional inertial measurement units, as well as pressure transducers with both higher temporal resolution. Although the test measurements were shown to have similar results, it is necessary to increase the number of measurements significantly (20-50 are likely required) in order to provide a sufficient picture of the complex dynamics that fish encounter as they pass through a hydropower turbine.

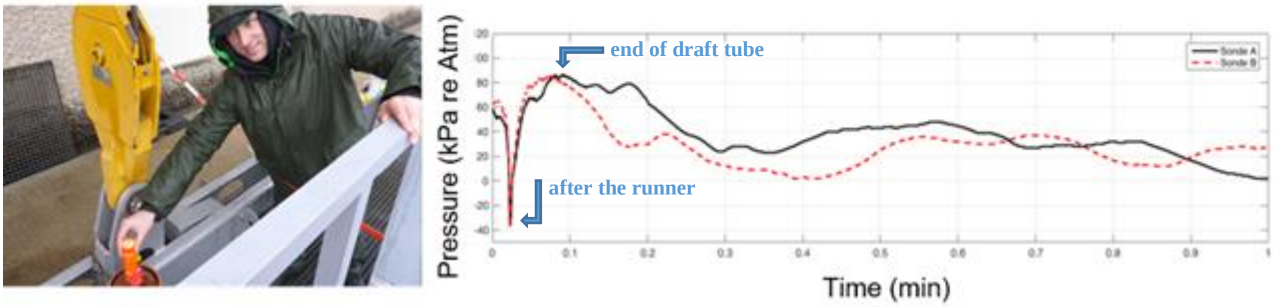

Figure 6. Left: Prototype BDS sensor being inserted into the hydropower intake. Right: Pressure time series recorded with two sensors (Sonde A and B), the sharp jump in the pressure readings for both sensors correspond to the passage through the turbine.

4. CONCLUSIONS AND RECOMMENDATIONS

We provide two different examples of how pressure sensitive measurements can aid in the study of the complex hydrodynamic conditions experienced by aquatic vertebrates in the field. First, it was shown that a prototype hydrodynamic pitot can help in adding information about local flow turbulence using a regression model based on ADCP data and a series of point measurements. Next, we show that a waterproof transducer in a small enclosure with data logger can be sent through a hydropower turbine in order to recover the rapid pressure change which can cause barotrauma.

Future work with both systems will enable the combination of biological field observations with physical measurements of the pressure field. The understanding of fully turbulent flow fields and fish behavior in the field can support the development of measures (e.g. positioning of bypass channels), as fish can be guided by those flow fields. Low mortality rates are reported for Kaplan turbines (ACOE 2013), i.e. this turbine type supports – depending on size, number of blades and speed – a safe passage for downstream migrating fish. However to assess this site specifically the application of blade-strike models and assessments of pressure conditions using BDS – as suggested herein – are a promising tool.

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