ECOHYDRAULIC FLOW SENSING AND CLASSIFICATION USING A LATERAL LINE PROBE

JEFFREY A. TUHTAN[ǂ]
SJE Ecohydraulic Engineering, GmbH, Viereichenweg 12
Stuttgart, BW 70569, Germany

JUAN FRANCISCO FUENTES-PEREZ, GERT TOMING, MAARJA KRUUSMAA, NAVEED MUHAMMAD
[ǂ]*Centre for Biorobotics, Tallinn University of Technology*
Tallinn, Akadeemia tee 15A-111, 12618, Estonia

NATALIYA STROKINA, JONI-KRISTIAN KÄMÄRÄINEN
Department of Signal Processing, Tampere University of Technology
Tampere, P.O.Box 533, FI-33101, Finland

MARK MUSALL, RUTH CARBONELL-BAEZA
Institute of Water and River Basin Management, Karlsruhe Institute of Technology
Karlsruhe, Kaiserstraße 12, 76131, Germany

MARKUS NOACK
Institute of Modelling Hydraulic and Environmental Systems, University of Stuttgart
Stuttgart, Pfaffenwaldring 61, 70569, Germany

MARTIN SCHLETTERER
TIWAG-Tiroler Wasserkraft AG
Innsbruck, Weißgatterstraße 27, 6020, Austria

Natural flows are a complex amalgam of velocity, pressure, and vorticity, which often cannot be directly measured or simulated due to their physical interdependence and scaling. Ecohydraulic investigations require not only an accurate description of the natural flow, but must also consider the fluid-body interactions between the indicator organism and the surrounding flow field. In this work, we show how a fish-shaped lateral line probe (LLP) can be used for *in situ* flow sensing, including fluid-body interactions in a laboratory scale vertical slot fish pass. The LLP consists of a synchronous collocated sensor array with 16 pressure sensors measuring at 2.5 kHz with an acquisition frequency of 250 Hz. Using a signal processing workflow with time-domain features based on the Bernoulli equation, the multi-sensor fusion capabilities of the device can be leveraged to provide current velocity estimates similar to conventional measuring devices such as acoustic Doppler velocimeters (ADVs). Finally, it is shown that the LLP can be used for spatial flow signature clustering and classification using semantic inputs in conjunction with supervised learning algorithms. Our objective is to introduce the LLP as a new type of ecohydraulic flow measurement and classification device to simplify the evaluation of natural flows and expanding the analytical capabilities of ecohydraulic investigations.

1 LATERAL LINE SENSING USING A FISH-SHAPED PROBE

Fish experience the surrounding flow field with the octavolateralis system [1]. Biophysical studies have largely investigated species-specific properties of neuromast geometry, neurophysiological activity and stimulus-response sensitivity [2]. In general, the octavolateralis system can be viewed as a multimodal mechanosensory apparatus with stimuli from the inner ear, swim bladder, and lateral line [3]. Considering near field hydrodynamics (neglecting hydroacoustic stimuli) we are interested specifically in the estimation of a fish's lateral line stimulus response as its spatial network of innervated neuromasts result in a unique distributed sensory apparatus for the detection of local (near-body) fluid acceleration, velocity, pressure, pressure gradients and shear stresses [4].

The LLP used in this work (Figure 1) consists of 16 piezoresistive pressure sensors (SM5420C-030-A-P-S, Silicon Microstructures) mounted within an ABS plastic fish-shaped body. In contrast to our plastic body, the biological lateral line also includes mechanical filtering due to viscous dampening of the neuromasts in the boundary layer (especially the superficial) [5, 6] . However, the extent of any effect of difference in roughness has not yet been investigated. LLP geometry is taken from a 3D scan of an adult rainbow trout (*Oncorhynchus mykiss*) having a body length of 45 cm (Figure 1). The pressure transducers have a sensitivity of 8 Pa/LSB over a 0-207 kPa span. The signals undergo first and second stage amplification (AD8656ARMZ, Analog Devices) digitized using a 16-bit analog to digital converter (AD768BSPZ, Analog Devices). Temperature is estimated via current consumption with a shunt resistor. The output signals are 10x oversampled and transmitted with a serial connection at 250 Hz. The five bottom sensors (sensors 2, 5, 8, 11 and 14) are nonparallel to the primary lateral line. In this work, we used only the 11 side sensors (nose, 5 on each side: 0, 1, 3, 4, 6, 7, 9, 10, 12, 13 and 15).

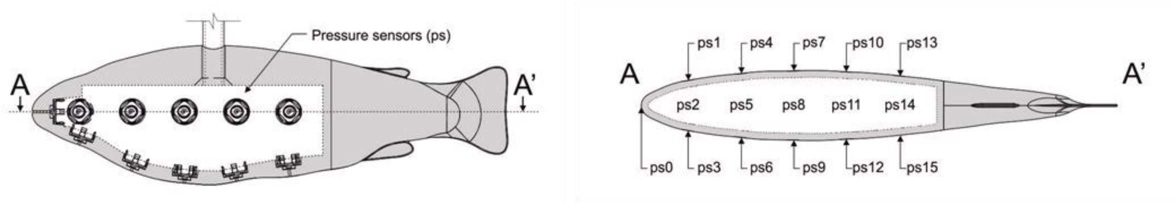

Figure 1. Locations of collocated pressure transducers, all of which are mounted normal to the body surface.

2 CURRENT VELOCITY ESTIMATION

The current velocity (*U*) is the most commonly used hydraulic parameter in studies of fish swimming [7] and behavior [8], and is defined as the magnitude of the three Cartesian velocity components (u_x, u_y and u_z):

Estimation of the current velocity is performed using the Bernoulli approach invoking conservation of energy to relate the pressure difference between a stagnation point (here taken as the nose sensor *ps0*) and the free stream static pressure, taken using one of the 10 lateral sensors with index *l*, *psl* ($\Delta P_{0,l} = ps0 - psl$). The lateral sensors are not ideal as they experience static and dynamic pressure, making it necessary to apply a correction factor, β. Theoretically, β approaches zero with decreasing distance between the sensors using the nose (stagnation pressure) as the reference, and reaches a maximum of 1 when the reference is taken such the static pressure is dominant (e.g. Figure 1, sensor pairs 7 and 9)[9]. Bernoulli's law then allows for the approximation of the current velocity as:

$$U = \sqrt{\frac{2 \cdot \beta \cdot \Delta P_{0,l}}{\rho}} \quad (1)$$

where ρ is the density of water. In total, three sets of velocity experiments were carried out using the LLP. The first two sets of laboratory experiments were carried out over a range of 0-50 cm/s in both the closed flow tunnel at the Centre for Biorobotics, Tallin, Estonia and in an open channel flume at the Institute for Modelling Hydraulic and Environmental Systems, Stuttgart, Germany. This was done in order to test the signal processing workflow for velocity estimation under two different settings. Ten replicates were taken for each measurement at 25%, 40% and 60% of the flow depth, which was fixed at 35 cm Each LLP measurement was taken at 250 Hz with a duration of 60 s, and the velocity was simultaneously recorded using an ADV (Flowtracker, Sontek) directly upstream of the LLP. The location of the ADV was adjusted until it did not impact the LLP flow measurements (the signals with and without the ADV were statistically indistinguishable). The slope of the flume and discharge were varied in order to obtain a range of current velocities taken as the time-averaged velocity at 40% of depth ranging from 0.1 to 0.5 m/s in 0.1 m/s increments. Due to the relaxation of the channel geometry, both upstream of the measuring device and at the free surface, the open channel flows are subject to non-uniform turbulence as well as large temporal and spatial fluctuations of the water surface. The open channel conditions are therefore more representative of natural hydrodynamic flows, and a comparison of both laboratory settings for the same time-averaged velocities is thus of interest when considering field applications. After establishing the velocity estimation workflow, the LLP was tested at the Institute of Water and River Basin

Management (KIT, Karlsruhe, Germany) in a scale fish pass model and the results were used to produce LLP-flow maps for direct comparison to flow maps generated by ADV measurements under a range of flow conditions [10].

Results comparing the LLP current velocity estimates to the ADV show that the device is capable of reproducing flow maps similar to that of conventional measurement techniques (Figure 2). The error range for the LLP from 0-50 cm/s was also compared between the CfB and KIT datasets, revealing similar trends (mean average error of both is 4 cm/s). A major challenge in using a large bluff body for flow estimation is the change in hydrodynamic response as a function of background turbulence. Using the current probe, boundary layer separation accompanied by a transition of the fluid-body interactions occur at velocities in the range of 70-80 cm/s. As it is our goal to measure from 0-1.5 m/s in the field, new signal processing methods for the LLP need to be developed and tested both in the lab and innatura in order to ensure that the LLP is robust enough for ecohydraulics studies.

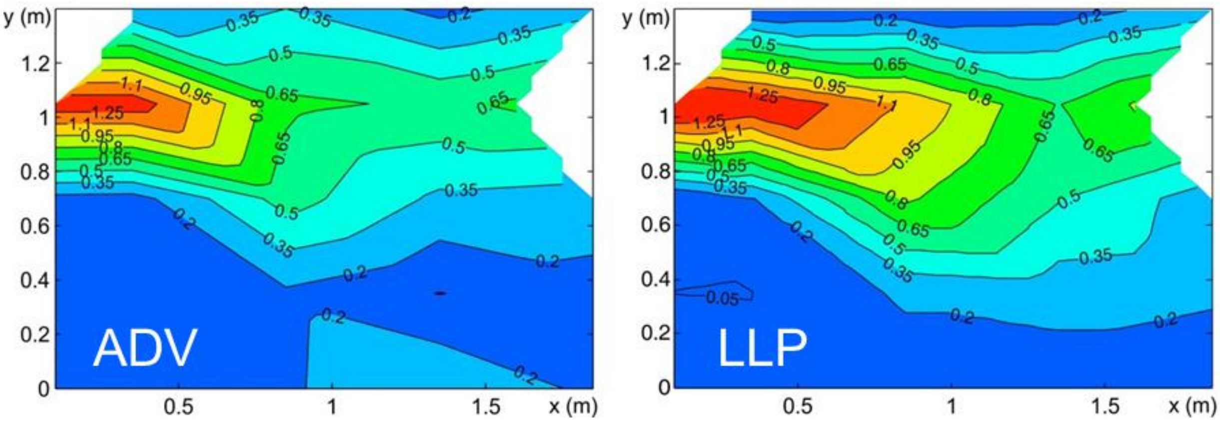

Figure 2. Velocity contours from ADV and LLP measurements at KIT in a scale vertical slot fish pass.

3 NATURAL FLOW CLASSIFICATION

The natural flow experiments were conducted in the Keila River, Estonia in February 2014 (Figure 3) using a similar prototype to that shown in Figure 1, but with a soft body and lower data acquisition frequency. The LLP was mounted on a metal rod at a fixed height of 20 cm above the bed. A total of four sampling locations were chosen based on a visual (semantic) classification of four distinct flow regions, measured in succession (A-B-C-D) four times. Each repetition sampling location was similar, but not identical within individual regions [11].

Parameter selection and tuning was performed by choosing the time step *dt* and histogram bins *df* and then performing cross-validation. One experimental set for each of the four regions was randomly selected for training, and the remaining data sets were used for validation. The validation was performed four times, and the average performance was then considered for parameter tuning. The classification results were computed per time step *dt* and per measurement. The decision about the flow class is made based on voting in each time step over the total measurement time (in this case taken to be 50 s). The acceptable interval for the time step was found to range from 0.3 to 1 s. As shown in Figure 3, the best performing time step size was found to be *dt* = 0.5 s. The choice of histogram bin sizes was not found to have a significant impact on the mean results. As the flow conditions investigated were turbulent, focus was put on the higher frequencies, choosing *df*=[1Hz,2Hz,4Hz,8Hz,16Hz,25Hz].

It was determined that the classification accuracy was largely determined by the duration of the sampling time step, *dt* (Figure 3, right panel). Sampling performed while holding the LLS at a fixed location and classifying using 0.5 s intervals provided the maximal mean accuracy of 85%. An interesting find was that counter to velocity measurement under steady flow conditions, where the estimation accuracy generally increases with increasing sampling duration; the LLP classification performed the best at shorter intervals. Thus contrary to velocity estimation, natural flow classification using the LLP performs best when the analysis is limited to short-duration events. The underlying physics of this finding is currently under investigation, one possibility is the non-local nature of the pressure field in conjunction with the wide bandwidth (Hz to kHz) of pressure oscillations. Thus the description of flow signatures using pressure-based devices tend to perform poorly when time-averaging is applied, which smooths out much of the information content.

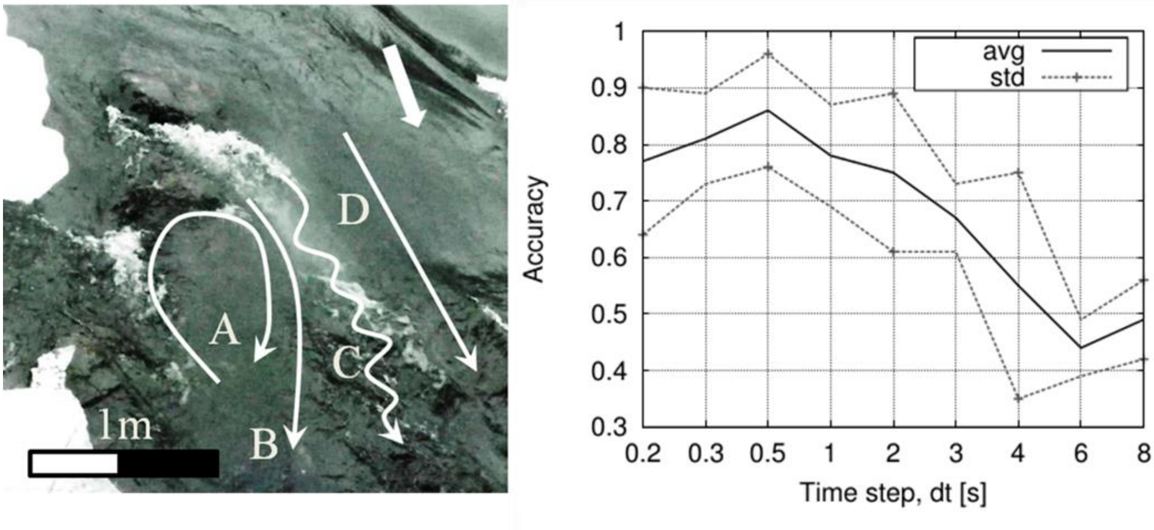

Figure 3. (left panel). Four distinct flow regions around a large boulder classified in the Keila river. The direction of the bulk flow is shown by the arrow in the upper left corner. (A) Recirculation zone, (B) shear region, (C) turbulent wake and (D) critical flow in main river channel. (Right) Classification accuracy as a function of the sampling interval *dt*.

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