Ecological Engineering 85 (2015) 296–300

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Short communication

Current velocity estimation using a lateral line probe

Juan Francisco Fuentes-Pérez[a,*], Jeffrey A. Tuhtan[a,b], Ruth Carbonell-Baeza[c], Mark Musall[c], Gert Toming[a], Naveed Muhammad[a], Maarja Kruusmaa[a]

[a] Centre for Biorobotics, Tallinn University of Technology, Tallinn, Estonia
[b] SJE Ecohydraulics Engineering, GmbH, Stuttgart, Germany
[c] Institute of Water and River Basin Management, Karlsruhe Institute of Technology, Karlsruhe, Germany

ARTICLE INFO

Article history:
Received 31 March 2015
Received in revised form
27 September 2015
Accepted 7 October 2015

Keywords:
Lateral line probe
Current velocity
Field measurements
Pressure sensor

ABSTRACT

Freshwater ecosystems are inhabited by a vast spectrum of organisms, each with their own complex biotic–abiotic relations. Considering the management and conservation of these environments, it is necessary to understand the underlying hydrodynamic interactions to which aquatic organisms are subject. Outside of bulk flow properties such as the time-averaged velocity, it is currently difficult or impossible to obtain detailed observations of the fluid–body interaction using current measurement technology. It is in this context that the lateral line probe (LLP) has been developed. The LLP mimics the performance of flow sensing modalities present in many aquatic vertebrates. Research in the last decade has demonstrated that such devices are able to reproduce signals relevant to fish behavior and estimate the hydrodynamic stimulus response of the lateral line. However in most cases, the application of LLPs have been limited to idealized conditions, subject to rigorous calibration. In this paper we present an algorithm that allows the use of LLPs for current velocity estimation without sensor calibration. The method makes use of the fluctuations in the near-body pressure field induced by fluid–body interactions and introduces a semi-empirical resampling process based on the conservation of energy. The algorithm is calibrated using a closed flume and measurements taken using a laser Doppler anemometer. Validation of the approach is carried out by comparing results obtained with an acoustic Doppler velocimeter (ADV) in a vertical slot fishway. The mean error as compared to direct measurements with the ADV was found to be 0.11 m/s with a correlation of 0.92.

1. Introduction

Freshwater ecosystems are among the most threatened habitats worldwide and their management requires a comprehensive understanding of their complex ecological relations (Mitsch, 2012; Jiang et al., 2015). Due to this complexity, it is not always feasible to use existing measuring devices to accurately record field measurements of biological significance, and thus the influence of many physical variables remains poorly understood (Goettel et al., 2015). In this work, we present a new measuring device, the lateral line probe (LLP) which can be used to measure the flow field and extract hydrodynamic parameters from "the fish's perspective".

There are multiple tools to measure the hydrodynamic parameters in field conditions (e.g. Doppler velocimeters, propellers, rotors, electromagnetic current meters, etc.). However, none of them can be considered as the ideal tool due to the influence of obstacles, suspended particles, or gas bubbles (Dombroski and Crimaldi, 2007; Mori et al., 2007). Additional considerations may be complex calibration processes (MacVicar et al., 2007) and the inefficiency of measuring in low flows (Hammond et al., 1986). Despite these challenges, useful algorithms have been developed to cope with them (Finelli et al., 1999; Mori et al., 2007).

In order to measure biologically relevant parameters, it is necessary to use sampling rates in the range of natural hydrodynamic receptors from 1 to 150 Hz (Venturelli et al., 2012), which lie outside the majority of available field measuring devices. Furthermore, to establish the fluctuating components of flow signatures and turbulence metrics which may be related to fish preferences, higher frequency acquisition is required (Silva et al., 2012; Alexandre et al., 2013; Bleckmann et al., 2014).

It is within this context that our research in the application of LLPs arises, with the goal of creating devices capable of mimicking the stimulus response of lateral lines, the flow sensing organs present in aquatic vertebrates. As its organic analog, the LLP consists of a discrete set of sensing units distributed over the body which are able to sense local mechanical changes in water particle

---

* Corresponding author.
E-mail address: Juan.Fuentes@ttu.ee (J.F. Fuentes-Pérez).

http://dx.doi.org/10.1016/j.ecoleng.2015.10.008
0925-8574/

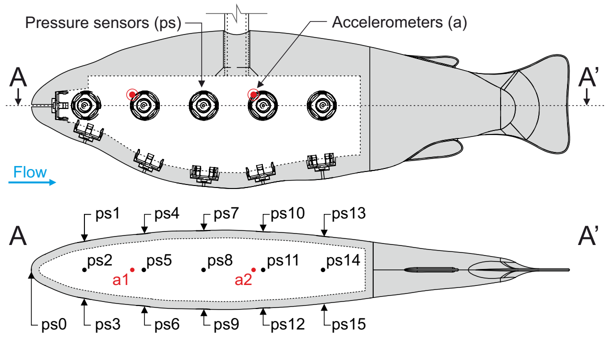

Fig. 1. Location of the 16 pressure sensors and 2 accelerometers in the LLP.

motion (Dijkgraaf, 1963). Recent research in LLPs has demonstrated their capacity to reproduce some of the functions and behaviors of biological lateral lines (e.g. hydrodynamic mapping, object and prey detection, flow classification, rheotaxis, etc.) (Chen et al., 2006; Yang et al., 2007; Klein and Bleckmann, 2011; Salumäe et al., 2012; Muhammad et al., 2015).

These capacities suggest the interesting potential of this technology for ecological studies of aquatic vertebrates. Furthermore, due to their high sampling frequency (250 Hz for the LLP used in this work), LLPs provide the opportunity to record interactions between the sensor body and the surrounding flow field, making it possible to study the flow field from the point of view of the aquatic organism (Tuhtan et al., 2015).

One of the main disadvantages of LLP systems is that the sensors require calibration before and after each use due to small changes in the transducer signals caused by the drift between sensors. Drift is primarily caused by sensitivity due to temperature changes (Venturelli et al., 2012). Although the observed pressure changes will usually be small, they do have the potential to bias estimates of the measurements.

In this work, we propose a new two-stage signal processing pipeline which can be applied to estimate the time-averaged current velocity without the need for sensor calibration. The first step of the algorithm applies frequency domain analysis of pressure fluctuations over a sampling interval of several seconds. In the second step, the Bernoulli relation is applied to resample estimates at the original acquisition rate.

2. Materials and methods

2.1. Sensing platform

Our LLP consists of an acrylonitrile butadiene styrene (ABS) plastic device in the shape of an adult, farm-raised rainbow trout (*Oncorhynchus mykiss*) with a body length of 0.45 m. The body cavity has 16 pressure sensors (SM5420C-030-A-P-S) and two 3-axis accelerometers (ADXL325BCPZ) (Fig. 1). The pressure sensors have full sensitivity over a 0–207 kPa range.

The signals from the pressure sensors after two-stage amplification (AD8421ARMZ and AD8656ARMZ) reach a resolution of 0.46 Pa/LSB (least significant bit). The signal is then digitized with a 16-bit analog to digital converter (AD7682BSPZ). All signals are acquired at 2.5 kHz and are oversampled 10× times by means of a microcontroller (AT32UC3C1512) and stored at a 250 Hz sample rate.

2.2. Theoretical background

2.2.1. Current velocity estimation

The current velocity (U) is defined as the magnitude of the velocity vector:

$$U = \sqrt{u_x^2 + u_y^2 + u_z^2} \tag{1}$$

where u_x, u_y and u_z are the longitudinal, transverse and vertical components of the velocity vector, respectively.

The main approach used for the estimation of U in LLPs uses the Pitot equation derived from Bernoulli's principle (2) (Dubois et al., 1974). This method considers pressure differences between the stagnation point (P_1, nose sensor) and a second point on the body which registers the free-stream static pressure (P_2, lateral sensors). As the lateral sensors experience the static and dynamic pressure, a semi-empirical correction factor (β_U) is applied to the equation (Salumäe and Kruusmaa, 2013) (2).

$$\frac{\rho \cdot U^2}{2} = (P_1 - P_2) = \Delta P_{1,2} \quad \rightarrow \quad U = \sqrt{\frac{2 \cdot \beta_U \cdot \Delta P_{1,2}}{\rho}} \tag{2}$$

$\beta_{U,1}$ depends on the pressure sensors used to calculate P_2 as well as on the body shape.

Although this method provides a way to directly relate pressure readings to velocity estimates in order to calculate ΔP, the sensors are typically subject to a calibration process before each individual measurement (Venturelli et al., 2012). This severely hampers the range of applications outside of the laboratory, making the use of LLP systems practically impossible for field applications.

In order to avoid sensor calibration, we created a signal processing pipeline which uses the pressure fluctuations to estimate the flow velocity (Fig. 2).

First, the pressure signal is separated in two terms via Reynolds decomposition: a time average component ($\bar{P}$), which captures the atmospheric pressure, hydrostatic pressure, the pressure due to any far-field effects, and the near-field pressure as the fluctuations about the time-averaged mean (p'). Fundamentally, the fluctuations experienced by the LLP are caused by the dynamic superposition of normal (pressure) and shear stresses induced by the flow and fluid–body interactions.

The stimulus response of fluid–body interactions increases with the increase of velocity and turbulence, producing higher pressure signal fluctuations, which in turn are translated into an average increase of the amplitude of the signal. To separate the turbulence and velocity effects, the fast-Fourier transform is applied to the time-domain signal (p'). Afterwards a band-pass filter (BPF) is applied (Venturelli et al., 2012). Finally, linear regression is used to obtain the relationship between the mean amplitudes of the remaining frequency components and the observed mean velocities.

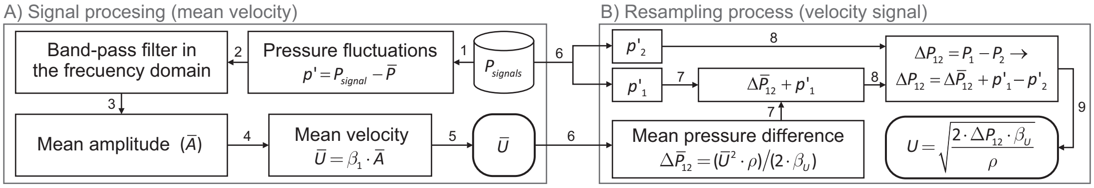

Fig. 2. Signal processing and resampling process flowchart.