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PRESSURE LAPLACIAN MEASUREMENT WITH A BIOINSPIRED FISH-SHAPED LATERAL LINE PROBE

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Abstract

In Nature, turbulence is the rule and laminar flows are the exception. Despite rapid advances in laboratory flow sensing equipment, field-ready technologies are needed to measure, quantify and categorize turbulent flows in-natura. Motivated by fishes' highly-evolved flow sensing system, we have built and tested a bioinspired lateral line probe capable of measuring turbulent flows in the field. Fundamentally, the velocity and pressure fields are related by their gradients via the pressure Laplacian. We show that the lateral line probe as a synchronous collocated pressure sensing array provides the ability to measure these gradients, providing a new source of turbulent flow information from "a fish's perspective".

Keywords: turbulence, vorticity, pressure, Laplacian, lateral line probe

1. INTRODUCTION

Hydrodynamic turbulence is the chaotic motion of fluid, driven by the interaction of tangled vortices. Although turbulent flows are ubiquitous in Nature, it is currently only possible to study turbulence in its entirety considering relatively simple flow geometries such as the flow over a step, by using high-resolution computational fluid dynamics models or particle image velocimetry (PIV). As a result, many practical applications in river engineering rely heavily on simplified metrics describing the bulk turbulence to investigate flows through and around hydraulic structures. These metrics rely on Reynolds averaging, which makes use of the fluctuations from a steady time-averaged flow, and are now commonplace in both scientific and engineering studies of natural flows. Thus turbulence metrics are well-established in both the hydromechanics and aerodynamics communities (Tennekes and Lumley 1972), and have been subject to rigorous physical validation in laboratory experiments, there remains a technology gap allowing for the direct measurement of turbulence for assessment in the field.

The presence of turbulence within a flow manifests itself as chaotic fluid motion, driven by interacting entangled vortices (Davidson 2004). There exist several measurement methods suitable to measure the properties of turbulent flows within laboratory settings, but a large technology gap exists for devices capable of field measurements. Fish have evolved a flow sensing system called the lateral line, capable of detecting body-oriented changes in the flow field over a wide spectrum of flow conditions. Our goal is to design and implement a fish-inspired flow sensing platform, the lateral line probe (LLP), inspired by fishes' 300+ million years of experience in flow sensing (Boord and McCormick 1984). In doing so, we aim to create new sources of hydrodynamic information by designing and implementing the LLP as a robust flow sensing technology to investigate complex turbulent flows both within the lab and out in the field.

Fish sense the surrounding flow using their octavolateralis afferent system which consists of the lateral line and inner-ear sense organs. The lateral line itself contains a series of innervated linear arrays. Each array in turn is made up of sensing organs on the head and along the body, and is principally sensitive to changes in the spatial derivatives of the near-body flow field. Each sensing organ, or neuromast, consists of gelatinous cupulae whose deflections correspond to the local motions of the fluid, relative to the motion of the body. Superficial neuromasts located at the surface serve to detect a fractional derivative of the local velocity, whereas canal neuromasts, embedded within subcutaneous canals connected by pores to the surrounding flow, act primarily as local acceleration detectors (Figure 1). Thus fishes sense the water via the relative motion of their bodies to the surrounding flow. The inner ear, outfitted with sensory maculae as well as semicircular canals, responds to changes in the speed of the fish, acting as linear and angular accelerometers and is sensitive to the average bulk motion of the body within the surrounding flow field (Kalmijn 1988).

The fish-shaped lateral line probe used in this work measures the spatiotemporal distribution of the total pressure (hydrostatic + dynamic) around the fish-shaped body. Thus is should be considered to more closely resemble the pressure-acceleration sensitive canal lateral line submodality of fishes. Close to a source (e.g. a sudden disturbance within the water column) and with no ambient flow, the phase shift between adjacent lateral sensor signals in the time domain becomes the most salient feature in the stimulus experienced along the probe body. Subjected to flow, the lateral line system is most sensitive to changes in near-body spatial gradients which are transmitted and filtered through the boundary layer (Bleckmann 1994).

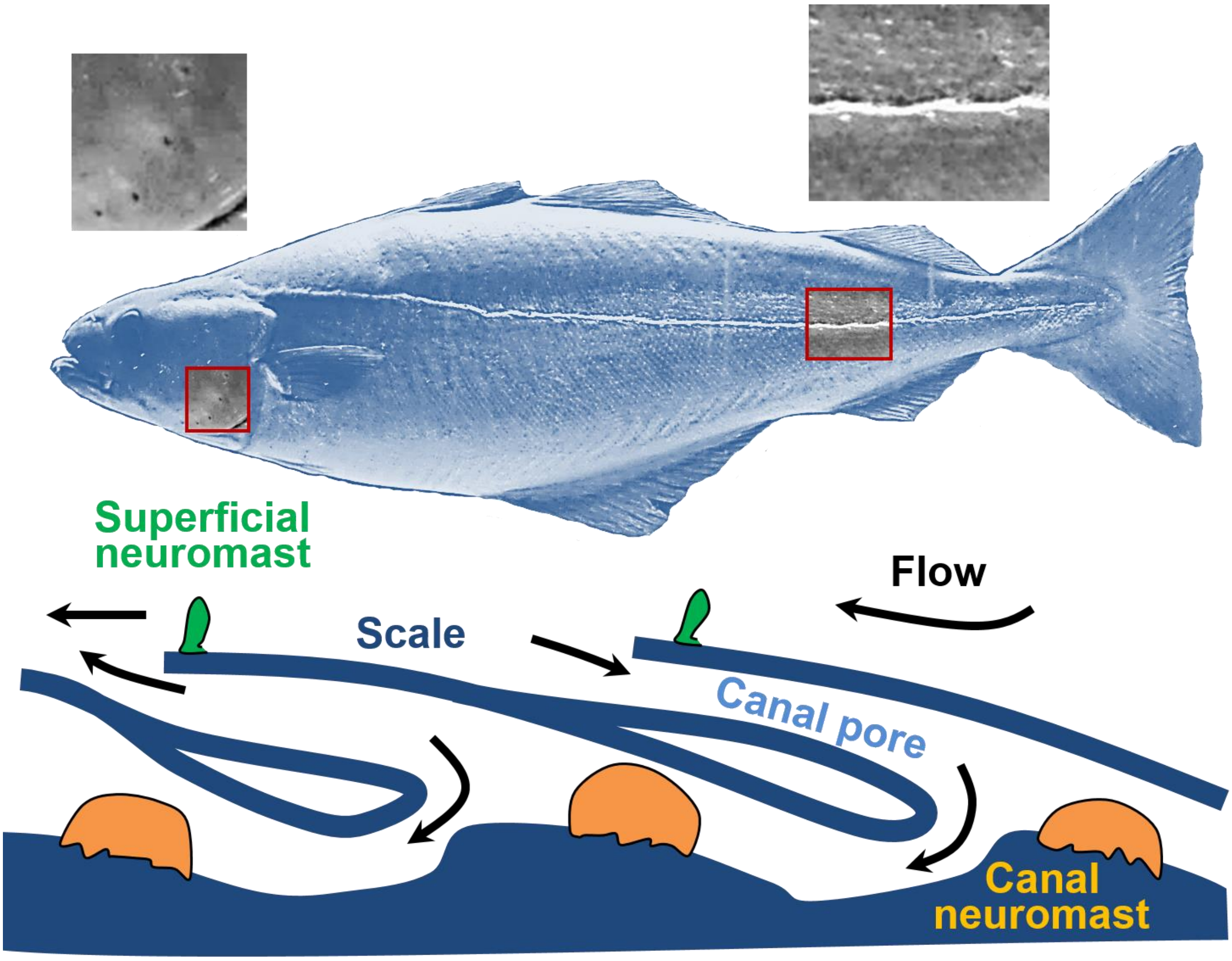

Figure 1.The lateral line sensory apparatus of a fish. Top: neuromasts along head and body are visually apparent (inset images) on an adult Pollack (*Pollachius Virens*). Bottom: the lateral line system of fish consists of superficial neuromasts (green) and subdermal canal neuromasts (orange). Illustration after (McHenry and Liao 2013).

Natural flow fields can be described as a complex amalgamation of velocity, vorticity and pressure terms, acting over a wide range of spatiotemporal scales (Davidson 2004). As such, it is not possible to directly record the complete spatiotemporal evolution of the field with reference to these terms. Inspired by fishes, our objective is instead to extract and study hydraulically-relevant features such as the pressure Laplacian by utilizing the LLP's fluid-body interaction in both natural flow and laboratory investigations. The collected data can then be assessed in the time and frequency domains, delivering new source of physically-based hydrodynamic flow information. A major advantage of the LLP is that it delivers spatially distributed flow field data which cannot otherwise be captured using conventional measurement technologies. As an example, a flow oriented parallel to the body delivers a pressure signal response which is laterally symmetric, whereas a flow having an oblique angle to the body will create a net pressure differential between the left and right sides. The synchronous collocated array thus allows for a larger and more complex data set from which flow features can be obtained. Previous works have shown that the LLP is capable of calibrated bulk velocity estimation in a limited range of 0-0.5 m/s, including angular deviations of the sensor body with respect to the freestream flow (Fuentes-Pérez et al. 2015; Strokina et al. 2016). Here we introduce a new turbulence parameter estimation workflow, testing using laboratory flow experiments in a scale vertical slow fish pass. This methodology is shown to provide direct physical evidence of coherent flow structures in the form of a vertically-aligned vortex passing along the body of a fish-shaped probe body.

2. THEORY

The pressure Laplacian is relevant not only because it relates the velocity and pressure fields; it also contains useful information about the underlying *structure* of a turbulent flow field, which can be broken down into vorticity and strain rate contributions, Eq. [1]. Outside of the laboratory, it is difficult or impossible to obtain using point measurements of velocity components u, v, w (m/s) or pressure, P (Pa). Specifically, larger vortex tube structures (Figure 2) are more prevalent for values of the pressure Laplacian with high vorticity and low strain rate contributions, whereas vortex sheets are manifested in regions where the vorticity and the strain rate contributions are roughly in proportion (Tanaka and Kida, 1993).

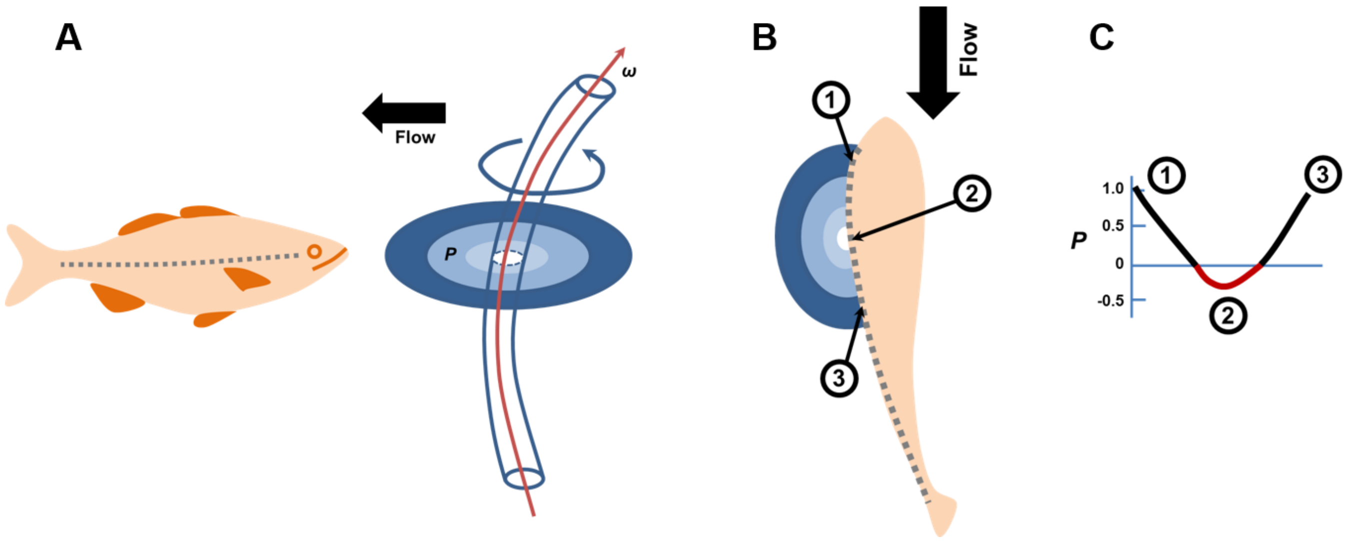

Figure 2. (A) A vertical vortex tube near a fish's body has a pressure minimum at its core. (B) Once passing over the body, the value of the pressure varies along the lateral line. (C) Depiction of the pressure distribution at locations 1, 2 and 3 and along the lateral line.

As a vertically-oriented vortex passes along a fish's body (Figure 2b), the spatial gradient of the pressure field can be detected as a series of peaks and troughs of the surrounding pressure field (Figure 2c). Laboratory observations of swimming fish have shown that the presence of coherent vortices in a turbulent flow can act as a double-edged sword. At the proper scale and orientation, vortices can be used by fish to enhance the energetic efficiency of locomotion. However, they can also lower swimming ability if their interaction with the body leads to dynamical instability (Lacey et al. 2012). Our long-term goal is thus to develop a new method to decompose the measured pressure Laplacian into the vorticity and strain rate contributions. Such a method would provide significant insight into the structure of innatura turbulent flows, of which little is known. Here we take the first step by introducing a methodology providing the magnitude, timing and spatial distribution of the pressure Laplacian using a lateral line probe. Focusing our analysis to the horizontal plane along the LLP midline, the pressure Poisson equation is expressed as:

$$\nabla^2 P = -\rho\left\{\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial u}{\partial y}\frac{\partial v}{\partial x}\right) + \left(\frac{\partial v}{\partial y}\right)^2\right\} = Q - D \qquad [1]$$

where ρ is the density of water (here taken as 1000 kg/m³) u and v are the velocities in the x and y directions and $Q = \frac{1}{2}\omega^2$ is the vorticity contribution, and $D = s_{xy}s_{yx}$ is the strain rate tensor contribution. The principle difficulty of solving the velocity-pressure coupling lies in the non-linearity of the source terms, compounded by the requirement of using Neumann boundary conditions (which cannot be measured in the field) to solve for the pressure field. Thus far, the pressure Poisson equation has only been solved numerically using high-resolution PIV velocity field data and with limited success.

Given the pressure, $P(x)$ along the streamwise linear array of the LLP at fixed locations of spacing Δx (5 cm), Eq. [1] can be calculated using a numerical approximation with a second order central difference scheme:

$$\frac{\partial^2 P}{\partial x^2} \approx \frac{P(x-\Delta x) - 2P(x) + P(x+\Delta x)}{\Delta x^2} \qquad [2]$$

The second-order scheme in Eq. [2] is implemented using the fish-shaped probe in MATLAB by taking the adjacent pressure sensor readings and using the known, fixed distance between sensors on the prototype body. This method considers only the pressure Laplacian in the streamwise (x) direction, as the pressure ports are located along the body center line in a similar fashion to that of a biological specimen's canal neuromasts, which typically run from the head to the tail.

Considering time-averaged turbulent flows, it is also advantageous to investigate the pressure Laplacian from the point of view of a Poisson equation relating the turbulent velocity and pressure fields (Gurka et al. 1999):

$$\nabla^2 P = -\rho \cdot (V \cdot \nabla V) + \nabla \cdot \frac{\partial}{\partial x_j}\left(\overline{u_i' u_j'}\right) \qquad [3]$$

where $\nabla^2 P$ is the pressure Laplacian, V is the velocity time-average, x_j is the Cartesian spatial coordinate in the jth direction, and u' is the velocity fluctuation from the time-averaged mean. It is worth noting that this method is more suitable for use with spatially resolved PIV data to determine the time-averaged Laplacian, whereas we calculate the instantaneous value of the Laplacian using Eq. [2] in this work.

Equation 3 relates the velocity-pressure coupling in a continuous domain by taking the divergence of the momentum equation using the Navier Stokes equation and enforcing continuity. The main advantage of studying the pressure Laplacian using this formulation over Eq. [1] is that it provides a more concrete physical interpretation of the underlying physical phenomena. The term $\nabla^2 P$ represents the rate at which pressure at a given location deviates from the fluid mean pressure (e.g. space and time-averaged piezometric pressure). Thus the pressure Poisson relation indicates that the rate of pressure deviation is driven by the sum of two source terms; the first source term on the right is induced by the local gradients in the mean velocity field, whereas the second source term includes the contribution of fluctuating velocity components in the form of Reynold's stresses. It is worth noting that the Reynold's stress tensor considers both the shear and normal stresses to a fluid element.

3. METHODOLOGY

A fish-shaped lateral line probe (LLP) has been developed to facilitate reliable measurements in the laboratory and in natural flow conditions. The LLP used in this work consists of 16 piezoresistive pressure sensors (SM5420C-030-A-P-S, Silicon Microstructures) mounted within an ABS plastic fish-shaped body. The geometry is based on a 3D scan of an adult rainbow trout (Oncorhynchus mykiss) with a body length of 45 cm (Figure 1). The pressure sensors with a span of 0-207 kPa are supplied with 4.096 V providing a full range sensitivity of 81.92 mV. The signals undergo a first stage amplification of factor 20.84 with instrumentation amplifiers (AD8421ARMZ, Analog Devices) and a second stage amplification of factor 16.43 with operational amplifiers (AD8656ARMZ, Analog Devices) resulting in a total amplification factor of 342.46. Due to the two stage amplification, it is possible to amplify a 396 nV/Pa signal to 136 µV/Pa signal. The first and second stage amplified signals are then digitized with a 16-bit analog to digital converter (AD7682BSPZ, Analog Devices) with the reference voltage 4.096 V, providing a resolution of 7.6 Pa / LSB for the first stage amplified signals and 0.46 Pa / LSB for the second stage amplified pressure signals (Tuhtan et al. 2016).

The LLP has been shown to be capable of providing current velocity estimates in a closed laboratory flume from 0-0.5 m/s, including angular deviations of up to 90˚ (Strokina et al. 2016). Additionally, a LLP signal processing workflow for time-averaged velocity estimation using the frequency mean amplitude of Reynolds-averaged pressure fluctuations has also been developed and tested in a scale vertical slot fishway (Fuentes-Pérez et al. 2015). It was found that both methods provide a systematic overestimation at velocities less than 0.2 m/s, and thus the LLP does require calibration to a given experimental setup.

LLP measurements (250 Hz for 30 s) were carried out in a 1:1.6 scale model of the VSF installed in Koblenz, Germany in order to investigate a similar range of hydraulic conditions to those experienced in the field. The scale model has a total of three basins (fixed bed, constant elevation). The discharge was adjusted as well as the upstream and downstream water surface elevations Two flow scenarios were studied; Q1 = 0.130 m3/s with a mean water depth, h_0 = 0.52 m as well as Q2 = 0.170 m3/s, h_0= 0.56 m. The LLP was mounted on a robotic gantry at three reference depths: 0.25h_0, 0.4h_0, and 0.6h_0. For each depth, a total of 24 measurement locations were obtained (Figure 3), as well as planar estimates of the time-averaged velocity magnitude. The point velocity measurements at 0.25h_0 and 0.4h_0 were taken using a laser Doppler anemometer (LDA) (2D FlowExplorer System, Dantec Dynamics) at 1 Hz for 60 s, and at 0.6h_0 with an ADV (Vectrino, Nortek) at 25 Hz for 60 s. Further detailed descriptions of the device, it's design and comparison to commercial ADV velocities are also provided in Tuhtan et al. 2016.

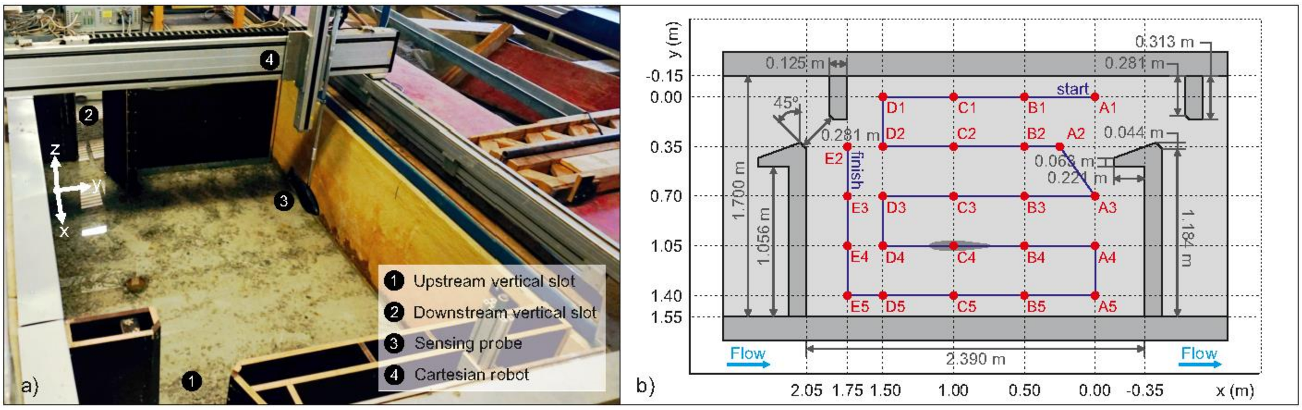

Figure 3. Experimental setup of the KIT fish pass. Right: locations and orientation of the investigated basin. Left: schematic showing the dimensions as well as the horizontal (x,y) measurement locations taken for a single vertical position of the probe.

4. RESULTS AND CONCLUSIONS

Measurements taken in a scale vertical slot fishway (VSF) at the Karlsruhe Institute of Technology (Fuentes-Pérez et al. 2015) were investigated for the tell-tale presence of large body-oriented vortices. Based on the theory presented in the previous section, vertical vortices of sufficient diameter should appear as a series of phase-shifted peaks as the low-pressure core passes over the LLP sensing array. An example of two vortices passing the LLP at approximately 0.25 and 1.5 seconds can be seen in the time series plots of the body-oriented pressure Laplacian (Figure 4).

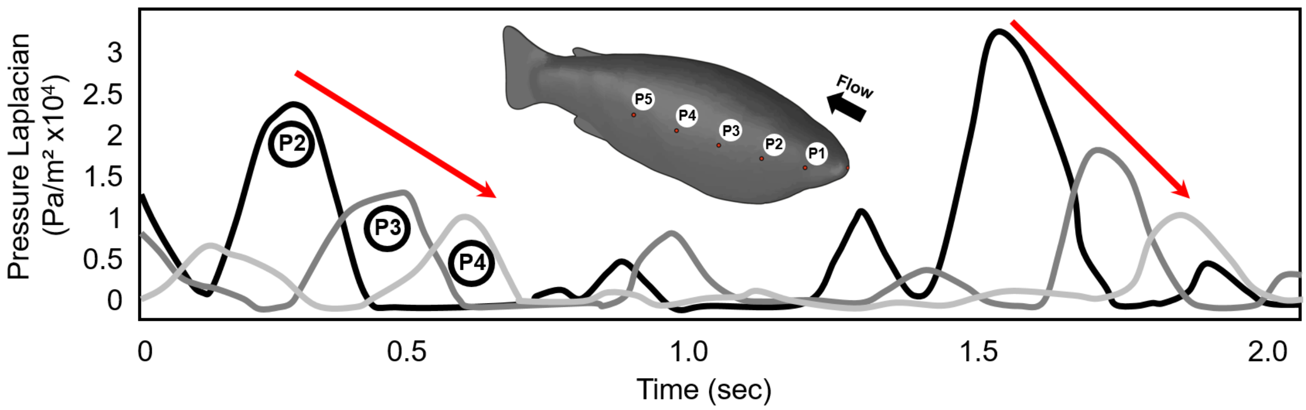

Figure 4. Two vortex events recorded using the LLP pressure Laplacian. The red arrows show the cascade of the Laplacian as the vortex core passes along right lateral sensors P2, P3 and P4. The negative slope indicates that the vortex strength is decreasing over time.

It was found that depending on the location of the sensor in the fish pass (Fig. 3b), coherent structures could indeed be detected by the pressure Laplacian method. Notable locations where large structures were detected were near the shear region of the downstream wake (e.g. A2 – C2), and no vortices could be detected near the far wall recirculation area (A5 – E5). Due to the method's reliance on a limited number of individual pressure sensors, this does not necessarily mean that vertically-oriented vortices do not exist in these regions, but rather points out one of the limitations of measuring with a limited number (and spacing). Future probes should include a larger number of overall sensors (10 or more) with smaller spacing (1 cm or less) in order to ensure that coherent vertically-oriented vortices over a wider range of length scales can be detected.

Another interesting possibility would be to investigate the differences in phase and group velocity between the attenuated pressure Laplacian peaks. It is clear that the presence of a vertically-oriented vortex large enough to be detected can be readily identified as a series of peaks with decreasing magnitude. Therefore, it can safely be assumed that the low pressure vortex core is also undergoing deformation. By combining high-resolution PIV studies of regular turbulence (e.g. in the wake of a von Karman vortex street) it may also be possible to study in greater detail the fluid-body interactions between coherent vertical structures and streamlined bodies.

The LLP pressure Laplacian method was found to be able to detect the presence of vortices in an experimental VSF. Future work will focus on the measurement of von Karman vortex streets where the size, frequency and intensity of vortices can be experimentally controlled. Additionally, the number and sensitivity of LLP pressure sensors will be increased in order to increase the spatial resolution of the pressure. Time-resolved analysis of the pressure Laplacian will facilitate more in-depth analysis of the spatiotemporal development of turbulent flow structure around a fish-shaped body.

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