The simple reason why pressure sensors are not adequate to replicate the lateral line in free swimming fish-like robots

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1 Introduction

The lateral line organ allows fishes to sense the activity of the surrounding flow. Gathering flow information is crucial for fishes to measure their own speed relative to the flow, their direction, and even to detect obstacles, as well as enabling more complex behaviors like schooling, rheotaxis, and other flow based adaptations during swimming [1]. Having an engineered replica of such a sensory system would enable swimming robots and large maritime vehicles to better exploit their interactions with the flow and improve swimming capabilities (e.g. manoeuvrability).

The biological lateral line in fishes is a complex microscale physical arrangement that allows mechanoreceptors (neuromasts composed by epithelial/hair cells), to detect slight water displacements (either on the surface of inside small skin canals) and transduce these signals into electrical synapses [2]. The sense of flow in fishes is then directly related to mechanical deformation of such small structures.

There have been efforts to replicate the sensing of such flow based deformations at several scales in order to create artificial lateral lines. In particular, the use of a variety of electromechanical systems such as piezoresistive, piezoelectric, MEMS, capacitive, dipole, and optical sensors is popular [3]. These systems allow the measurement of velocity fields and other flow paramaters. However, the miniaturization of such devices, including their power and signal conditioning peripherals, to become a portable and functional artificial mechanoreceptor for robotic applications had not yet been achieved.

To this end, several authors have explored the implementation of artificial lateral lines by using other physical principles, that are fundamentally different from measuring the deformation of micro-structures. In particular, measuring the pressure field of the complex fluid surrounding a body [3]. Arguably the information of the flow surrounding the swimming body can be reconstructed by measuring the pressure in several points of body. This can be approximately achieved by using Bernoulli's principle of mass conservation in ideal fluids. Although theoretically it make sense, at least for the 2D planar case, in practice, where the robotic fish is able to swim freely, the results are very different. The main culprit: the hydro-static pressure term of Bernoulli's flow equation.

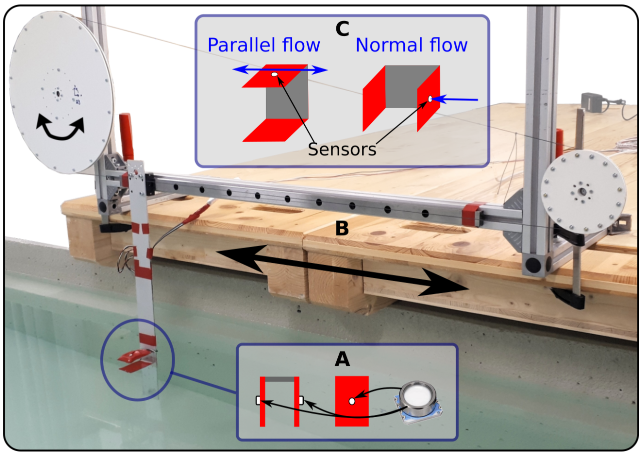

Figure 1: a) Schematic of the front and side views of the tested frame showing the pressure sensor used: MS5803-01BA (same as in [4–6]). b) The experimental set-up, consisting of a linear guide driven by a servomotor and a pulley reel system (disks), accurately moving the sensors in a sideways oscillation (black arrow). c) The two flow configurations tested.

Reported attempts to measure the flow with pressure sensors use pressure based altimeters adapted for swimming due to their sensitivity ($\Delta P \approx 2$ Pa) [3–6]. Unlike these laboratory controlled experiments, where the testing body remains perfectly locked horizontally at a fixed depth, a free swimming robot is susceptible of roll sideways. We noticed this when testing an artificial lateral line in our undulatory swimming robots, where sideways motion of the centre of mass produces an undesirable 3D rolling as the planar robot (i.e. 2D, co-planar joints) undulates. It revealed drawbacks of this technique as pressure differences in left/right sensor pairs are inevitably affected by the hydro-static pressure difference. An artificial lateral line using this technology relies on the hydro-dynamic components of the measured absolute pressure, but so far the hydro-static term has been disregarded in the reported literature. Here we show that decoupling such quantities is more challenging than it appears. Moreover, noise and hydro-static to hydrodynamic signal ratios render these type of artificial lateral line sensor arrays unsuitable for free swimming robots.

2 Experiment and results

In our experiment (Fig.1), the sensors mounted on a robot frame were subjected to an oscillatory controlled flow in their parallel and normal configurations. We carried out

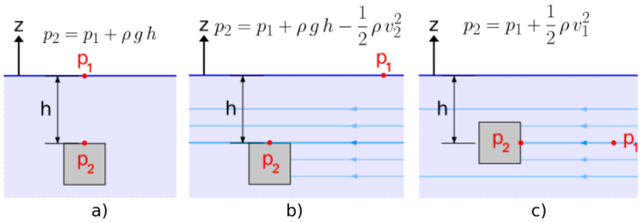

Figure 2: Diagrams of a small immersed object in a fluid during a) static flow, b) parallel flow, and c) normal flow.

experiments at several depths and with different oscillatory speeds. The purpose of the experiment was to compare the resultant speed of the frame, indirectly measured with the pressure sensors, and the real speed controlled by the motor. To calculate the speed using the measured pressure, we used Bernoulli's principle of mass conservation assuming an inviscid fluid (i.e. energy dissipation due to friction in the fluid is neglected). It states that along a streamline arbitrary pressures p_1 and p_2 relate to one another by:

$$p_1 - p_2 = \frac{1}{2}\rho(v_1^2 - v_2^2) + \rho g(z_2 - z_1) \tag{1}$$

Where p_i[Pa] denotes the pressure at a certain point, v_i[m/s] the fluid's velocity, and z_i[m] the elevation against gravity of the testing point. In our experiment, the Bernoulli's flow equation (1) can be seen from three perspectives (Fig.2). Solving for the speed in the configurations in Fig. 2b and 2c (i.e. parallel and normal flow respectively), its magnitude can be found using the pressure at points p_1 and p_2.

We tested the aforementioned rationale with real data. Pressures p_1 and p_2 in Fig. 2b and 2c, were gathered and carefully conditioned for analysis as shown in Fig.3. These are the results of pressure measurements and their associated filtered noise. Instead of calculating the speed, in the scope of this work, we would like to focus our analysis on the values of measured pressure.

Pressure ranges for parallel flow show values of ≈20 Pa. However, they present noise of ≈10Pa. This is 50% of value of the signal (i.e a poor signal to noise ratio SNR≈4). Similarly, for the normal flow experiments, the pressure results in ≈ 70 Pa, with noise of ≈40 Pa (SNR ≈3). These pressure values are consistent with the ones reported in [4–6]. However, noise values are clearly high, making these signals, in our opinion, statistically unreliable for practical purposes.

3 Concluding remark

Despite poor SNR shown in our results (a sample from n=320 experiments), arguably a good selection of filters and signal post processing can isolate useful signals to compute the flow speed. This may have been the aim in previous work [3–6] when implementing artificial lateral lines. However, the high sensitivity of the absolute pressure sensors makes them susceptible to additional hydro-static pressure readings (as seen in differences in Fig.3a,c). This raises an important question: Hydro-static pressure calculated using eq.(1), as in Fig.2a for a negligible fluid height difference of 1 cm, yields $\Delta P = \rho g h \approx 100 Pa$ for the water. This means that in a free swimming robot, a simple water splash of a minuscule wave will create signals that are comparable, if not higher than the actual desirable readings. It this not enough reason to stop using pressure sensors to emulate lateral lines?

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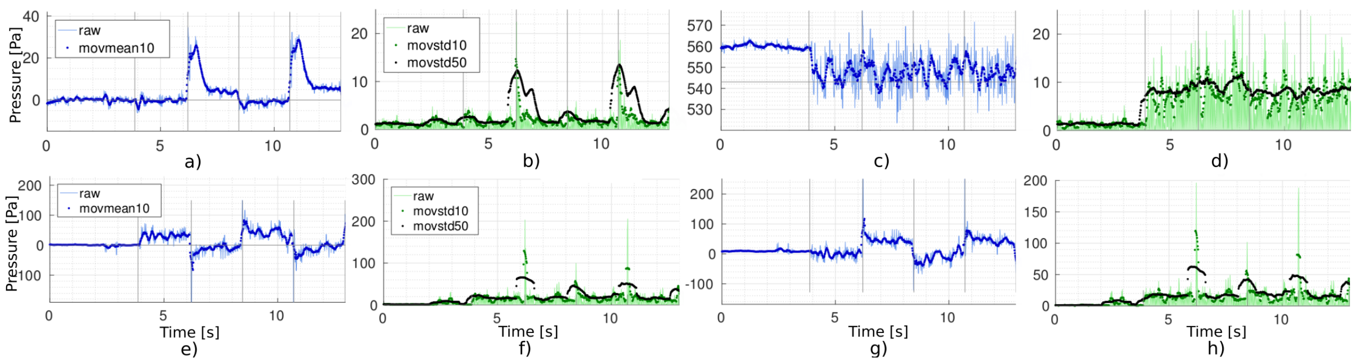

Figure 3: Experimental results with v=0.265 m/s (blue, pressure readings, green, standard deviation (noise), dark dots, moving mean). a-d) parallel flow, where a,b) is a trial with (height) h=0.1 cm, while c,d) h=6 cm. e-h) a single trial normal flow, with h=18 cm where e-f) show left sensor and g-h) right sensor.