Hydromast: A Bioinspired Flow Sensor with Accelerometers

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Abstract. Fish have developed advanced hydrodynamic sensing capabilities using neuromasts, a series of collocated inertial sensors distributed over their body. We have developed the hydromast, an upscaled version of this sensing modality in order to facilitate near bed sensing for aquatic systems. Here we introduce the concept behind this bioinspired flow sensing device as well as the first results from laboratory investigations.

Keywords: Hydromast · Biomimetic · Flow sensing

1 Introduction

Fish experience the surrounding flow using their lateral line and inner-ear sense organs. The lateral line organs consist of linear arrays of neuromasts on the head and along the body, sensitive to changes in the spatial derivatives of the flow field. Neuromasts consist of gelatinous cupula whose deflections correspond to the local motions of the fluid, relative to the motion of the body. Superficial neuromasts located at the surface are sensitive to local changes in the velocity, whereas canal neuromasts, embedded within subcutaneous canals connected by pores to the surrounding flow, act primarily as acceleration detectors. The inner ear 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 fish's body within the surrounding flow field [1].

Natural flow fields, such as those occurring in rivers and coastal waters can be described as a complex amalgamation of velocity, vorticity and pressure terms, acting over a wide range of spatiotemporal scales [3]. As such, it is not possible to directly record the complete physical evolution of the flow field with reference to these terms. Instead, our aim is to extract salient, hydrodynamically-relevant features such as the near-bed bulk flow velocity and bed shear stresses by utilizing the fluid-body interaction in natural flow and laboratory investigations. Measurement data can be analysed in both the time and frequency domains to provide a new source of physically-based hydrodynamic measurements. We have shown in previous works that bioinspired measurements based on a fish-shaped lateral line probe consisting of a collocated pressure sensing array is capable of calibrated bulk velocity estimation in a limited range (0–0.5) m/s, including

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large (up to 90°) angular deviations of the sensor body with respect to the freestream flow [4, 5]. Here we introduce a new hydromast device, inspired by the single superficial neuromasts of fish's lateral line for turbulent, flume experiments. The hydromast can be viewed as a bioinspired upscaled inertial measurement device tailored for near-bed studies of complex in-situ flows which are often difficult or impossible obtain using conventional approaches such as acoustic Doppler current profiling (Fig. 1).

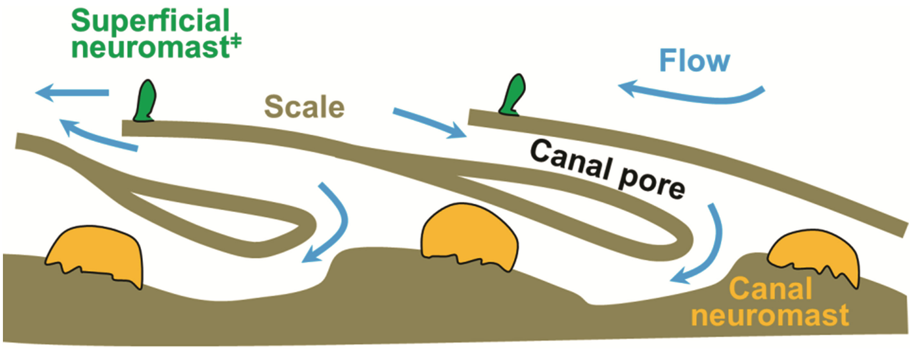

Fig. 1. The lateral line sensory apparatus of a fish, consisting of superficial neuromasts (green) and subdermal canal neuromasts (orange). Illustration after [2]. (Color figure online)

Fishes have the capability to sense local hydrodynamic stimuli close to their bodies using the lateral line modality. We show that an artificial inertial neuromast can be reconstructed and the base biological design can be exploited to measure flow characteristics with accelerometers.

2 Design Concept of the Artificial Neuromast Sensor with Accelerometers

The first approximation to create an upscaled superficial neuromast has been made with a stiff plastic stem of circular cross-section having a 10 mm diameter (see Fig. 2). The stem was fixed onto a silicone membrane (casted from Elite Double 22, Zhermack SpA), which acts similarly to the gelatinous cupula, as a spring element allowing the stem to pivot in the water flow. The stem was fixed trough the membrane with a bolt onto a clamp that held an accelerometer with 10×10 mm printed circuit board. The membrane was fixed between two surfaces in the casing (see Fig. 2).

To remove offsets caused by any slight misalignment of the sensor prototype in the flume, and to measure the stem tilt angles in the casing frame we installed a second stationary accelerometer to the casing close to the moving accelerometer (see Fig. 2). The difference between the base and stem angles from accelerometers thus provides an output signal largely free from any body self-motion due to mounting.

Accelerometers were interfaced with 32-bit ARM microcontroller (ST Microelectronics) over 400 kbps I2C bus. We use the earth gravity vector and arctangent function to calculate the sensor inclination in X, Y coordinates. It is assumed that sensor does

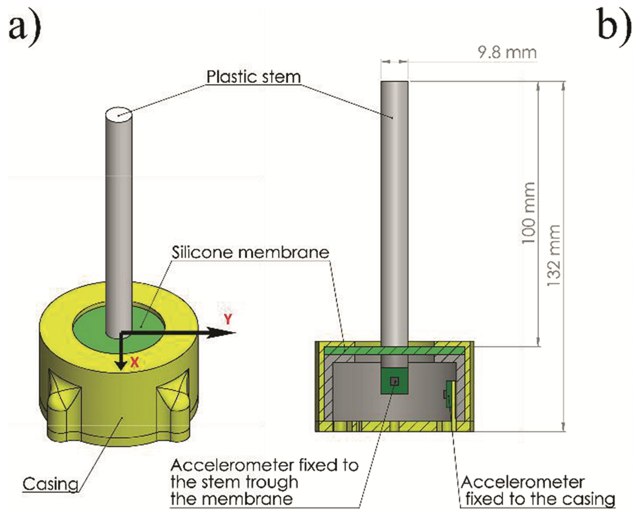

Fig. 2. (a) Schematic of the hydromast prototype and (b) image of the sensor in the flow tunnel

not rotate about the Z axis, and the random acceleration noise caused by water turbulences can be eliminated through the time averaging of the output signal. According to the experimental results more sophisticated sensor inclination measurement methods do not provide large benefits in accuracy over the simple method described. This is because the inertial and magnetic sensor fusion algorithms do not perform well when high frequency acceleration is present.

The accelerometers were connected to the ARM microcontroller using 4 thread thin ear phone wires to minimize disturbance due to wire movement and bending. The accelerometers were coated with Plasti Dip plastic (Plasti Dip International) to make them waterproof.

3 Design Evaluation and First Results

3.1 Experimental Setup

We tested the sensor in a flow tunnel with a working section of 0.5 m × 0.5 m × 1.5 m embedded into a test tank (see [6] for the test tank description). Uniform flow (constant water surface, no change in flowrate over time) in the working section was created with the help of a U-shaped flow straightener and two sequential collimators. An AC motor was used to create the circulation inside the flow tunnel, and the flow speed was calibrated using a digital particle image velocimetry system.

The sensor was fixed onto a metallic plate which was placed in the middle of the bottom in the flow tunnel. We ran experiments at 0.05 m/s speed increments, with maximum speed of 0.5 m/s. The flow was let to stabilize for 30 s and the data was logged for 30 s on each speed.

3.2 Calibration Results

The calibration results showed that the hydromast with the chosen parameters (stem height, diameter, membrane thickness and elasticity) has threshold shift in its behaviour above speeds of the 0.25 m/s. The root mean square (RMS) of the hydromast's stem pivot angles in the water flow (offsets were removed using the data recorded by the secondary accelerometer fixed to the casing from 10 experiments) are plotted in Fig. 3.

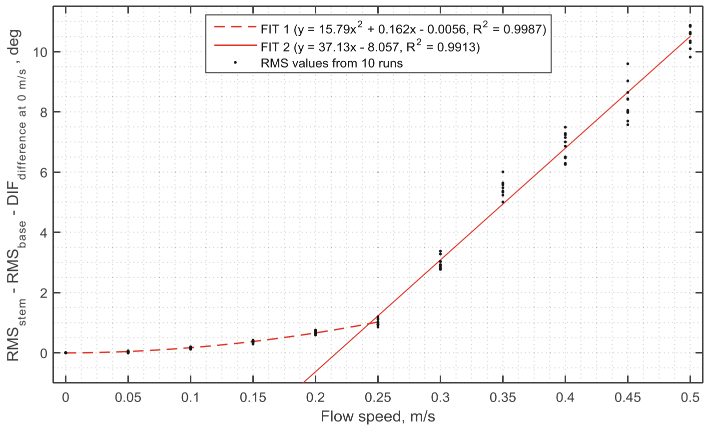

Fig. 3. RMS of the stem tilt angle along the flow direction with removed initial offsets and RMS of the base

At to velocities of up to 0.25 m/s, the hydromast's relation to flow speed was quadratic ($R^2 = 0.9987$) whereas from speeds 0.25 m/s to 0.5 m/s the hydromast responded linearly to increasing flow speed ($R^2 = 0.9913$). This shift is due to the transition to turbulence over the body, where at velocities > 0.25 m/s, larger vortices are suddenly shed from the stem surface, creating a new fluid-body interaction between the skin drag, vortex-induced drag, buoyancy and restoring force by the membrane creating a new fluid-body interaction. The dynamic balance of forces causes a lock-in of the oscillatory motion of the hydromast particular to each flow velocity. This dynamical loading results from the interplay of fluid drag and restoring forces driven by the hydromast's positive buoyancy in conjunction with the membrane stiffness.

The frequency spectra analysis with fast-Fourier-transform (FFT) from the concatenated signal of 10 experiments showed that distinguishable frequencies appear above flow speeds of 0.3 m/s. The experimental data from 10 runs was concatenated to analyse all of the runs as one single dataset. The results from the concatenated data compared with the single runs data showed no significant difference in the FFT spectrum. Before the FFT was performed the casing vibrations were removed from the stem signal by subtracting the casing accelerometer signal from the stem accelerometer signal. The signal was then filtered using median filter and linear trends were removed. The frequency spectra are plotted on Fig. 4.

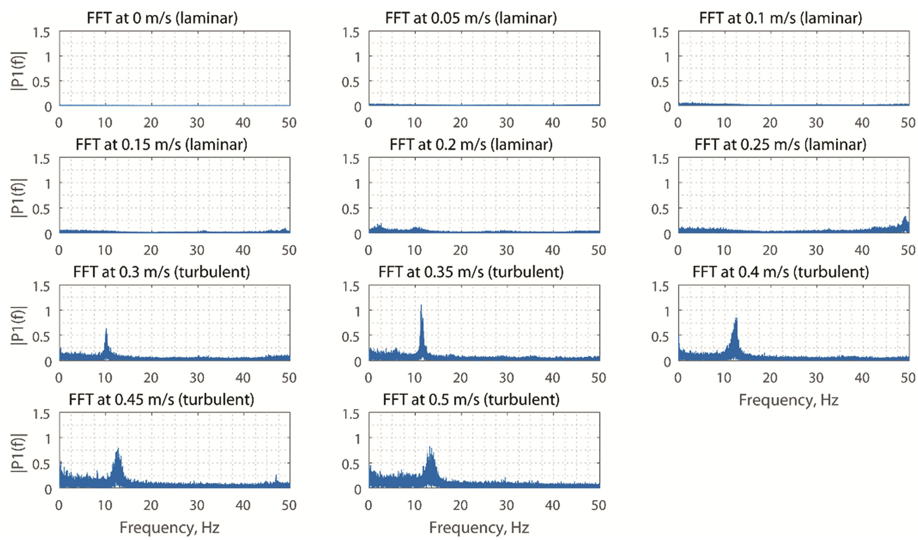

Fig. 4. FFT frequency spectra from the stem-casing signals for flow speeds from 0–0.5 m/s in 0.05 m/s intervals. Peaks arise due to the transition from laminar to turbulent flow.

The mean amplitudes of the frequencies increase with the speed. From the FFT we calculated frequency spectra mean amplitudes which are plotted against the flow speed in Fig. 5. The relation of the mean frequency amplitudes and flow speeds resulted in a quadratic relation with $R^2 = 0.9913$). This trend is due to the size and frequency of vortices shed from the cylinder body, with increasing velocity the vortices become larger and are shed at a proportionally higher rate increasing the force imbalance on the stem and creating larger magnitude fluctuations.

The two flow regimes of the hydromast can also be noted in the standard deviation (STD) values of the vibrations. The stem's vibration standard deviation along flow is increasing around 0.25 m/s with corresponding Reynolds number over 2000. The STD values are plotted of the mean stem angles in the flow are plotted in Fig. 6.

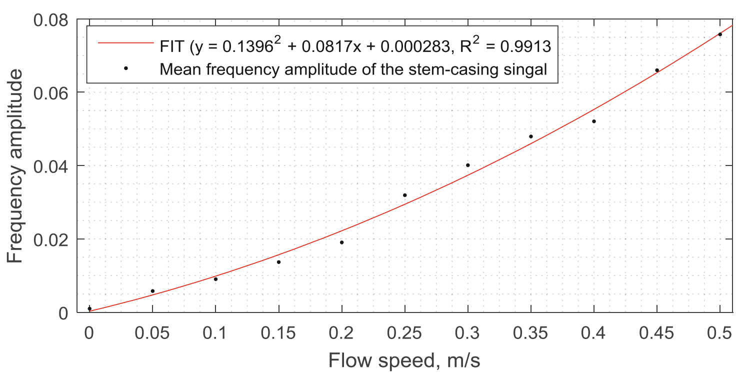

Fig. 5. Mean frequency amplitudes from the stem-casing signal on flow speeds 0–0.5 m/s.

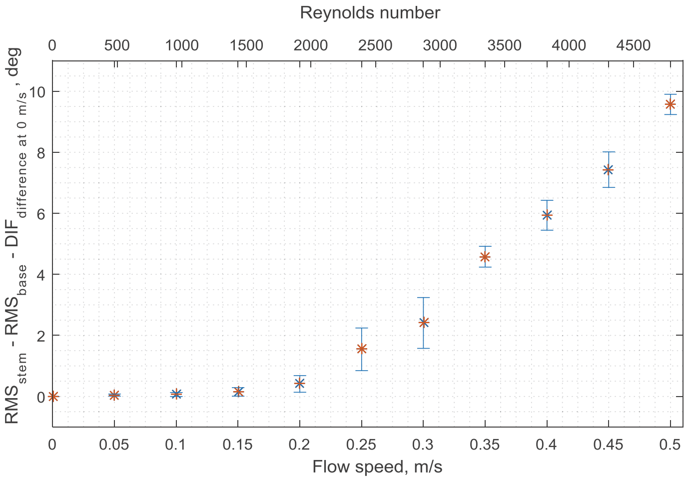

Fig. 6. RMS of the stem angle along the flow corresponding Reynolds numbers and standard deviations, where the highest STD are found during the unstable transition from laminar to turbulent flow (0.25 and 0.30 m/s).

4 Discussion

In contrast to previous work based on bioinspired mammalian tactile whiskers [7] whose sensing ability is based on active detection, relying on the purposeful motion of the sensor within the fluid, our device is based on measurements using passive hydromechanical detection. Passive sensing based on the lateral line sensing modality of fish has the added advantage that knowledge of the instantaneous displacement of the sensor body, relative to the flow, can be directly related to the frequency, amplitude and phase of the flow stimulus [8].

The change in the hydromast's behaviour can be related to the change from near-laminar flow to fully turbulent flow. With a 9.8 mm cylindrical stem the Reynolds numbers indicate that around speeds 0.20 to 0.30 m/s, the flow transition occurs from near-laminar to turbulent (with corresponding Reynolds numbers Re = 1952 to Re = 2928). At the Reynolds numbers between 2000 and 4000 the flow around the cylindrical stem is transient, the flow is therefore in between near-laminar and fully turbulent.

The change from near-laminar to fully turbulent flow region can well be seen in the FFT graphs (see Fig. 4) where distinct frequencies appear at 0.3 m/s. The turbulence can be also noted in the standard deviations of stem vibrations. There is a larger increase of the standard deviation around the speed of 0.25 m/s (see Fig. 6).

The flow speed from hydromast's readings could be detected in two ways. One solution is to use the mean angle of the stem in the flow to estimate flow speed from the sensors. The emergence of clearly distinguishable frequency peaks from the FFT then tells us whether we need to use the linear or quadratic regression of the mean angle of the stem to calculate the flow speed. A second, and complimentary solution is to use the quadratic relation between mean amplitude of the frequency spectra of the stem and the flow speed. The second method has been shown to work with pressure sensors, even at higher velocities (> 1 m/s) and extreme turbulence [5]. The combination of two techniques would possibly give better results.

The hydromast's bilateral reaction to flow speed allows us to design sensors differently for low and high flow speeds. With the current prototype, if we know the characteristic curves of the sensor, we can use the sensor both in laminar and turbulent flow regimes. The sensors membrane and stem properties can be tuned as key parameters in order to define sensor performance criteria.

By altering the hydromast's membrane dimensions or elasticity, it would be possible to increase or decrease the sensibility of the sensor at low laminar flow speeds. With softer membrane material the hydromast would bend more in the laminar and near-laminar flow regimes where the drag forces are caused largely due to skin friction. In the fully turbulent flow region, the softer membrane would allow the light hydromast's stem catch the turbulent wake frequencies better but on the other hand there is also a higher change that the turbulences would match the natural frequency of the moving stem.

The dimensions of the hydromast's stem affect the speed at which the flow around the stems reaches the transition point from laminar to turbulent. Stems with smaller diameters (and smaller Reynolds numbers) would reach the transition point at higher speeds and vice versa in case of larger stem diameters. Thus, even though the fluid-body interactions between the stem and the fully turbulent flow field are complex, the system has only a few simple parameters which can be tuned when developing neuromast-inspired flow sensing devices.

The best suitable sensor combinations will be parameterized in ongoing investigations where we take into account a wider diversity of conditions where the sensors will be applied.

5 Conclusion

In confined laboratory experiments we have shown that a bioinspired hydromast equipped with accelerometers can be used to detect flow speeds up to 0.5 m/s. It is possible to relate the flow speed to the hydromast stem motions both in the near-laminar and turbulent flow regions.

Future research will be focused on the study of how the hydromast behaves at higher flow speeds and how the sensibility is dependent on the hydromast stem and membrane properties.

The areas of interest where we want to apply the hydromast sensors are related to both freshwater (e.g. rivers) and salt water (e.g. sediment transportation on the seabed, current flow speed and direction monitoring in ports etc.) environments where near-bed flow sensing is often difficult, if not impossible to achieve.

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