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Tracking Fish Trajectories through Dynamic Pressure Signals: A Dual-Sensor System for Hydrodynamic Cues Monitoring

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Summary: Accurate characterization of hydrodynamic cues produced during fish locomotion is essential for understanding behavioral dynamics. In this work, a novel pressure sensor system is presented to isolate the dynamic pressure components associated with fish movements, while compensating for wave induced pressure. The system combines a differential pressure sensor and a water level sensor. Its accuracy has been demonstrated through experimental validation against a classical potential flow model around a cylinder, confirming the robustness and effectiveness of the proposed approach.

Keywords: Sensors, dynamic pressure, instrumentation, wave, hydrodynamic model, embedded systems

Introduction

Understanding the social behaviors and navigation strategies of fish has long been recognized as a significant challenge in marine ethology, and bio-inspired engineering [1]. During locomotion, fish are known to generate complex hydrodynamic signatures composed of vortices and persistent pressure fluctuations [2]. These flow-induced cues can offer valuable insight into their orientation strategies.

Traditionally, such phenomena have been studied using optical techniques like Particle Image Velocimetry and Laser Doppler Velocimetry. Although these methods are highly accurate, they typically involve complex instrumentation, invasive setup, and limited deployability in naturalistic environments. Moreover, their intrusive nature may interfere with the spontaneous behavior of the observed animals.

To address these limitations, pressure-based sensing has emerged as a promising alternative. However, in aquatic environments, pressure recordings often conflate dynamic contributions from fish movements with hydrostatic components induced by surface wave fluctuations [3]. Disentangling these overlapping signals remains a major technical bottleneck.

To overcome this, a sensor system has been developed to isolate the dynamic pressure component, while filtering out wave-induced hydrostatic disturbances. The device integrates a differential pressure transducer and a water-level sensing module. Its performance has been experimentally evaluated and benchmarked against a theoretical model: the potential flow around a rigid cylinder [4].

Materials and Methods

Dynamic pressure measurement system

An experimental device was developed, consisting of two complementary sensors designed to isolate the dynamic pressure component (P_{dyn}) generated by swimming fish, while compensating for hydrostatic fluctuations (P_{wave}) induced by surface waves.

The primary sensor was implemented as a high-sensitivity piezoresistive differential transducer. It measured the pressure difference between a measurement point, subjected to both P_{dyn} and P_{wave}, and a reference point located inside a submerged cavity. This cavity, being shielded from dynamic flow effects, allowed for the measurement of only the static pressure (P_{stat}), comprising atmospheric pressure and hydrostatic pressure at rest. The resulting signal was expressed as:

$$\Delta P = P_{\text{mes}} - P_{\text{ref}} = (P_{\text{dyn}} + P_{\text{wave}} + P_{\text{stat}}) - P_{\text{stat}},$$

The sensing element was composed of a membrane coupled with a strain gauge, offering a resolution of 0.2Pa and a bandwidth of 1kHz [5].

To estimate hydrostatic fluctuations, a secondary sensor was used to continuously monitor the instantaneous free-surface elevation $h(t)$. The sensor operated via impedance measurement in an AC oscillator circuit connected to submerged electrodes, thereby avoiding polarization effects and long-term electrochemical drift [6].

This formulation assumes shallow water conditions, where wave-induced pressure variations are approximately hydrostatic and do not decay significantly with depth [7].

The two sensors were interfaced with an ESP32 microcontroller, which ensured synchronized signal acquisition at 125 Hz. The dynamic pressure component was then obtained by subtracting the estimated hydrostatic pressure:

$$P_{\text{dyn}} = \Delta P - P_{\text{wave}}, \quad \text{with} \quad P_{\text{wave}} = \rho\, g\, h(t).$$

where ρ is the water density and g is the gravitational acceleration.

Experimental validation setup

To evaluate the accuracy and robustness of the proposed system, an experimental validation was conducted using a classical hydrodynamic benchmark [4]. The experiments were carried out in a laboratory water tank equipped with a motorized mechanism for translating a rigid cylinder (diameter: 5 cm) at a constant velocity of 0.13 m/s. The pressure sensor was positioned 5 cm from the centerline of the cylinder. The experiments was repeated 12 times to ensure measurement repeatability.

Figure 1 presents the sensor (a), the experimental setup (b), and the block diagram of the data acquisition board (c).

The raw dataset and analytical tools were made publicly accessible via GitHub [8].

Results and Discussion

Comparison with theoretical reference case

To assess the system's ability to isolate dynamic pressure, the corrected experimental measurements were compared to analytical predictions derived from potential flow theory around a cylinder [4]. As illustrated in Figure 2(a), the differential pressure signal ($P_{\text{dyn}} + P_{\text{wave}}$) and the wave-induced pressure signal (P_{wave}). This representation highlights the contribution of hydrostatic disturbances to the total measured signal. Figure 2(b) presents the dynamic pressure signal compared to the theoretical

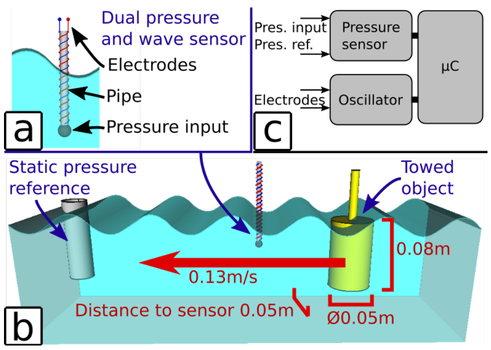

Fig. 1: (a) Dual pressure and wave sensor, (b) Experimental setup, (c) Block diagram of the electronic board.

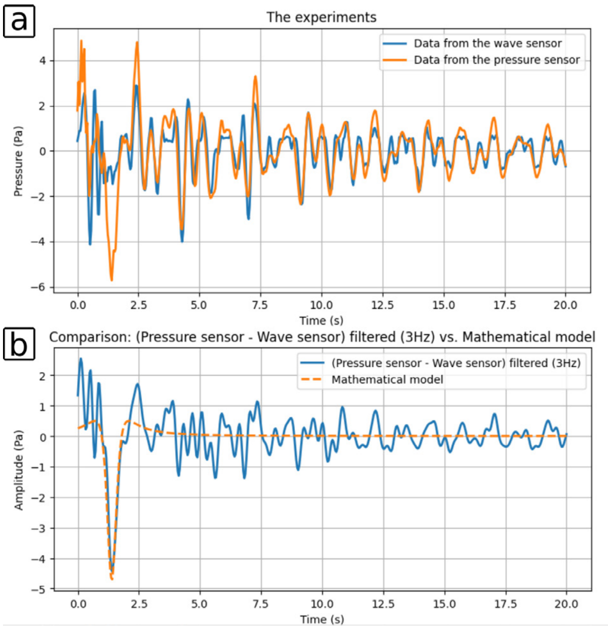

Fig. 2: (a) Raw differential pressure signal $(P_{\mathrm{dyn}} + P_{\mathrm{wave}})$ *and wave-induced component* (P_{wave})*, (b) Corrected dynamic pressure compared with the theoretical model.*

prediction. The experimental results show excellent agreement with the analytical model in both amplitude and temporal evolution, confirming the system's ability to accurately extract key hydrodynamic features.

The analytical model used for validation is publicly available in an open-source repository [8].

Discussion and practical implications

The sensor successfully captured the dynamic pressure generated by the moving body while significantly attenuating wave-induced perturbations. Although some residual noise remains, its amplitude was reduced by approximately a factor of four. The proposed system enables direct and non-invasive measurement of dynamic pressure fields, offering data well suited for trajectory estimation and flow analysis. In contrast to optical systems, it is easy to deploy, and does not require tracers or external illumination, making it ideal for experimental and semi-natural environments.

Conclusion

A dual-sensor system was designed and experimentally validated to isolate the dynamic pressure component from wave-induced hydrostatic fluctuations in aquatic environments. The device combines a differential pressure sensor with a water level sensor and enables correction of pressure signals.

The system was evaluated under controlled conditions using a benchmark case based on potential flow theory. The comparison with theoretical predictions confirmed the accuracy and robustness of the proposed approach.

Owing to its compactness, the system represents a valuable alternative to conventional optical techniques. Ongoing developments aim to extend the system into sensor arrays capable of reconstructing pressure and velocity fields for advanced hydrodynamic analysis in biological, without being invasive to aquatic organisms.

Future work will focus on deploying a network of these sensors to generate spatially resolved pressure maps. These maps will allow for the reconstruction of velocity fields and enable a more detailed analysis of wake structures and hydrodynamic cues.

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References

[1] J. C. Liao, “A review of fish swimming mechanics and behaviour in altered flows,” *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 362, no. 1487, pp. 1973–1993, 2007.

[2] W. Hanke, C. Brücker, and H. Bleckmann, “The ageing of the low-frequency water disturbances caused by swimming goldfish and its possible relevance to prey detection,” *Journal of Experimental Biology*, vol. 203, no. 7, pp. 1193–1200, 2000.

[3] F. Zonta and M. Onorato, “Growth and spectra of gravity–capillary waves in countercurrent air/water turbulent flow,” *Journal of Fluid Mechanics*, vol. 777, pp. 245–259, 2015.

[4] E. Guyon, J.-P. Hulin, and L. Petit, *Hydrodynamique Physique*. Paris: CNRS Éditions, 2001.

[5] C. Porcon, B. Lagneaux, G. Jodin, F. Razan, and B. Sun, “Experimental system of synchronized pressure sensors for hydrodynamic measurements,” tech. rep., IETR, ENS Rennes and Westlake University, 2024. Technical Report.

[6] N. Liu, R. Wei, P. Zhang, Y. Sun, and Z. Li, “Design and test of large-range wave height sensor based on water resistance measurement and fuzzy system,” *Personal and Ubiquitous Computing*, vol. 25, pp. 457–465, 2021.

[7] J. Bosboom and M. J. F. Stive, “Coastal hydrodynamics,” 2022. `https://geo.libretexts.org/Bookshelves/Oceanography/Coastal_Dynamics_(Bosboom_and_Stive)/5.04\%3A_Wave_orbital_velocity_pressure_and_bed_shear_stress/5.4.2\%3A_Dynamic_Pressure`.

[8] C. Porcon, “Hydrodynamic model – experimental data and code.” `https://github.com/41PortCom/Model_Hydrodynamics/`. GitHub repository.

[9] HFSP, “Human frontier science program research grant rgy0059/2022.” `https://doi.org/10.52044/HFSP.RGY00592022.pc.gr.153593`, 2022.