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Underwater Object Detection And Identification Using Distributed Pressure Sensors

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1. Progress statement

Introduction

Underwater vision is usually limited. Object detection and identification is therefore one of the main challenges of underwater navigation. A new sensing modality, specifically developed for underwater environments, would greatly increase the scope of underwater missions. Taking inspiration from the lateral line of fish, I believe that pressure sensing can be a viable alternative to vision in order to detect and identify obstacles. Recent advances in the area of micro-engineering will soon enable to build sensors that match the size and mimic the functions and organization of the lateral line. However, little is known about how the pressure distribution along a fish relates to an obstacle location and shape. Detecting and identifying obstacles from distributed pressure sensors is a complex inverse problem that can be solved using Bayesian inference. For Bayesian inference to be practical, one needs to be able to solve the direct problem in real-time. Therefore, the aim of this project is to provide a tool for fast estimation of the pressure distribution along a vehicle caused by an obstacle.

Computational Fluid Dynamics (CFD) is a great tool to investigate flow characteristics because it can give access to information that is not easily accessible experimentally (such as the pressure field). However, the configuration of interest here, which features a vehicle in motion relative to a static obstacle, is very challenging for traditional CFD tools. Such tools (referred to as body-fitted) require the computational grid to conform to the boundaries of the fluid domain. Deforming and re-generating a grid to comply with prescribed motions can eventually become more time consuming that actually calculating the flow properties. Immersed Boundary (IB) methods are much more convenient since they allow the boundaries to move independently of the grid. Unfortunately, currently existing IB methods do not perform satisfactorily for flow over a streamlined body at high Reynolds number (typically between 1000 and 10000 for small fish) because of the thin boundary layer. I have showed that widely used IB methods referred to as direct forcing methods only have a first order treatment of the immersed boundary. I have proposed the addition of a higher order term to an existing method which results in an easy to use flow prediction tool for the configuration and Reynolds number of interest [1]. Though this Navier Stokes solver allows me to accurately calculate the pressure resulting from an obstacle, it is orders of magnitude too costly for real-time use.

Results

Since the Reynolds numbers considered are large, a commonly used approximation is that of inviscid flow ($Re = +\infty$). Potential flow solvers can very efficiently solve the resulting Euler equations, but after investigating the case of an airfoil passing a circular cylinder I found that this is not a satisfying approximation. Cylinder diameters ranging from 5% to 160% of the airfoil cord and Reynolds number (based on the cord) from 2000 to 20000 have been simulated using the Navier Stokes solver discussed above. It appeared that the amplitude and shape of the pressure distribution along the airfoil is significantly affected by the Reynolds number, with some configurations resulting in wave packets propagating along the boundary layer. The discrepancy between the viscous and inviscid pressure estimates is due to the boundary layer along the airfoil. Steady state potential flow solvers are traditionally improved by adding some thickness (the displacement thickness) to the solids in order to compensate for the boundary layer caused by viscosity. If the boundary layer is thin, as is the case at high Reynolds number, the addition of the displacement thickness does not significantly affect the pressure, which is why the inviscid approximation is usually good. However, when the airfoil passes an obstacle, the displacement thickness has to dynamically adjust to the changing flow. The local acceleration of the displacement thickness affects the pressure distribution along the airfoil more than the static displacement thickness. I have shown that the flow field around an airfoil passing a cylinder can be approximated by the superposition of a steady-state flow (that only needs to be calculated once), an inviscid perturbation due to the obstacle (that is easy to calculate with the Euler equation) and dynamic changes to the boundary layer [2].

The dynamics of the boundary layer can be understood by locally simplifying the Navier Stokes equation assuming the velocity field experiences small variations in the streamwise direction and the normal component of the velocity is much smaller than the tangential component. Further assuming the changes in the boundary layer are small, the equation can be linearized, resulting in the Orr-Sommerfeld equation. Using linear stability analysis of the boundary layer, I have found that the aft portion is convectively unstable, meaning that disturbances of certain wavelengths are exponentially amplified as they are convected downstream along the boundary layer in the form of wave packets. Using the potential flow solver to estimate the initial disturbance of the boundary layer, the Orr-Sommerfeld equation is easily solved to estimate its growth and propagation speed. The dynamics of the boundary layer thus estimated can then be fed back to the potential flow solver in order to significantly improve its accuracy at a very low cost.

Significance and impact

Advancing the state-of-the-art IB CFD methods has been crucial to this project as I am now able to accurately simulate the encounter of a fish and an obstacle at the Reynolds numbers found in nature. The tool can also be valuable for studying other exciting themes such as animal swimming and flying, vortex induced vibration, etc. Understanding how viscosity affects the pressure distribution along a vehicle passing an obstacle sheds light on major differences between the use of pressure sensing for small fish and full size submarines. Finally, identification of the role played by the dynamics of the boundary layer and how it can be estimated constitutes a major advance toward the possible use of distributed pressure sensing for obstacle identification. Combining the inviscid approximation outside the boundary layer and the Orr-Sommerfeld equation near the body has the potential for providing a reasonably accurate simplified model practical for real-time applications.

Where might this lead?

The lateral line is a simple sensory system that fish can use intuitively. Though I do not believe in the need to exactly reproduce the lateral line of fish, the idea of taking best advantage of the surrounding medium (here, water) to sense its environment is an interesting idea that will probably be used by underwater vehicles in the future. If cheap sensors inspired from the lateral line were available, they could foster the emergence of a new kind of small inexpensive Autonomous Underwater (AUVs). Since an important limitation in the use of current AUVs is their price, such small AUVs could become invaluable tools for ocean sciences as well for the off-shore industry.

2. A list of all archival journal papers or scholarly reports.

Publications:

[1] Audrey Maertens, Gabriel Weymouth. Accurate Cartesian-grid simulations of near-body flows at intermediate Reynolds numbers. *Journal of Computational Physics*. Under review.

Talks:

[2] Audrey Maertens, Gabriel Weymouth, Michael Triantafyllou. Limits of the potential flow model for obstacle detection and identification using a lateral line. *65th Annual Meeting of the APS Division of Fluid Dynamics, November 18-20, 2012; San Diego, California*.

3. A statement of how discretionary funds were spent.

Discretionary funds have been used to travel to present my work at the APS conference in San Diego and contributed to the purchase of a desktop for running simulations.

4. How did the Fellowship make a difference?

I was awarded the Fellowship at a crucial time in my PhD when many doors were still open for me. The award convinced me to pursue in the direction I had chosen for myself, without having to worry about funding. Furthermore, it made me aware of the underlying community supporting this field of research, and fostered my long-term professional commitment to the development of new tools for the study of the ocean and engineering applications.