Fluid-structure interaction with multi-body collision: application to collective fish swimming in an impermeable or porous enclosure

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Abstract: Modeling and numerical simulations of fish like swimming in open domains have been largely studied other the last decade. Here we propose to to further considering possible contacts between several fishes and between fishes and an external boundary, called enclosure. The enclosure can be impermeable or porous giving rise to different swimming behaviors.

Keywords: Fluid-structure interactions, Numerical simulation, incompressible flows, self-propelled swimming, lubrication and collision models.

1 Introduction and context of the study

Several numerical simulations of an individual fish-like swimmer as well as fish schooling have already been performed en 2D [2] and more recently in 3D [3]. The possible contacts and collisions between (non-spherical) active swimmers has however, to our knowledge, never been taken into account. We consider a flow configuration with several swimmers immersed in a small enclosure where collisions necessarily occur.

We have developed a digital twin of the experimental set up proposed by Hamid Kellay's group in Bordeaux. The swimmers have an unsteady imposed swimming law (shape deformation), and the enclosure can either be impermeable or porous. A global displacement of the porous enclosure is also possible. Depending on the experimental set-up (enclosure permeability and number of swimmers), different organization behaviors are observed in the experiments. The goal of our numerical model is to give insights and quantitative explanations of these experimental observations.

2 Problem statement and preliminary results

The fish shape ($\ell = 7.6$cm, see figure 1 left) and swimming law, as well as the enclosure size (diameter $D = 15$cm), are defined to be as close as possible to the experimental set-up. The numerical simulations are performed using a fictitious domain approach with Volume Penalization [1], where the governing equations are solved on a fixed Cartesian mesh. The unsteady positions of the N swimmers are defined by the characteristic functions[1] χ_i associated with

[1] $\chi = 1$ inside the body considered i and $\chi_i = 0$ outside.

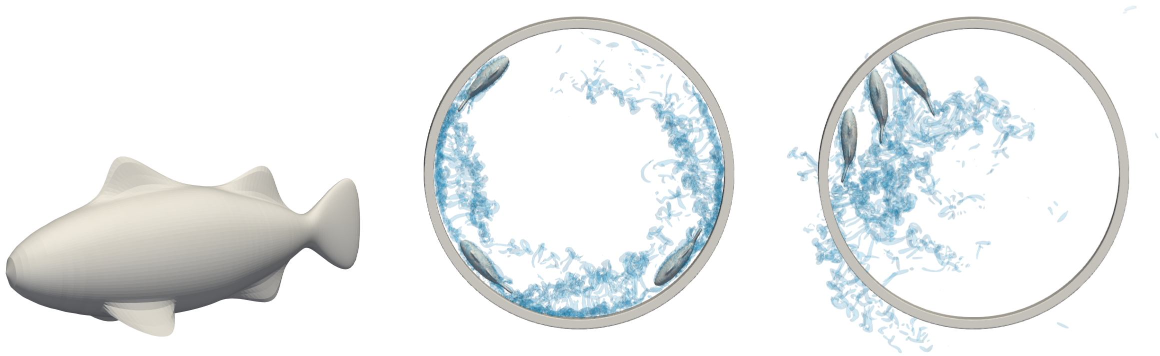

Figure 1: Fish shape (left) and top view for three fishes behaviors in impermeable (middle) and porous (right) enclosures.

low permeability ($\varepsilon = 10^{-8}$). The position of the enclosure is defined by χ_r associated with variable permeability ($10^{-8} < \varepsilon_r < 10^{8}$). Let us consider the three-dimensional incompressible Navier-Stokes equations (1) written in a domain Ω including the enclosure:

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla})\boldsymbol{u} = -\frac{1}{\rho}\boldsymbol{\nabla} p + \frac{1}{\rho}\boldsymbol{\nabla} \cdot \mu(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T) + \sum_{i=1}^{N} \frac{\chi_i}{\varepsilon}(\boldsymbol{u}_i - \boldsymbol{u}) + \frac{\chi_r}{\varepsilon_r}(\boldsymbol{u}_r - \boldsymbol{u}), \tag{1a}$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{u} = 0. \tag{1b}$$

The rigid motions of the fishes $\boldsymbol{u}_i$ and the enclosure $\boldsymbol{u}_r$ (if permeable) are computed from the forces and the torques exerted by the fluid onto the body plus some corrections based on lubrication models. These corrections are computed from local lubrication and collision models allowing interactions between non-spherical particles recently developed in [4, 5]. Numerical solutions are obtained with the in house massive parallel solver *NaSCar*.

Preliminary results for different kind of enclosures are reported in Figure 1. Numerical results are in good agreements with recent experimental results obtained by Hamid Kellay's group. For impermeable enclosure, fishes are swimming in an individual way, almost parallel to the enclosure. For the porous case, fishes are swimming in a (almost) stable group organisation with an average angle approximatively equal to $\pi/4$ with the enclosure. Further developments include elastic enclosures: 2D results have already been obtained with Eulerian Mooney Rivlin elasticity.

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