Coupled simulation of valve motion and cavitation
Application to mechanical heart valve

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Abstract

The Immersed Boundary Method is studied in order to be applied in problems of cavitating flows through complex geometries or moving boundaries, as the one of bi-leaflet Mechanical Heart Valve (MHV). Two different approaches have been tested on two benchmark cases of incompressible flows and the results have been compared with the ones found in literature. The two methods seem promising but ask for further refinement and validation in more complex flows, in order to be mature enough to be used in fluid-solid body interaction problems. OpenFOAM has been chosen as the working environment.

Introduction

During the operation of MHV, static pressure drops are observed when the leaflets close, and cavitation is induced, that, apart from erosion on the metal leaflets, causes also chemical changes in blood that may lead to thrombosis. In this complex problem, we aim to model the moving MHV parts in means of Immersed Boundaries, resulting in simpler mesh and shorter computation time, avoiding conformal to the boundary meshes and re-meshing due to moving or altered mesh parts.
The Immersed Boundary Method, applies on a simple, non conformal, mesh, and models the influence of the boundary on the flow, by either introducing a forcing term or blanking the computational cells enclosed by the boundary.
Two IB approaches are investigated in this study, according the categorization by Mittal and Iaccarino, one "continuous" method, which adds a source term at the momentum equation, and one "discrete", which blanks the IB area and interpolates field variables to near cells.

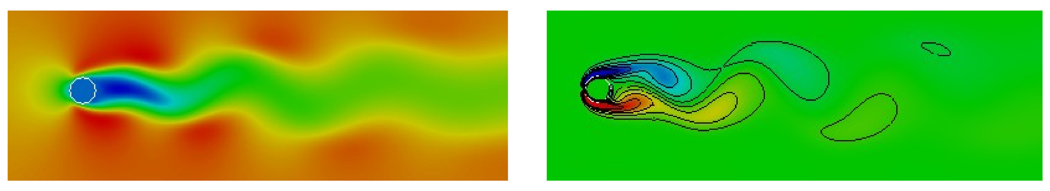

Figure 1. Velocity (left) and vorticity (right) for flow past cylinder, at Re=100, using Discrete IB Method.

Table 1. Characteristic numbers for incompressible flow around cylinder at Re=100, compared with literature.

	CD	CL	Str
Braza	1.366	±0.25	0.16
Ding	1.356	±0.287	0.166
IB Discrete	1.25	±0.175	0.1337
IB Continuous	1.195	±0.161	0.132
OF Conformal	1.3	±0.22	0.14

Methods

There is already an IB implementation in OpenFoam-extend, which can be categorized as a "Discrete Direct" method, where the IB area is blanked, thus not solved, and either Dirichlet or Newmann boundary conditions are applied to cells cut by the interface, based on interpolation of field values of nearby cells and the values set by the IB.
Additional, an other method is being developed, which falls into the "Continuous" methods category.
According to this approach, we model the IB by introducing a source term of the form

$$F_{ib}=k\cdot\left(U-U_{adjusted}\right)\cdot Mask_{ib}$$

with $U_{adjusted}$ being either the IB velocity or an interpolation or approximation of it. We use a mask, so as to apply this source term only on the area of the IB. This method has already been tested on ANSYS Fluent and gives promising results, in incompressible, compressible and even cavitating flows.

Results

The two methods have been tested on simple two dimensional benchmark cases of incompressible flow past a stationary cylinder and oscillating cylinder in incompressible fluid at rest, both at Re=100. For the oscillation KC=5 has been chosen. Results have been compared with the literature.
Three meshes with different densities have been tested, of cells sizes that correspond to 5%, 2.5%, 1.25% of the diameter D of the cylinder, in an square area 6Dx6D around it.
Results show dependence on mesh density regardless the method.
Velocity field follows the observed patterns but fails to predict the same maxima and match experimental data.
The C_L and C_D prediction is not satisfactory by both methods and the Strouhal Number not high enough.

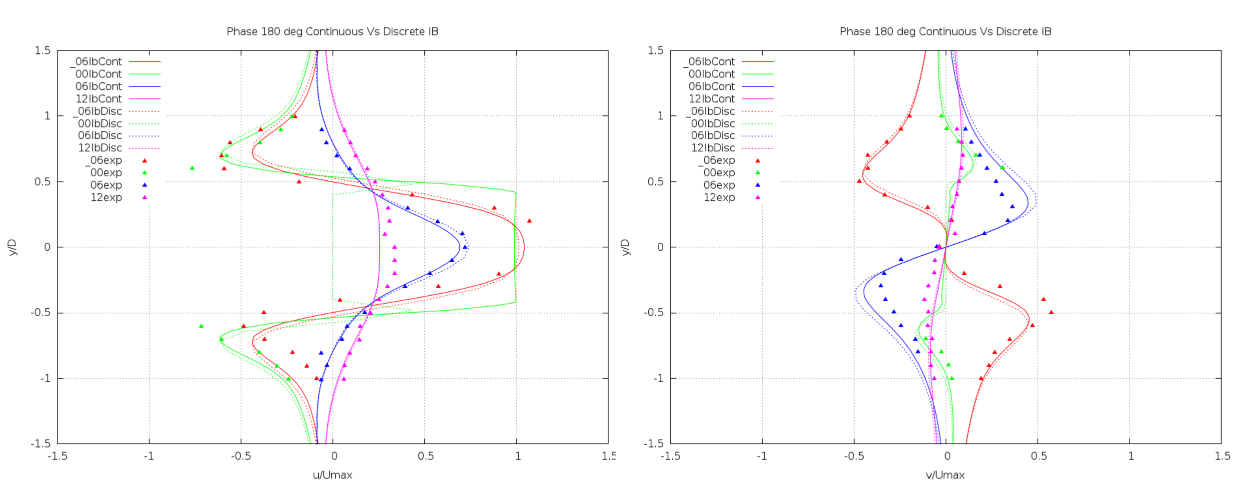

Figure 2. U_x (left) and U_y (right) velocity profiles comparison between "Discrete" (*dashed line*) and "Continuous" (*continuous line*) IB method, for coarse mesh, with experimental data from Dutsch[5] (*points*).

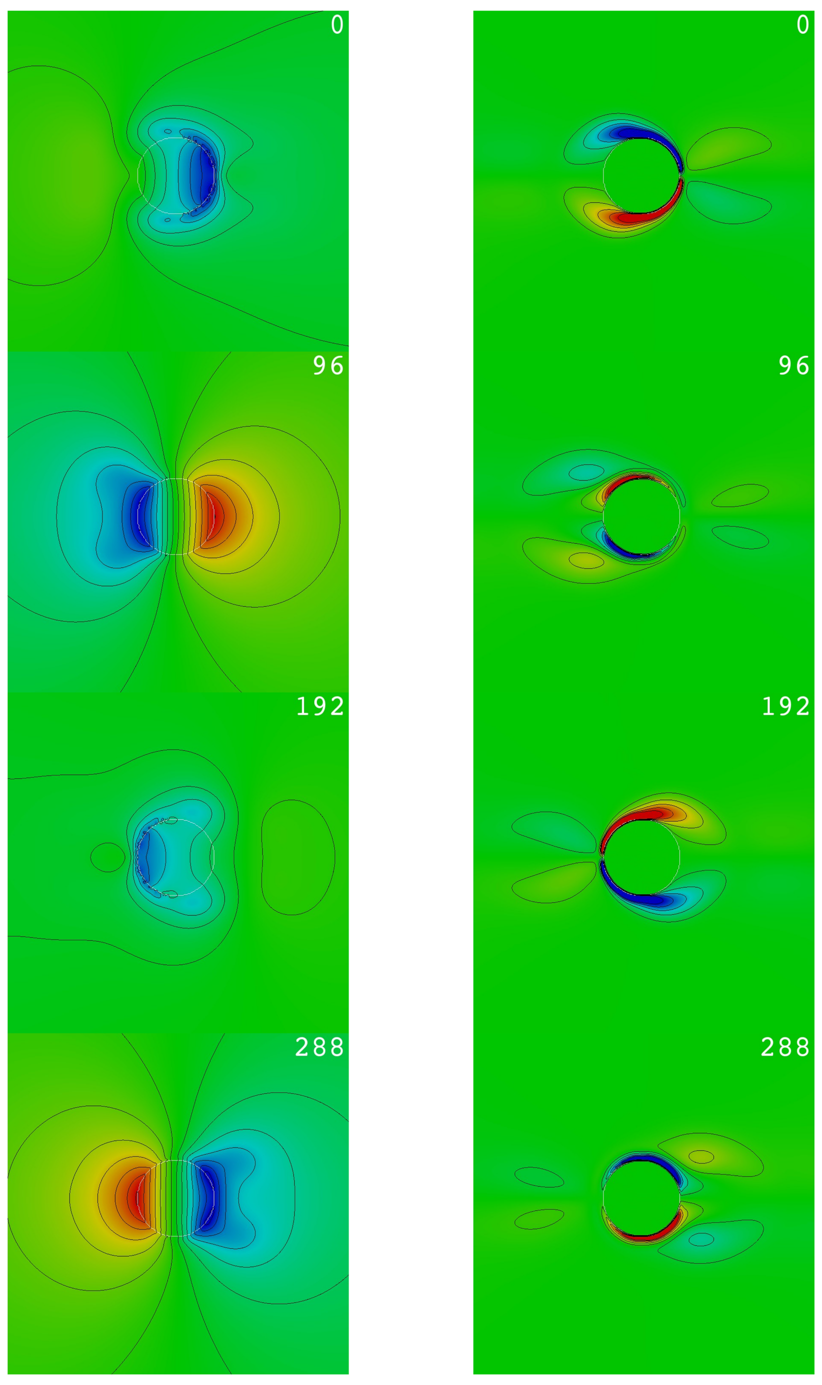

Figure 4. Pressure (left) and vorticity (right) contours at four different phase angles, for in line oscillating cylinder in incompressible fluid at rest, with Re=100 and KC=5, using continuous IB method .

Discussion

The aim of this PhD is to use the IB method for a moving body, and thus accuracy and smoothness in forces calculation is important for the convergence of the solution.
A dense mesh seems to help in this direction so re-meshing following the moving interface should be investigated.
The application of a continuous mask seems also to give better results.
Numerics have to been taken into account also.
Next steps include tests on multiphase and cavitating flows, compressible flows, higher Mach numbers flows.
Interpolation schemes for cells near the IB interface will be studied as well.

Conclusions

Immersed Boundary Method proves a good alternative for demanding simulations with complex geometries.
Mesh quality near the IB interface proves to be a key parameter for good results.
Different techniques are being tested in order to determine the best to address problems of multiphase cavitating flows and moving geometries.
The gains in mesh generation and computational cost are great motivation for further study and improvement of the current techniques or even development of new ones, like cut cells methods.

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