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Abstract: A coupling of vortex methods with penalization method is proposed in this work in order to accurately and easily handle solid-fluid-porous media. This immersed boundary approach indeed maintains the efficiency and the robustness of vortex methods and allows to model the three different media without prescribing any boundary condition. In this paper, we propose an application of this immersed boundary method to passive flow control past a semi-circular cylinder, realized adding a porous sheath around the obstacle in order to smooth the flow dynamics.

The numerical model

In this work, flow simulations are based on particle methods. The fluid particles which are displaced by convection, stretching and diffusion are characterized by their position and their vorticity. The vorticity transport is expressed by the Vorticity Transport Equation, obtained taking the curl of the incompressible Navier-Stokes equations and expressed as follows, where one can distinguish the advection, the stretching and the diffusion terms:

$$\frac{\partial \boldsymbol{\omega}}{\partial t} + (\mathbf{u}\cdot\nabla)\boldsymbol{\omega} - (\boldsymbol{\omega}\cdot\nabla)\mathbf{u} = \frac{1}{\mathrm{Re}}\Delta\boldsymbol{\omega} \quad \text{in } D, \tag{1}$$

where $\boldsymbol{\omega}$, $\mathbf{u}$, Re and D respectively denote the vorticity, the velocity, the Reynolds number and the computational domain. This equation is approximated using a remeshed Vortex method [1]. The latter is very robust and low-cost to simulate high Reynolds number recirculating flows. It relies on approximating separately the different terms at each time step. The convective part is solved using a "Vortex-In-Cell" (VIC) method with a semi-Lagrangian resolution: the fluid particles are displaced with the convective velocity and then remeshed on the original grid in order to avoid Lagrangian distortion. The stretching term is solved on the grid through a 4th order FD scheme. Finally diffusion and Poisson equation, given by $\Delta\mathbf{u} = -\nabla\times\boldsymbol{\omega}$ and allowing to recover velocity from vorticity field, are also solved on the grid, using Fast Fourier Transforms.

This work is devoted to the study of flows in solid-porous-fluid media and the method used to handle such problems is the vortex penalization technique. This method appears as a very good approach since it involves a unique equation for the whole domain. The latter is the non-dimensional Brinkman-Vorticity Transport Equation obtained from Eq. (1) by adding a penalization term and expressed as:

$$\frac{\partial \boldsymbol{\omega}}{\partial t} + (\mathbf{u}\cdot\nabla)\boldsymbol{\omega} - (\boldsymbol{\omega}\cdot\nabla)\mathbf{u} = \frac{1}{\mathrm{Re}}\Delta\boldsymbol{\omega} + \nabla\times[\lambda\,\chi_S(\mathbf{u}_s - \mathbf{u})] \quad \text{in } D, \tag{2}$$

where λ essentially depends, in the inverse proportion, on the intrinsic permeability k of the medium. Varying the λ value thus directly defines the different media. Indeed, in the fluid, the intrinsic permeability coefficient k goes to infinity, thus the fluid can be considered numerically as a porous media with a very high permeability. We set $\lambda = 0$ in this region. On the contrary, the solid has a permeability coefficient k which goes to zero, it can be consequently modeled setting the penalization parameter λ to a very high value. In this study λ equals 10^8 in the solid. It was proved in [2] that solving Eq. (2) with such a value of λ was equivalent to solve Darcy's law in the solid. Furthermore, setting the λ parameter to an intermediate value,

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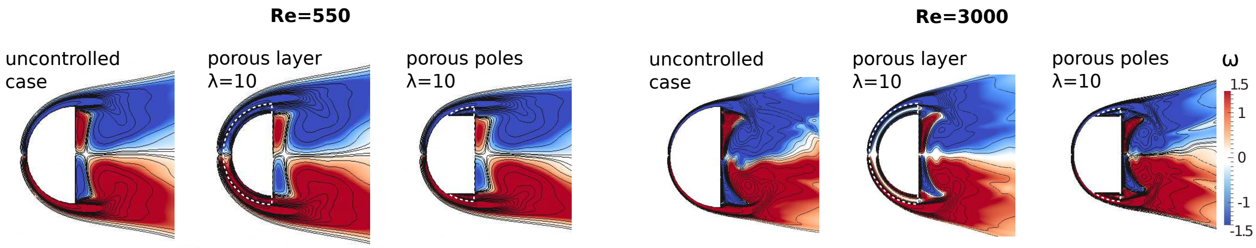

Figure 1: Zoom of the mean vorticity fields and isolines at Re = 550 and Re = 3000.

reasonably chosen between these two extreme values ($\lambda = 0$ and $\lambda = 10^8$), would model a porous medium in which the flow has a Darcy velocity. The accuracy and efficiency of the penalization method come from its capability to take into account these variations of λ and to capture the induced steep velocity variations at the different interfaces with a minimum number of discretization points.

Application to passive flow control in 2D

Here, the solid-porous-fluid configuration is applied to cover a semi-circular cylinder geometry with a porous coating in order to decrease the shear forces applied on this body and to smooth the flow dynamics [3]. The semi-circular cylinder can be considered as a simplified section of an outside rear-view mirror of a car or a motor cycle. The subsequent flow control simulations are performed at transitional (Re = 550) and highly transitional regime (Re = 3000) in a 2D computational domain. In order to analyze the effects of our control approach, we compare global flow quantities like the drag force (F_D) and the enstrophy (Z), expressed as $Z = \int_D |\boldsymbol{\omega}|^2 \, \mathrm{d}\mathbf{x}$, allowing to measure the dissipation effects in the flow. A parametric study considering different values of λ in a surrounding porous and homogeneous layer was achieved in order to determine the influence of the permeability on the control efficiency. This study shown that setting $\lambda = 1$ (high permeability) inside the layer, clearly appears as the best solution compared to uncontrolled case for both regime in terms of flow regularization (F_D : -29% at Re=550 and -6% at Re=3000, Z: -38% at Re=550 and -29% at Re=3000). Nevertheless, the position of the permeable zone also has a great importance in passive control effects. To illustrate this statement, we perform a comparison between the porous layer configuration and the "porous poles" configuration where the permeable zone is only located on top and bottom of the semi-circular cylinder, i.e in the vicinity of the detachment points. For manufacturing easiness we choose to set these poles to an intermediate permeability, $\lambda = 10$. And surprisingly, the results obtained with the "porous poles" device are very satisfactory. Figure 1 indeed shows that it allows an eddy detachment from the wall and a decrease of the transverse dimension of the wake implying a drag force reduction, which is about 23% at Re=500 and 7% at Re=3000 (more than the $\lambda = 1$ porous layer case).

Conclusion and Future Work

In this work, a hybrid vortex-penalization method is proposed in order to easily carry out complex flows involving solid-fluid-porous media. An application to passive flow control past a semi-circular cylinder is performed at transitional and highly transitional regimes, showing the emergence of a very suitable "porous-poles" device. This preliminary 2D study can be useful to supply information on general trends for a control. However, such a flow is three-dimensional and this 2D study should be complemented by 3D computations to get qualitative physical results. These on-the-way 3D results will be presented at the conference.

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