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Vorwort

Das Tätigkeitsfeld des Fraunhofer-Instituts für Techno- und Wirtschaftsmathematik ITWM umfasst anwendungsnahe Grundlagenforschung, angewandte Forschung sowie Beratung und kundenspezifische Lösungen auf allen Gebieten, die für Techno- und Wirtschaftsmathematik bedeutsam sind.

In der Reihe »Berichte des Fraunhofer ITWM« soll die Arbeit des Instituts kontinuierlich einer interessierten Öffentlichkeit in Industrie, Wirtschaft und Wissenschaft vorgestellt werden. Durch die enge Verzahnung mit dem Fachbereich Mathematik der Universität Kaiserslautern sowie durch zahlreiche Kooperationen mit internationalen Institutionen und Hochschulen in den Bereichen Ausbildung und Forschung ist ein großes Potenzial für Forschungsberichte vorhanden. In die Berichtreihe werden sowohl hervorragende Diplom- und Projektarbeiten und Dissertationen als auch Forschungsberichte der Institutsmitarbeiter und Institutsgäste zu aktuellen Fragen der Techno- und Wirtschaftsmathematik aufgenommen.

Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Dieter Prätzel-Wolters

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

A goal oriented survey on immersed boundary methods

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Abstract

Solving flow problems in complex-shaped geometries is required in many scientific and practical problems. The choice of the discretization method, especially in practical problems, is governed by a number of criteria, which often do differ for the specific applications. Those criteria include different combinations of specific accuracy and robustness requirements for the solvers, for the grid generators, for the CPU time, for the qualification of the developers, for the qualification of the users, and so on. Having in mind developing a fast and moderately accurate algorithm for simulation of the thermal stratification in containment pools of nuclear power plants, we carry out a systematic discussion on the discretization methods which can satisfy the specific requirements for this problem, and at the end explain our choice.

Key words: immersed boundary method, survey, fictitious domain method, containment pool simulation

1 Introduction

1.1 Motivation

Solving flow problems in complex-shaped geometries is required in many scientific and practical problems. In such situation boundary fitted grids theoretically allow for achieving higher accuracy, but at the same time can face severe difficulties in developing robust grid generators. The alternative is to discretize the governing equations on a Cartesian, taking special care for the discretization near the boundaries. The choice of the discretization method, especially in practical problems, is governed by a number of criteria, which often do differ for the specific applications. Those criteria include different combinations of specific accuracy and robustness requirements for the solvers, for the grid generators, for the CPU time, for the qualification of the developers, for the qualification of the users, etc. Our task was developing a fast and moderately accurate algorithm for simulation of the thermal stratification in containment pools of nuclear power plants, NPP. The algorithm has to be really fast in order to allow the simulation of many scenarios, related to NPP safety analysis. Grid generation has to be very easy and robust, in order to allow the usage of the software from engineers without, or with little experience in CFD. As a starting point, we decided to stick to Cartesian grid. This paper is a result on our review of the literature in this area. It should be noted that there exist excellent reviews on IB methods, e.g., [MI05], but they did not provide systematization according to our criteria (see below), and therefore we had to perform an own review. Mostly immersed boundary methods, IBM, and fictitious domain methods, FDM, are used for solving flow problems on Cartesian grids in complex shaped geometry. While there is no big variety of FD methods, a number of IB methods were developed during the years. The paper reflects this fact by spending most of the time on systemizing and classifying IB methods. At the end we perform some numerical simulations on a classical test problem, aiming to understand if immersed boundary and fictitious region method give similar accuracy for the quantities which are of interest for us (the pressure drop is one of them). Our final choice is the fictitious domain method, because at comparable accuracy it over performs IBM with its simplicity and robustness.

1.2 Immeresed boundary method: preliminaries

Peskin introduced in 1972 a concept of immersed boundary (IB) method [Pes72] where he used this method to compute flow patterns around heart valves. The main feature of this method was that in contrast to methods where body-fitted grid was used in order to represent accurately the immersed body geometry, the simulation was performed on Cartesian grid (Eulerian coordinate system) while the immersed boundary was represented by a set of elastic fibers, which moved with local flow velocity (Lagrangian coordinate system).

Depending on the way how boundary conditions are imposed IB methods can be divided into following categories:

- continuous forcing methods,
- discrete forcing methods,
- ghost cell immersed boundary methods,
- cut-cell methods.

We will review the methods using following criteria list:

- *Type of Cartesian grid it deals with: staggered grid or collocated grid.* On a staggered grid, the velocity components are stored at the cell face and the scalar variables such as pressure are stored at the central nodes in contrast to the collocated grids, where all parameters are defined at the same location at the central nodes. The advantage of staggered grids is more accurate pressure gradient estimation. Type of a grid is an important issue especially when it is planned to incorporated IB method to the existing code.
- *Does it focuses on moving boundaries or on static boundaries?* As was mentioned before the reason of developing immersed boundary method is to have an accurate representation of a boundary, but in a more efficient way than using body-fitted grid. Main drawback of body-fitted grid is that generation of such grid is time consuming. This drawback impacts more in case of simulations with moving boundaries, because grid should be adapted to the new position of the boundary. So when such type of simulations is required one may benefits a lot from switching to the immersed boundary method.
- *What number of dimensions does it support?* As in a case of grid type when IB method is chosen in order to be incorporated in an existing software it is important to know does it support required number of dimensions.
- *Does it satisfy mass conservation law?* The law of conservation of mass, states that the mass of an isolated system (closed to all matter and energy) will remain constant over the time.

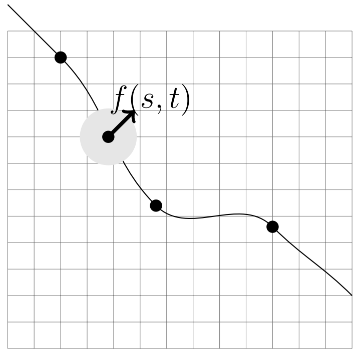


Figure 1: Shaded region is the area of force spread from fibers point.

> Therefore if the method violates conservation law it can lead to the unphysical behavior. In immersed boundary methods solid boundaries are not described by the mesh, but treated in a separate way. Therefore there is no guarantee that normal velocity is zero in impermeable walls. Thus the immersed boundary method should take special care to control mass conservation.

The remainder is organized as follows in sections 2, 3, 4, 5 we will give an overview of the IB methods from categories listed above. At the end of each section we summarize in a table answers for each criteria from the list. As attentive reader might notice, in our criteria list we've payed attention to the fact how easy it is to incorporate a particular IB method into existing code. Another class of methods for solving flow problems on Cartesian grid is the fictitious domain (FD) method. One of its distinguish feature is ease of implementation,therefore FD method is suitable when one need to get working software fast. In section 6 we provide short summary on FD formulations for flow problems. In section 7 we will provide results from comparing numerical solution for flow around cylinder obtained by an IB method and by FD method. Finally, in 8 some conclusions are drawn.

2 Continuous forcing approach.

Series of papers [Pes72, Pes77, Pes82, PM80, PM89a] written by the group of C. Peskin introduces a continuous forcing approach for elastic boundaries. They consider simulation of a viscous incompressible fluid in a region containing immersed boundaries which interact with the fluid. The fluid motion is governed by Navier-Stokes equations:

$$\mathbf{u}_t + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla^2 \mathbf{u} + \mathbf{F} \tag{1}$$

$$\nabla \cdot \mathbf{u} = 0 \tag{2}$$

The boundary configuration is described by the curve $\mathbf{x}(s,t)$, where each value of a parameter s has a corresponding physical point of the boundary for all times t. The equation of motion of the boundary follows from the fact that boundary moves with the local flow velocity:

$$\mathbf{x}_t(s,t) = \mathbf{u}(\mathbf{x}(s,t))$$

The effect of immersed boundary is incorporated by transferring the fiber stress to the fluid. The forces which the fiber boundary exerts on the fluid are described by function $\mathbf{f}(s,t)$. The force field $\mathbf{F}$ can be derived from constitutive law (e.g. Hooke's law):

$$\mathbf{F} = \int_{\Gamma} \mathbf{f}(s,t)\delta(\mathbf{x} - \mathbf{x(s)})ds, \tag{3}$$

$$\mathbf{f} = \mathbf{M}(\mathbf{x}),$$

where δ is Dirac delta function, $\mathbf{M}$ is a non linear operator describing the elastic properties of the boundary. For the construction of difference equation from equation 3, special care should be taken for discrete representation of the δ function. This representation should appear from the fact that fiber stress in Lagrangian point is spread over surrounding grid nodes (see figure 1). Therefore the sharp delta function is replaced by smoother distribution function d, which is suitable for use on a discrete mesh:

$$\mathbf{F} = \int_{\Gamma} \mathbf{f}(s,t)d(\mathbf{x} - \mathbf{x(s)})ds \tag{4}$$

Various variants of distribution functions were developed over the years, for details see [SB96, LP00, BL92].

This method has been applied to variety of problems in two and three space dimensions, including blood flow in the heart [PMY82, PM89b], the design of prosthetic cardiac valves [PM83], platelet aggregation during blood clotting [Fog84], aquatic animal locomotion [FP88] and many others. In [PP93] is mentioned that from time to time volume conservation in this type of methods is not exact.

Peskin's method is well suited for elastic bodies but has a limitation in case of rigid bodies. The origin of this limitation is in the application of a constitutive laws, namely Hooke's law (see equation (3)), which is not well posed in the rigid limit. One way to deal with this problem is to assume that the body is elastic, but extremely stiff, see e.g. the discussion in [MI05].

Another approach which allows to handle rigid boundaries, called *virtual boundary method*, was introduced in [GHS93, GHS95]. The main idea of the virtual boundary method is to treat the body surface as a virtually existing boundary embedded in the fluid. The force filed from the boundary if formulated in a way that no-slip condition is handled on the surface.

As before, body surface is denoted by $\mathbf{x}(s,t)$. The force on the element of surface $\mathbf{f}(s,t)$ is determined by the requirement that the fluid velocity $\mathbf{u}(\mathbf{x},t)$ should satisfy the no-slip condition on the boundary:

$$0 = \mathbf{u}(\mathbf{x}(s,t),t) = \int_{\Omega} \mathbf{u}(\mathbf{x},t)\delta(\mathbf{x} - \mathbf{x}(s,t))d\mathbf{x}$$

The body force is not known a priori, thus it must be calculated in a feedback way, so that the velocity on the boundary is used to determine the desired force [LP00]. In the virtual boundary formulation, the force is governed by the following feedback loop:

$$\mathbf{f}(s,t) = \alpha \int_0^t \mathbf{u}(\mathbf{x}(s,t),\tau)d\tau + \beta\mathbf{u}(\mathbf{x}(s,t),t),$$

where $\mathbf{u}$ is the fluid velocity at surface points, α, β are negative constants, chosen in such a way that $\mathbf{u}$ stays close to zero. This method was used for simulation of the two-dimension flow around a circular cylinder, three-dimensional plane- and ribbed-turbulent channel flow.

The main disadvantage of the virtual boundary method is that it contains two free constants that need to be tuned according to the problem being solved. In particular, for unsteady flows this forcing introduces a time step limitation that reduces the efficiency of the algorithm. Another disadvantage of the described method is that, in order to avoid equation stiffening and unphysical

Table 1: Summary table for continuous forcing methods.

Criteria	[Pes72], [Pes77], [Pes82], [PM80], [PM89a], [PP93]	[GHS93, GHS95]	[SB96]
Type of Cartesian grid	coll.	coll.	stagg.
Support moving boundaries	yes	-	yes
Two- or three-dimensions[1]	3D	3D	2D
Conservation of mass	yes	-	-

flow oscillations, the boundary forcing terms are spread across the boundary which therefore is smeared over the grid, thus decreasing the solution accuracy [GI03].

In [SB96] a modification of the forcing method, such that spurious oscillations caused by feedback forcing are eliminated, was suggested. Modified forcing function proposed there has a following form:

$$\mathbf{f}(s,t) = \alpha \int_0^t (\mathbf{u}(\mathbf{x}(s,t),t)dt - \mathbf{v}(\mathbf{x}(s,t),t)) + \beta(\mathbf{U}(\mathbf{x}(s,t),t) - \mathbf{v}(\mathbf{x}(s,t),t)), \tag{5}$$

where the velocity of the boundary is controlled by specifying velocity field $\mathbf{v}$ at the boundary points. In case of moving boundary ($\mathbf{v} \neq 0$) the position of the boundary point at each time step is computed by the integration of $\mathbf{v} = d\mathbf{x}(s,t)/dt$.

Thereby continuous forcing approach is a good choice when flow with elastic boundaries has to be simulated, but when flow problems involve rigid bodies then continuous forcing approach can lead to a stiff numerical system. Also, this type of methods unable to give for a sharp representation of the boundary, because of the smoothing of the forcing function.

3 Discrete forcing approach.

The idea of discrete forcing approach has first appeared in the work [MY97]. To describe that idea let us consider Navier-Stokes equations (1, 2). In this method the forcing term has to be defined in a way that the velocity $\mathbf{u}$, tends to a desired value $\mathbf{v}$ on some immersed boundary Γ . If we know the velocity $\mathbf{u}$, then the forcing term is simply:

$$\mathbf{F} = \begin{cases} \mathbf{u}\cdot\nabla\mathbf{u} - \nabla^2\mathbf{u} + \nabla p + \frac{1}{\Delta t}(\mathbf{v} - \mathbf{u}^n), & \text{on } \Gamma \\ 0, & \text{elsewhere} \end{cases} \tag{6}$$

Most of the discrete forcing methods follow this idea on the continuous level, but differ on a discrete one. In general, the equation for the forcing (6), would be correct if the position of the unknowns on the grid coincide with that of the immersed boundary. In general this is not true because it would require the boundary to lie on coordinate lines or surfaces which is not the case for complex curvilinear geometries. Therefore, an interpolation procedure is needed [FVOMY00]. For completeness, let us provide few examples of such interpolations.

[1] 3D in most of cases means that method also supports 2D

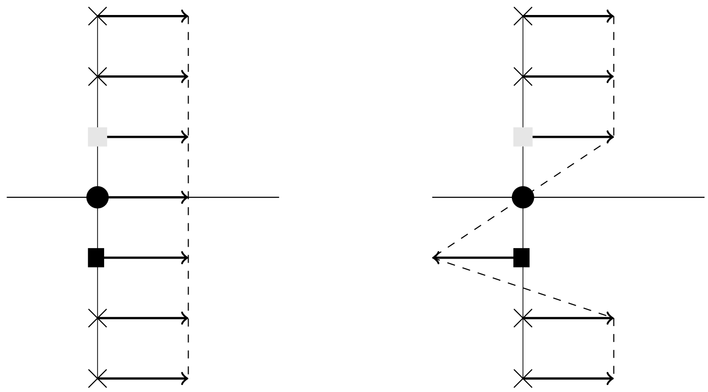


Figure 2: Sketch showing the effect of forcing. (a) initial velocity field, (b) velocity field imposed by forcing.

In [MY97], forcing is applied to the grid points immediately inside the immersed boundary. As example, let us consider no-slip walls, so the velocity at the point immediately interior to the surface is forced to be reverse of the velocity at the point immediately exterior to the surface with interpolation. This approach is also called *mirroring*. In the figure 2 the effect of forcing is shown.

As shown in [FVOMY00], methods based on mirroring satisfy the velocity boundary conditions with the accuracy of the interpolation method. In [MvW08] it was reported that due to the reverse velocity field in the boundary cells, problems with mass conservation can arise. Furthermore, an adaptation of the method from [MY97] was given in [FVOMY00].The main difference between methods introduced in [MY97] and [FVOMY00] is in the interpolation procedure. In the proposed method the forcing is introduced at the first grid point outside the body using the velocity (u_i in figure 3) obtained by linearly interpolating the velocity at the second grid point (u_{i+1}) and the desired velocity ($\mathbf{v}$). The interpolation direction (the direction towards the second grid point) is either the stream-wise (x) or the transverse (y) direction. The wrong choice of the interpolation direction can generate problems in complex configurations.

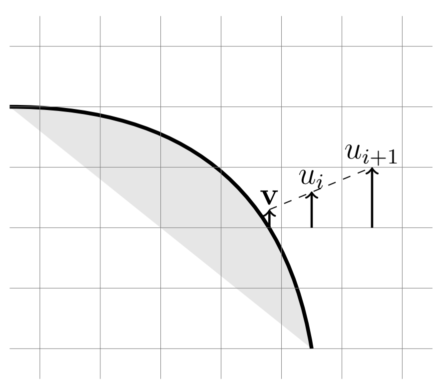


Figure 3: Velocity interpolation proposed in [FVOMY00].

In the approach presented in [FVOMY00], mass conservation at the immersed boundary is satisfied by the velocity fields both in fluid and solid regions. In this case, the (nonphysical) velocity field in the solid becomes important because it affects the pressure and velocity distribution through the velocity divergence across the immersed boundary. For the method proposed in [FVOMY00] this issue can become very serious, since treatment of the velocities at the first grid points into the solid region is notionally undefined [KIHM09].

In [KKC01] an approach for enforcing mass conservation in cells crossed by immersed boundary was proposed. The momentum forcing and mass source/sink in continuity equation were used to enforce the no-slip boundary conditions on the immersed boundary and to satisfy the continuity for the cells containing the immersed boundary. Let us shortly discuss the proposed mass source/sink approach. In [KKC01], along with the momentum forcing, authors introduced modified version of the continuity equation:

$$\nabla \cdot \mathbf{u} - q = 0, \tag{7}$$

where q is mass source/sink is defined at cell center on the immersed boundary or inside the body. On a discrete level the source term has the form:

$$q = \frac{1}{\Delta V} \sum_i \omega \mathbf{u} \cdot \mathbf{n} \Delta S_i, \tag{8}$$

where ΔV is the cell volume, ΔS_i is the area of each cell face, and $\mathbf{n}$ is the unit normal vector outward at each cell face. Furthermore, ω equals to 1 in the points where momentum forcing is applied and 0 everywhere else. Thus, on a discrete level sinks and sources are incorporated in a way that the total sum of the volume fluxes due to the mass sources over the computational domain is zero and the global mass conservation is satisfied.

It is shown in [KKC01] that mass source/sink term improves the quality of the solution and corrects the non-physical behavior. However, it was observed in [HS07] that the approximation used in [KKC01], namely that the grid points fall on the immersed boundary when calculating the mass source/sink term, may lead to a degradation of the quality of the solution. In order to solve this problem, in [HS07] authors derive more accurate representation of the source/sink term (8), which now is calculated for a *virtual cell* of arbitrarily shape, where virtual cell is a cell with discarded solid part.

Different flow problems, such as decaying vortices and flows over a cylinder and a sphere, were simulated with the immersed boundary method proposed in [KKC01] and [HS07].

One disadvantage of the proposed variants of the immersed boundary method is that these methods were successfully applied for flows with low and moderate Reynolds numbers, but faced difficulties with the simulations of high Reynolds flows.

In [COER07] finite volume immersed boundary method for complex incompressible flows and high Reynolds numbers was proposed. In this method the immersed boundary surfaces are defined as a cloud of points (which may be structured or unstructured). Immersed boundary objects are rendered as a level set in the computational domain, and concepts from computational geometry are used to classify points as being outside, near or inside the immersed boundary. The velocity field near an immersed surface is determined from separate interpolations of the tangential and normal components. Flow problems such as flow over circular cylinder, an in-line oscillating cylinder, a NACA0012 airflow. a sphere and stationary mannequin were successfully simulated with the proposed approach.

One advantage of the methods presented in this subsection is that forcing is determined from predicted velocity field, therefore there is no need in user-specified parameters (like α and β in the forcing function approach). Another advantage is that since the velocity boundary condition is enforced with implicit forcing, there is no limitation on the time step.

Table 2: Summary table for direct forcing methods.

Criteria	[MY97]	[FVOMY00]	[KKC01]	[COER07]	[HS07]
Type of Cartesian grid	coll.	coll.	stagg.	coll.	stagg.
Support moving boundaries	-	yes	yes	yes	yes
Two- or three-dimensions	2D	3D	3D	3D	3D
Conservation of mass	no	yes	no	yes	yes

4 Ghost cell immersed boundary methods.

Formally, ghost cell method belong to a *discrete forcing*, but we will put it in a distinct section. The idea of the ghost cell method will be first described on the basis of ideas proposed in [TF03]. Then some improvement of this approach will be discussed. The goal of the this immersed boundary method is to achieve a higher-order representation of the boundary using a ghost zone inside the body.

In [TF03] the same idea as in [MY97, FVOMY00] is used: the force depends on the location and the fluid velocity, and thus it is a function of time (for details see equation (6)). As in the direct forcing methods, ghost cell methods define their own interpolation procedure, which is based on the concept of *ghost cells*.

Ghost cell is defined as a cell in the solid that has at least one neighbor in the fluid. In [TF03] the local flow variable ϕ is expressed in terms of polynomial, and it is used to evaluate ghost point values. The accuracy depends on the degree of the polynomial. Although polynomials of higher degree are expected to be more accurate, they often lead to boundedness problems and numerical instability. Linear and quadratic approaches, which preserve the second-order accuracy of the overall numerical scheme, are presented in [TF03].

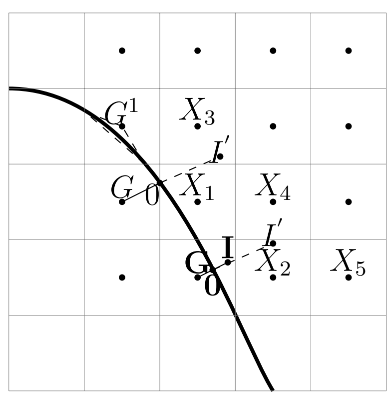


Figure 4: Various cell and node types: **G** – ghost cell, **0** – point at the boundary, $(X_1; X_2)$ – points in fluid for linear reconstruction, $(X_1; X_2; X_3; X_4; X_5)$ – points in fluid for bilinear reconstruction, **I** – image point from [DMI01, SGV09], G^1 – additional ghost cell if the boundary is close to the fluid points, I' – image point like in [PS09], $\delta = |OI'|$ distance from point on immersed boundary (O) to image point (I').

As example let us consider linear reconstruction scheme for Dirichlet boundary conditions. In this scheme the ghost cell value is a weighted combination of the values at the nodes (X_1, X_2 and O, see figure 4):

$$\phi = a_0 + a_1 x + a_2 y \tag{9}$$

$$a = \begin{bmatrix} 1 & x_O & y_O \\ 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \end{bmatrix}^{-1} \begin{bmatrix} \phi_O \\ \phi_1 \\ \phi_2 \end{bmatrix} \tag{10}$$

For three-dimensional domains the interpolation scheme in equations (9) and (10) should be modified, because more neighbor nodes are involved. Thus, for linear reconstruction, the variable in the cell center is interpolated using four points (three nearest neighbor nodes and one boundary point are involved). The proposed scheme is equally applicable to both, steady and moving, boundaries. In the case of moving bodies, the points at which the boundary condition is enforced must be recomputed at every time step, but this does not affect the reconstruction scheme.

The major drawback with this extrapolation is that large negative weighting coefficients are encountered when the boundary point is close to one of the fluid nodes used in the extrapolation. Although algebraically correct, this can lead to numerical instability, i.e. the absolute value at the ghost point may be greater than the nearby fluid point values and the solution may not converge. Two approaches are used to remedy this difficulty.

The first approach is to use the image of the ghost node inside the flow domain to ensure positive weighting coefficients [DMI01]. The point I is the image of the ghost node G through the boundary as shown in figure 4. The flow variable is evaluated at the image point using the interpolation scheme. The value at the ghost node is then $\phi_G = 2\phi_O - \phi_I$.

The other approach is to alter the piecewise linear boundary. When the boundary is close to a fluid node (normal distance of fluid point G^1 to the boundary $OG^1 < 0.1\Delta x$, Δx is the cell size) and far from the ghost point as in figure 4, we simply move the boundary point to the fluid node closest to the boundary [GFCK02]. Since the boundary is approximated as piecewise linear, the accuracy is hardly affected when the boundary segment is divided into two pieces. In [GFCK02] it is demonstrated that this approach could be used to obtain second order accuracy on irregular domains.

The above immersed boundary treatment focuses on the collocated grid arrangement. However it was stated in [TF03] that the ghost-cell approach can be extended to staggered grid arrangement in which all three velocity components and the pressure are computed on different grids. For each velocity component and for the pressure, one should find different weighted coefficients at the boundary, i.e., different linear system for each variable should be solved. This approach was validated on flow around a cylinder and on three-dimensional turbulent flow over wavy boundary.

Let us shortly comment on the mass conservation in [TF03]: ghost pressure is extrapolated from inside by the mirroring reflection procedure using Neumann condition. However, this practice leads to mass fluxes across the solid boundaries and mass error in ghost cells [SGV09].

In [SGV09], a ghost cell approach for staggered grids, whose primary feature is preserving the local mass conservation in each cell, was proposed. The idea is to satisfy the continuity equation directly for the ghost cells and to determine the pressure in the usual way through the Poisson equation. However, the mass errors should not be evaluated using the ghost velocities because they are not solutions of the momentum equations. Instead, the boundary velocities must be directly substituted, and the ghost velocities (outside the boundary) must be used only for the momentum equations. This practice preserves global continuity and avoids mass source/sinks in ghost cells. Also the idea to express the value in a ghost cell via values in image cell (like image point on figure 4), was used in [SGV09].

The discussed method was applied to study shear- and buoyancy-driven flows in number of complex two dimensional cavities. In [SGV09] it is also mentioned that authors had successfully implemented the method in three-dimensions.

Table 3: Summary table for ghost cell methods.

Criteria	[TF03]	[PS09]	[SGV09]	[BF08]
Type of Cartesian grid	coll./stagg.	coll.	stagg.	stagg.
Support moving boundaries	yes	yes	-	no
Two- or three-dimensions	2D	2D	3D	2D
Conservation of mass	no	no	yes	no

In order to deal with boundary points which lie close to one of the fluid nodes, different concept of image point was introduced in [PS09]. An image point of the ghost cell is defined as the point which is a distance δ away from the body surface. The point $I^{'}$ in the figure 4 is an image point of new type. Based on the new image point, also new and more stable reconstruction procedure was given. As example let us consider a extrapolation scheme for the velocity value at the ghost cell:

$$\mathbf{u}_G = \mathbf{v} - \frac{\mathbf{u}_{I'} - \mathbf{v}}{\delta} \|\mathbf{r}_G - \mathbf{r}_O\|, \tag{11}$$

where u_G is the velocity at the ghost point, $\mathbf{v}$ is the velocity at the immersed boundary, $\mathbf{u}_{I'}$ is the velocity at the image point, $\mathbf{r}_G$ and $\mathbf{r}_v$ are the position vectors of the ghost center and the projection point, respectively (various cell types are defined in the figure 4). Due to the fact that this model uses velocity value at the IB, it is able to handle moving bodies. It is claimed in [PS09] that the proposed method is second order accurate in space. Various steady and unsteady flows over a two-dimensional circular cylinder and a three-dimensional sphere were computed in order to validate the proposed method.

In [BF08] is noticed that approaches of obtaining ghost cell value, e.g. image point approach, are natural choices for smooth boundaries, but it is not that obvious for more irregular shaped geometries. Thus authors introduce an immersed boundary method for the solution of incompressible Navier-Stokes equations in the presence of highly irregular boundaries. This method is based on co-called a *local ghost cell* approach. This method extends the solution smoothly across the boundary in the same direction as the discretization it will be used for. The ghost cell value is determined locally for each irregular grid cell, making it possible to treat both sharp corners and thin plates accurately. The method was tested and validated for a number of problems including uniform flow past a circular cylinder, impulsively started flow past a circular cylinder and a flat plate, and planar oscillatory flow past a circular cylinder and objects with sharp corners, such as a facing square and a chamfered plate.

To summarize, among the advantages of the methods presented in this section are: (i) an ability to handle rigid bodies, (ii) absence of user defined parameters which may impact the stability of the methods, (iii) no need to compute flow variables inside a rigid body. Finally, since the boundary conditions are imposed directly in the numerical scheme, these methods are able to provide a sharp representation of the immersed boundary. A disadvantage of these methods is that they strongly depend on the discretization method. in contrast to the continuous forcing approach. It is worth noticing that methods in this category possess wide range of characteristics: three-dimension simulations, staggered grid, mass conservation.

5 Cut-cell methods.

The idea of cut-cell method is to use a uniform Cartesian grid over most of the domain with the Cartesian cells cut into a smaller irregular cells for any cell which is intersected by the boundary.

In the standard method of obtaining such cells, the immersed boundary is first represented by a series of piecewise linear segments, then cells that were cut by the immersed boundary are identified. After such a procedure, two types of cut-cells are created: cells whose nodes are in the fluid region (called regular cut-cells), and cells whose nodes are in the solid region (called small cut-cells). For an example of such cells see figure 9.

Given that a small cell can be arbitrarily small, discretization of the equations for these cells along the lines of that described for the regular cells can be highly problematic. While for convection-diffusion type of equations these small cells can cause CFL or viscous stability problems, for elliptic equations, such as the pressure Poisson equation, small cells produce ill-conditioned matrices that slow down the convergence of the iterative solution methods. Furthermore, discretization of these cells as separate finite-volumes changes the total number of unknowns that have to be solved for at any given time-step [SM11].

Another problem of the cut-cell method appears in the case of staggered grid: it is possible to have a velocity cell that does not have two pressure cells associated with it (an example of such a cell can be found in figure 7).

Each method cut cell method is characterized by three features:

1. way of obtaining sharp representation of immersed boundary,

2. finite volume discretization,

3. way of handling small cell and cells of non-standard shape.

For the methods described below. we will focus on the way they handle the third property.

Initially cut-cell method was introduced in [DMH86] as Cartesian grid method for inviscid flow computations. Then in [UMS99, UKSTST97] this method was adopted for solving two-dimensional incompressible fluid flow problems in the presence of both irregularly shaped solid boundaries and moving/free-phase boundaries. A related solver, developed in [YMUS99], uses a similar formulation but includes an improved interpolation scheme at the boundaries and a fractional time step method for time advancement.

In the method proposed in [YMUS99], small cut-cells are absorbed by neighboring cells. The result of this procedure is in the formation of trapezoidal control-volumes (see figure 5). Different treatments are applied to the uniform Cartesian cells and to the trapezoidal cells. For uniform Cartesian cells, the fluxes and pressure gradients on the face-centers can be computed with second-order accuracy by a simple linear approximation between neighboring cell-centers. This however is not the case for a trapezoidal boundary cell since the center of some of the faces of such a cell (marked by a shaded arrow in figure 5) may not lie in a location which puts it in the middle of neighboring cell-centers where a linear approximation would give an accurate estimate of the gradients.

In order to deal with flux evaluation for trapezoidal cells, it was proposed in [YMUS99] to express the flow variable ϕ in terms of two-dimensional polynomial interpolating function in an appropriate region, and then to evaluate fluxes (such as f_{sw} or f_e) based on interpolating function. For instance, in order to approximate flux f_{sw} (see figure 6a), ϕ is expressed in terms of a function that is linear in x and quadratic in y (*phi* is defined in the trapezoidal region shown in the figure 6b)):

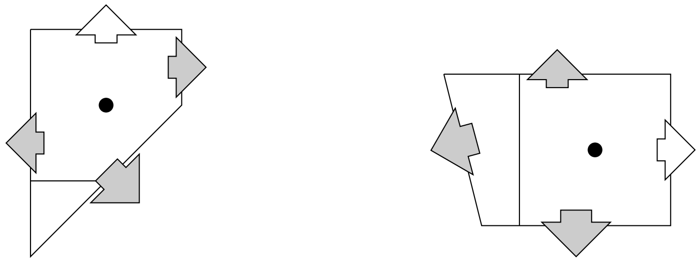
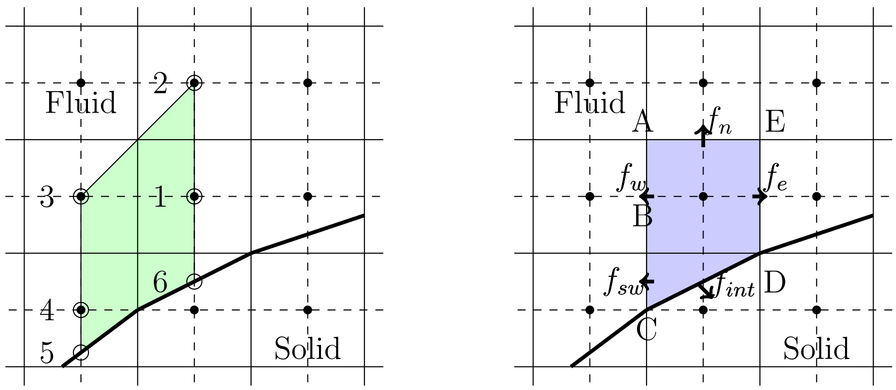


Figure 5: Typical reshaped trapezoidal boundary cells. Shaded arrows indicate fluxes that need special treatment.



(a) Various uxes required for trapezoidal boundary cell.

(b) Trapezoidal region, and stencil used in computing f_{sw}.

Figure 6: Schematic of interpolation for cell face values and derivative at boundary cells.

$$\phi = c_1 x y^2 + c_2 y^2 + c_3 x y + c_4 y + c_5 x + c_6, \tag{12}$$

where c_1 to c_6 are six unknown coefficients.

It can be seen in the figure 6b that the sides of the trapezoid in which the interpolation is performed pass through four nodal points and two boundary points. Thus, the six unknown coefficients in (12) can be expressed in terms of the values of ϕ at these six locations (these locations are shown in the figure 6b)

$$\begin{bmatrix} \phi_1 \\ \phi_2 \\ \dots \\ \phi_6 \end{bmatrix} = \begin{bmatrix} x_1 y_1^2 & y_1^2 & x_1 y_1 & y_1 & x_1 & 1 \\ x_2 y_2^2 & y_2^2 & x_2 y_2 & y_2 & x_2 & 1 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ x_6 y_6^2 & y_6^2 & x_6 y_6 & y_6 & x_6 & 1 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ \dots \\ c_6 \end{bmatrix} \tag{13}$$

Coefficients can now be expressed by inverting (13). When values of coefficients c_i are obtained, they can be used in order to evaluate the value of ϕ at the center of the face BC (see figure 6b) using interpolation similar to (12).

The overall solution procedure described in [YMUS99] is as follows:

- Determine the intersection of the immersed boundary with the Cartesian mesh.
- Using this information, reshape the boundary cells.
- For each reshaped boundary cell, compute and store the coefficients.

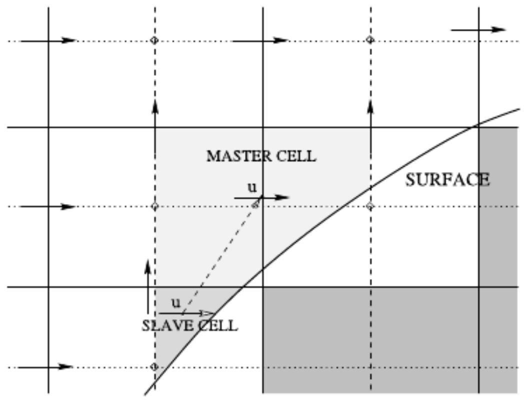


Figure 7: A master and slave cell are shown for the u component of velocity. The cell velocity has only one pressure node associated with it. It is moved to the same position as the master cell node. Image is a courtesy of [KAK03].

- Use these coefficients to develop discrete expressions and operators for the various terms in the discretized Navier-Stokes equations.
- Advance the discretized equations in time.

In [YMUS99], the authors claim that presented interpolation scheme coupled with the finite-volume formulation guarantees that the accuracy and the conservation property of the underlying algorithm re retained. In their test for the accuracy of the overall scheme they use simulations of Wannier flow [KAK03]. This method, with some modification, has been used to simulate various flows with stationary and moving boundaries, including flow-induced vibrations (see [MBU03]), flapping foils (see [MSSU02]), objects in free fall through a fluid (see [MSU04]), and diaphragm-driven synthetic jets (see [MI02]), moving boundaries (see [UMS99]) [MI05].

The benefit of this method is that merging procedure eliminates the small-cell problem, but the merging process is highly complex, especially in three-dimensions, and can also lead to additional dependencies in the computational stencil (one need to calculate fluxes with additional diagonally adjacent neighbors) that can adversely impact convergence properties [SM11].

In [KAK03], a second-order accurate Cartesian cut-cell method for the Navier-Stokes equations on a three-dimensional, non-uniform, staggered grid was presented. The article describes in details a finite volume discretization near immersed boundary cells. The main novelty of the proposed method is a cell-linking approach designed to avoid the problems related to the cell-merging procedure and to small-cells problem in case of staggered grid (see figure 7).

The idea of this approach is that instead of actually merging two cells in order to form a single cell, the two cells are linked as a *master/slave* pair in which the two nodes are made coincident while each cell remains a distinct entity. Because the slave node and slave cell continue to exist as entities separate from the master node and master cell, the fluxes and wall shear stresses, as well as the volumetric and surface information, are calculated in exactly the same way for the master and for slave cells, as they are calculated for the standard boundary cells.

The criteria used to determine when cell-linking is performed, are designed aiming to resolve problems associated with small cells. The first criteria is that any velocity cell which has only one associated pressure cell becomes a slave cell and is linked to a master cell. As a consequence, pressure gradient and velocity correction calculated for the master node can also be used for the slave node. The second criteria comes from fact that pressure cells with very small volumes can appear. This is overcome by requiring that the area of the larger face, in each pair of cell faces, is no less than 1% of the original cell face area. Pressure cells which do not meet this criterion are merged by removing the node from the calculation and treating the associated velocity cells as slave cells. Linking the master and slave velocity nodes is achieved in the following manner. The two nodes are not made exactly coincident but rather, the slave node is placed at a small distance from the master node. The diffusion flux between the two nodes then automatically becomes extremely high and forces the two velocities to take the same value. The described procedure is equally applicable to two- and to three-dimensional formulations.

The advantages of this method are obvious: (i) due to finite volume formulation, the method is mass conservative, (ii) it supports three-dimensions, and (iii) it supports staggered grid. A disadvantage is that the way in which master and slave velocity nodes are linked, can lead to problems for high Reynolds number simulations [Hen10]. This method had been used to simulate flow in square driven cavity containing a circular cylinder, laminar flow through a channel placed skewed to the grid, flow past a circular cylinder (in two- and three-dimension).

In [CB10], cut-cell method, called the LS-STAG method, for staggered Cartesian grids and where the irregular boundary is sharply represented by its level-set function, was proposed.

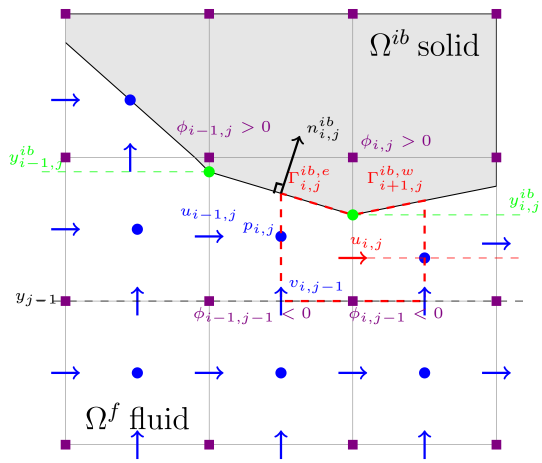


Figure 8: Staggered arrangement of the variables near the trapezoidal cut-cell $\Omega_{i,j}$ on the LS-STAG mesh, ϕ is a level set function which defines approximation of a curved boundary by linear line segments.

As a result of applying level-set function, the curved boundary is approximated by linear line segments. As observed in figure 8, there are three basic types of cut-cells: trapezoidal cells such as $\Omega_{i,j}$, triangular cells (e.g. $\Omega_{i-1,j+1}$) and pentagonal cells ($\Omega_{i-1,j}$). The discretization of the momentum equations will be performed in the staggered control volumes $\Omega^u_{i,j}$ and $\Omega^v_{i,j}$, whose shape has to be adapted to each type of cut-cells. For example, in figure 8, the faces of $\Omega^u_{i,j}$ read:

$$\Gamma^u_{i,j} = \Gamma^{u,w}_{i,j} \cup \Gamma^{u,e}_{i,j} \cup (\Gamma^{s,e}_{i,j} \cup \Gamma^{s,w}_{i,j}) \cup (\Gamma^{ib,e}_{i,j} \cup \Gamma^{ib,w}_{i,j}) \tag{14}$$

In [CB10] 12 types of such cut-cells in two-dimension and about 256 types of such cut-cells in three-dimensions, out of which 108 are admissible, are prescribed. The main feature of this method is that flow variables are actually computed in the cut-cells, and not interpolated. Furthermore, the LS-STAG method has the ability to discretize the fluxes in Cartesian and cut-cells in a consistent and unified fashion: there is no need for deriving an adhoc treatment for the cut-cells, which would be totally disconnected from the basic MAC discretization used in the Cartesian cells. Authors of [CB10] state that the method has conservation of the total mass, momentum and kinetic energy for flow with stationary boundary, but does not guarantee the discrete conservation of momentum or kinetic energy in the case of moving boundaries.

LG-STAG method was tested on flows at low to moderate Reynolds number: Taylor-Couette flow, flows past a circular cylinder, also simulation for flow with moving boundaries was performed: transversely oscillating cylinder flow in a free-stream.

The problem of pressure oscillations, observed when simulating moving boundary flow problems with sharp-interface immersed boundary methods (e.g. ghost cell method), was addressed in [SM11]. According to [SM11], the primary cause of pressure oscillations is the violation of the geometric conservation law near the immersed boundary. As a solution they adopt a cut-cell method to strictly enforce geometric conservation.

The incompressible Navier-Stokes equations are solved by a fractional time step method based algorithm. The key feature of this method is that the momentum equation is solved by a second-order central finite-difference discretization using the ghost-cell method from [MDB$^+$08] (see section 4), and one does not need to spend additional efforts in computing momentum fluxes and stresses for the cut-cells. Furthermore, the stability restrictions caused by small cut-cells can be avoided. The cut-cell approach is applied to Poisson pressure equation and velocity correction equations in order to achieve better volume and mass conservation.

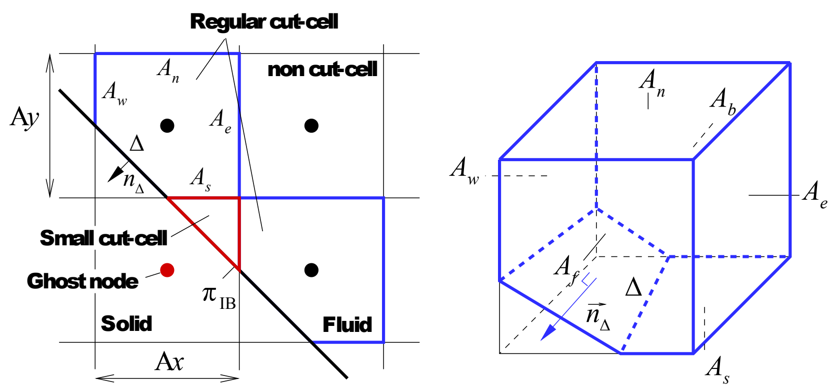


Figure 9: Cut-cell notations in 2D (left) and 3D (right, only one regular cut-cell is shown). Image is a courtesy of [SM11].

In this method the authors proposed different treatment for regular and for small cut-cells. For regular cut-cells, conventional discretization of the finite-volume equations are used (face-fractions and boundary surface for regular cut cell can be found on figure 9). A different approach is used for the small cells. The mass conservation associated with the small cells is accounted for via a *virtual cell-merging technique*. The idea it that source term of the Poisson equation for the small-cells is transferred to the adjacent cells (which may include regular cut-cells, as well as non-cut, regular Cartesian cells). The amount transferred to each target cell is chosen based on the direction of surface normal vector, as well as on the face area shared with the target-cell. This is consistent with the general notion that mass-transport associated with boundary motion would primarily be aligned with the direction normal to the boundary and the amount of mass flux would be proportional to the area. This method had been used to simulate flow around a circular cylinder and oscillating sphere.

An advantage of a cut-cell methods is that the cut-cell method is based on finite volume, so strict conservation of mass and momentum is guaranteed even in the vicinity of the immersed

Table 4: Summary table for cut-cell methods.

Criteria	[KAK03]	[UMS99, UKSTST97]	[YMUS99]	[SM11]	[CB10]
Type of Cartesian grid	stagg.	coll.	coll.	coll.	stagg.
Support moving boundaries	-	yes	-	yes	yes
Two- or three-dimensions	2D	3D	2D	3D	3D
Conservation of mass	yes	yes	no	yes	yes

boundary. One of the drawbacks of this approach is that implementing the boundary conditions in irregular cells requires a large number of special treatments, which could result in complex coding logic. When using cut-cells, these cell should not become too small. Otherwise this could not only lead to stability problems, but also lead to slow convergence of the Poisson solver.

6 Fictitious domain method.

In this section we will recall the basics of the fictitious domain (FD) method. This method pursues the same goal as IB-methods: handle complex-shaped geometries without introducing a body-fitted grid. In contrast to most of the IB-methods, FDM's implementation is relatively simple.

The fictitious domain approach was introduced by Petrowsky [Pet41] who utilized it to prove existence of a solution to the Dirichlet problem for the Poisson equation in a domain of a complex shape. The first works on fictitious domain method for Navier Stokes problems were published by [Sma79], see also references in [Vab91].

The basic idea behind the fictitious domain methods is that instead of solving the original equation(s) in complicated domain, properly perturbed equation(s) is solved in a simple domain. An abstract formulation of the fictitious domain method reads as follows (in this explanation we'll follow the ideas from [Vab91]). Assume that in some area $D \subset \mathbb{R}^n$ we are seeking for solution $u(x)$ of the equation:

$$Lu = -\phi(x),\ x = (x_1, x_2, \ldots, x_n) \in D \tag{15}$$

with boundary conditions:

$$lu = g(x),\ x \in \partial D \tag{16}$$

Instead of solving the above problem in irregular domain D, we will be seeking for a solution of a perturbed problem in "n"-dimensional parallelepiped domain Ω. The perturbed problem reads as follows:

$$L_\epsilon u_\epsilon = -\phi^\epsilon(x), x = (x_1, x_2, \ldots, x_n) \in \Omega \tag{17}$$

$$l_\epsilon u_\epsilon = g^\epsilon(x), x \in \partial\Omega \tag{18}$$

The value of the small parameter ϵ introduces jump in the coefficient of the operator L_ϵ on the interface between the original domain D and the fictitious domain $D_0 = \Omega \setminus D$. Therefore, special care has to be taken to use proper discretization approach for the perturbed problem.

It can be shown that the solution of the perturbed problem tends in D to the solution of the original problem when ϵ tends to zero:

$$u_\epsilon(x) \xrightarrow[\epsilon\to 0]{} u(x), x \in D \tag{19}$$

more details can be found, e.g., in [Vab91] or in other books/papers on fictitious domain method.

In order to solve (17)-(18) and get u_ϵ, usually a numerical method is applied. Therefore besides estimate for how close u_ϵ is to u (basis for fictitious domain method on a continuous level), we need a corresponding estimate for the numerical solution $u_{\epsilon h}$ (basis for fictitious domain method on a discrete level). So the full basis for fictitious domain method is based on following scheme: $u_{\epsilon h} \to u_\epsilon \to u$.

The current literature offers several possibilities to enforce Dirichlet or Neumann boundary conditions in a fictitious domain formulation. One of them is to include appropriate L^2 or H^1 penalty terms (see, e.g., [Ang99, Ang10]). Another one is to enforce them as a side constraint via Lagrange multipliers (see for example [GPH+99]).

The fictitious domain method was introduced above in a general setting, below we will provide specific formulations of FDM for flow problems. The penalty can be introduced in two different ways.

Navier-Stokes equations with L^2 penalty term read as:

$$\begin{aligned}&\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} - \nu\Delta\mathbf{u} + c_\epsilon\mathbf{u} + \nabla p = \mathbf{f},\\ &\nabla\cdot\mathbf{u} = 0 \text{ in } \Omega\times[0,T],\end{aligned} \tag{20}$$

where

$$c_\epsilon = \begin{cases}\frac{1}{\epsilon^2}, & \text{in } \in \Omega\setminus D\\ 0, & \text{in } D\end{cases} \tag{21}$$

Navier-Stokes equations with H^1 penalty term read as:

$$\begin{aligned}&\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} - \nu^\epsilon\Delta\mathbf{u} + \nabla p = \mathbf{f},\\ &\nabla\cdot\mathbf{u} = 0 \text{ in } \Omega\times[0,T],\end{aligned} \tag{22}$$

where

$$\nu^\epsilon(x) = \begin{cases}1, & x \in D\\ \frac{1}{\epsilon^2}, & x\in\Omega\setminus D\end{cases} \tag{23}$$

7 Simulation results

After introducing immersed boundary and fictitious domain methods, in this Section we will present comparison between a distinct immersed boundary method and L^2-penalty fictitious domain method. For this comparison we've chosen classical benchmark problem: flow around circular cylinder. This problem allows us to evaluate two quantities which are of interest for us. First, how well the velocity field around a body with complex geometry can be computed using Cartesian grid, and how well the pressure drop and the drag coefficient can be computed.

In [TS96] a full description of several test cases values for reference parameters obtained in a range of simulations are given. We have chosen two dimensional steady flow around circular cylinder.

In the figure 10 simulation geometry and boundary conditions are shown. In order to set the inflow condition following expression has been used:

$$U(0,y) = 4U_m y(H-y)/H^2, V = 0$$

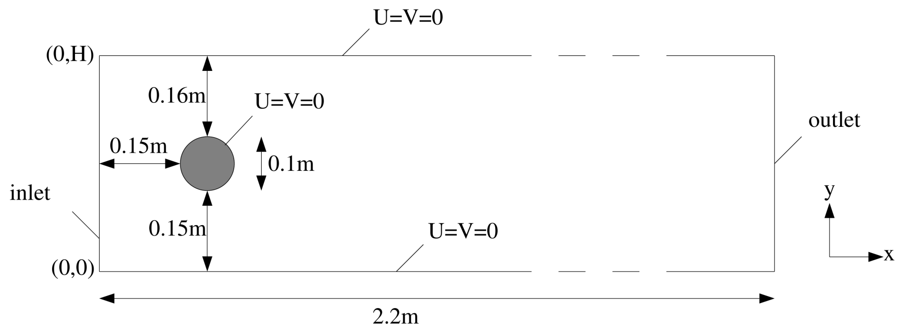


Figure 10: Test case geometry with boundary conditions. Image is a courtesy of [TS96].

$Re = 20$	FD	IB	Benchmark
C_D	5.56	5.679	5.57-5.59
ΔP	0.1115	-	0.1172-0.1176
$Re = 100$	FD	IB	Benchmark
C_D	3.1	3.333	3.22-3.24
ΔP	2.43	-	2.46-2.5

Table 5: Values for the reference parameters for the 2D flow over a cylinder asymmetrically placed in a channel.

with $U_m = 0.3m/s$, yielding the Reynolds number $Re = 20$ and with $U_m = 1.5m/s$, yielding the Reynolds number $Re = 100$.

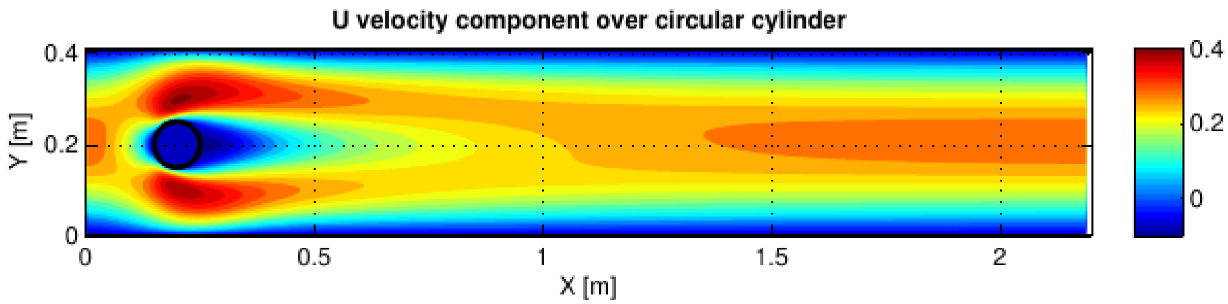
As a reference parameters we will use the drag coefficient (C_D), and the pressure drop $\Delta P = P(x_a, y_a, t) - P(x_e, y_e, t)$, between points $(x_a, y_a) = (0.15, 0.2)$ and $(x_e, y_e) = (0.25, 0.2)$. In [TS96], directions on how reference parameters should be computed, can be found.

Table 5 presents values for the reference parameters for the simulation results computed with fictitious domain, FD, method, and with ghost cell immersed boundary, IB, method. The latter are from [Lin06]. The range of the observed quantities obtained in [TS96] is also listed. In the figure 11, the first and the second components of the velocity computed with FD method and with IB method from [vM06] are shown.

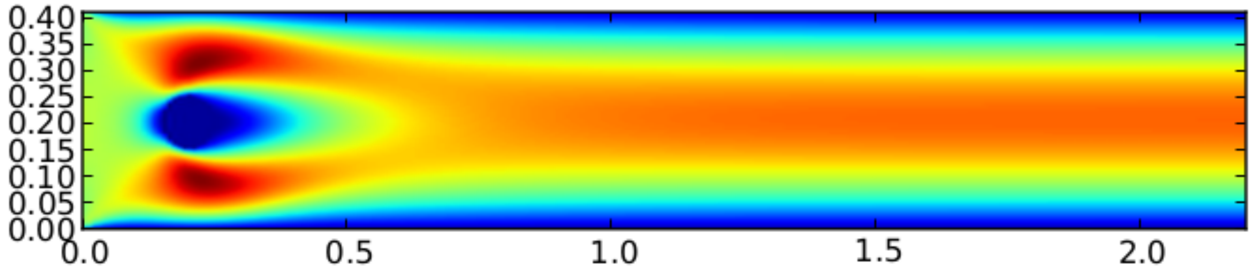
The results from the Table show that the fictitious region method provides accuracy which is comparable to the much more complicated immersed boundary methods.

8 Conclusion

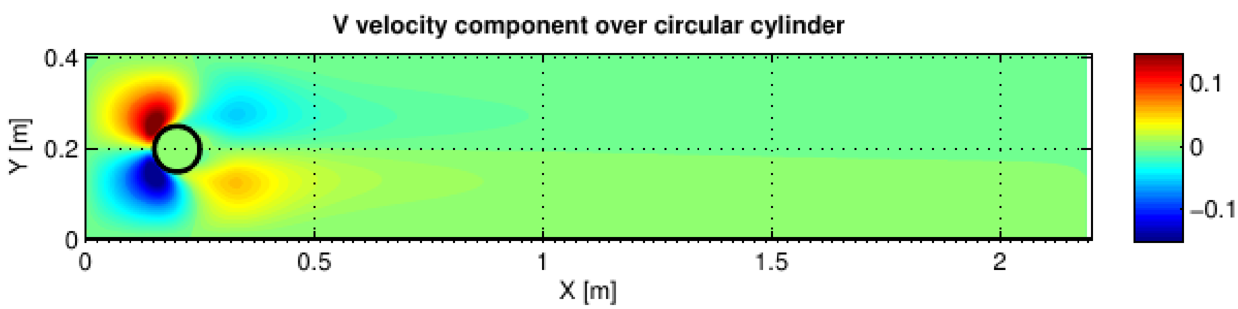
We have reviewed large number of immersed boundary methods. These methods vary in the boundary conditions imposition approach, in the difficulty of implementation, in the field of application. In general all these methods provide a way to resolve complex boundaries on a Cartesian grid. The numerical comparison to the fictitious region method shows that the latter is superior due to comparable accuracy achieved at significantly lower implementation and CPU costs. Thus, FD is used in our simulations of 3D flows in containment pools [GGIM13, GIMZ13].



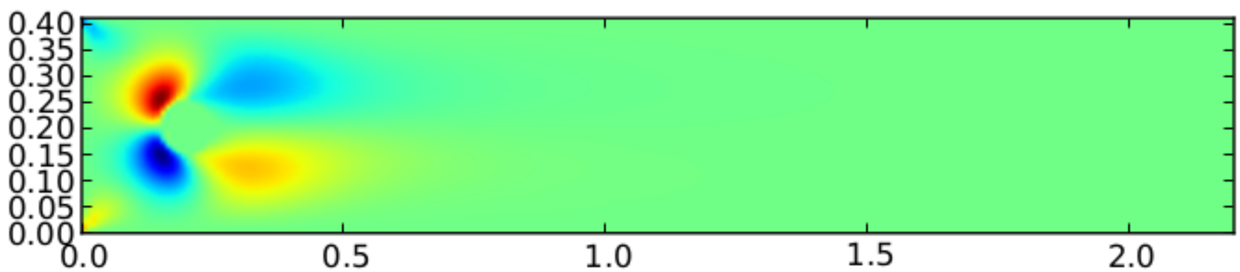
(a) First component of the velocity obtained with IB-method. Image is a courtesy of Reinout Vander Meulen [vM06].



(b) First component of the velocity obtained with FD-method; $u_{max} = 0.3966$



(c) Second component of the velocity obtained with IB-method. Image is a courtesy of Reinout Vander Meulen [vM06].



(d) Second component of the velocity obtained with FD-method; $v_{max} = 0.19$

Figure 11: Flow around cylinder computes with IB-method and FD-method.

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