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On the use of polyhedral unstructured grids with a moving immersed boundary method

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ABSTRACT

A moving immersed boundary method for unstructured grids is presented which offers several advantages over the standard ones with Cartesian grids. The flexibility provided by the unstructured grids allows for smaller grid sizes and meshing of complex flow configurations. The method features a conservative fluid domain characterization together with a flexible least-squares flow reconstruction to emulate the immersed body. The method is validated with several test cases and different grid types: polyhedral, triangular and Cartesian.

A static problem is first simulated in order to demonstrate the expected second order accuracy. Then, a benchmark moving body problem is studied, where the method is shown to compute the correct velocity and pressure fields independently of the grid type. The effects of the cell topology in the spurious force oscillations (SFO) are also studied and the polyhedral grids are proven to be superior to their Cartesian and triangular counterparts.

Finally, some examples of moving bodies in a computational domain with complex static boundaries are provided. The new method allows the use of unstructured grids for the outer fixed boundary, which allows good geometry conformance and therefore a better flow resolution. These grids can include a region with a reduced grid size and smooth transition, located at the body's path.

1. Introduction

Immersed boundary (IB) methods have been used for a multitude of flow problems since the pioneering work of Peskin [1], demonstrating great capabilities and flexibility. IB methods greatly simplify the grid generation process because body conformal grids are not required. This is particularly useful for moving or deforming bodies in a flow because meshing is not required at each time step. The body presence is simulated in the flow independently of the grid geometry, which makes IB methods extremely attractive for fluid-structure interaction (FSI) problems.

There are two distinct approaches of IB methods [2], the continuous and the discrete forcing ones, which are distinguished by the way the body influence is interpolated to the fluid. In the continuous forcing approach [1,3–7] a source term is included in the Navier–Stokes equations, at a region surrounding the fluid-body interface. Continuous forcing methods are extremely simple to implement in distinct variants of fluid solvers, but are unable to provide a sharp interface and good boundary layer resolution due the spread out nature of the forcing terms [2]. In discrete forcing IB methods [8–13] the body surface is simulated by imposing the discrete boundary conditions at fluid nodes or cells at the body surface's location. These methods have been reported to achieve sharp interfaces, providing accurate and well resolved fluid boundary layers. In addition, discrete forcing IB methods are also known to allow for larger time steps than continuous forcing methods and have a better performance when simulating rigid bodies [2]. Recently, a hybrid method has been proposed for compressible flows [14], which combines both approaches. The method uses continuous forcing to impose the no-slip condition in the momentum equations and direct forcing to impose the boundary condition in the density, energy and other scalar equations.

The great majority of IB simulations uses regular Cartesian grids, which are extremely popular for being very simple to generate and together with an IB method can solve flows around moving

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Nomenclature

a_i, b_i	least-squares coefficients
A_m	movement amplitude
a_p, a_l	momentum matrices entries
C_{body}	body Courant number
C_D, C_{D_p}, C_{D_V}	drag coefficient, pressure drag coefficient, viscous drag coefficient
C_H, C_V	horizontal and vertical force coefficient D - reference diameter
$\mathbf{d}$	distance vector between cells P and P_n
f	movement frequency
$\mathbf{f}$	distance vector between cell P and face f's centroid
h	cell reference length
P	cell or volume control (grid)
$\mathbf{P}_i$	position of cell i
p	pressure
p'	pressure correction
$\mathbf{p}_{TC}$	geometric decomposition vector for tangential correction
S_f	cell's face (grid)
$\mathbf{S_f}$	cell face's normal vector
T	time period of the body movement
t	time
U_f	face velocity
$\mathbf{u}$	velocity vector
u, v	velocity components
V_P	cell volume
x, y	cartesian coordinates
α_u, α_p	momentum and pressure relaxation factors
$\beta(x, y)$	source term
Δt	time step
ε	variable error
η	convective scheme weighing factor
ϕ	transported variable
ϕ_f	quantity ϕ at face f
ρ	fluid density
ν	kinematic viscosity
ω	angular velocity
$\zeta_1, \zeta_2, \phi_1, \phi_2, \psi$	analytic functions

Operators

$\nabla\cdot$	Divergence
∇	Gradient
$\frac{\partial}{\partial x_i}$	derivative
$\otimes$	tensor product

Subscripts and Superscripts

$\bar{a}$	interpolated from cell values of a
n	iteration number
$\mathbf{u}_s$, u_s, v_s	solid point's velocity vector and its components
$*$	approximated velocity

Acronyms

IB	Immersed boundary
SFO	Spurious force oscillation
FSI	Fluid-structure interaction
GCL	Geometric conservation law

bodies. However several arguments can be made in favor of using IB methods combined with curvilinear and unstructured grids. Sotiropoulos [15–17] has simulated heart flow dynamics using a fixed curvilinear grid together with an immersed boundary method for moving bodies. Zélicourt et al. [18], which uses a grid transformation with bijective mapping between an unstructured fluid grid and an underlying structured one. In the finite-element framework, the immersed or embedded method is combined with unstructured grids and adaptive refinement techniques [19–22]. The formulation of an IBM suitable to finite-volume methods with unstructured grids was present by Sun et al. [23,24], although the advantages of the method are not discussed due to the reduced number of results with these grids.

Unstable and oscillating pressure fields may arise when body motion exists in IB simulations and have been reported for virtually all types of IB methods [8–11,25–29]. The pressure oscillations occur when fluid cells/nodes enter or exist in the solid domain. In these circumstances the inconsistencies in the forcing terms, mostly in terms of fluid continuity, lead to severe instabilities in the pressure correction equation. SFOs have been shown to have a magnitude that decreases with grid refinement and with the increase of the time step [27], although the influence of grid type in these oscillations has not been reported in the literature.

In continuous forcing methods the oscillations can be swiftly suppressed by increasing the radius of the forcing stencil [30], although this has the added effect of further smearing the fluid body interface. For discrete forcing methods several approaches have been suggested to reduce oscillations and strictly enforce continuity. In [31] Kim and Choi presented a mass source/sink method that was shown to suppress the oscillations. Similar methods have been implemented to varying degrees of success by several authors [9,28]. In [8] Seo and Mittal presented a hybrid ghost-cell/cut-cell method that strictly enforces the geometric conservation law (GCL), thereby reducing the magnitude of pressure oscillations. A different approach was successfully implemented by Luo et al. [11] who achieved SFO suppression by locally smoothing the IB treatment and reducing temporal interpolation inconsistencies. Recently, Martins et al. [32] has proposed a continuity constraint in the least-squares interpolation which reduced the amplitude of the SFO.

The main objective of this work is to present and validate an immersed boundary method that is suitable for an unstructured grid fluid solver and with good SFO suppression properties. Additionally, the effects of the grid type are evaluated and quantified, namely in terms of numerical accuracy and pressure oscillations.

The current work is organized as followed. Firstly, the fluid governing equations and unstructured fluid solver are presented, followed by the description of the novel IB method with SFO suppression proprieties suitable for unstructured grids. Then the method is validated for both static and moving body conditions, always comparing several grid types. Cartesian, triangular and polyhedral grids were considered and compared in similar circumstances to evaluate the advantages of using an unstructured grid with the IB method. In moving body conditions the advantages in terms of domain geometry and local refinement of the unstructured grids are explored and it is demonstrated that polyhedral grids produce smaller pressure oscillations than the other grid types. Two idealized examples of rotating bodies are then provided to illustrate the application to complex 2D moving flow problems. The paper ends with summary conclusions.

2. Numerical method

In this section, the hybrid unstructured immersed boundary method and the flow solver are described. The bulk flow is solved with a SIMPLE finite-volume based implicit algorithm in a collocated grid arrangement. The convective and diffusive terms were discretized by second order accurate discretization schemes extensively verified for both unstructured and adaptive grids in previous works of the Authors [33,34].