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Sharp interface immersed boundary methods and their application to vortex-induced vibration of a cylinder

Martin D. Griffith [a,b,*], Justin S. Leontini [a]

[a] *Swinburne University of Technology, Hawthorn, Victoria, 3122, Australia*
[b] *Fluids Laboratory for Aeronautical and Industrial Research (FLAIR), Department of Mechanical and Aerospace Engineering, Monash University, Melbourne, Victoria 3800, Australia*

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ABSTRACT

The sharp interface immersed boundary method is assessed for suitability and accuracy in simulating flow-induced vibration, specifically the phenomenon of vortex-induced vibration (VIV) in the two-dimensional flow past an elastically-mounted cylinder. Inherent to immersed boundary methods are the spurious force oscillations observed when the immersed boundary moves across the underlying grid. This deficiency in immersed boundary methods is acute in flows featuring fully-coupled fluid–structure interaction, where these oscillations are fed directly back into the coupled system and have the potential to significantly affect the solution. Here, the immersed boundary method is tested and compared directly and in detail to an accurate and validated spectral-element method. The immersed boundary method performs well for the given problem, excepting a few cases, such as those featuring disordered vortex-shedding. A heuristic model is developed to analyze the frequency content of the observed spurious force oscillations and their potential to affect the global solution. A guide to the resolution required for spatial accuracy is proposed, that around 40 points should span the peak-to-peak distance of any significant oscillation.

1. Introduction

The ability of immersed boundary methods to efficiently model moving boundaries makes them ideal candidates for the simulation of flows with complex interfaces. Recent applications of variants of these methods include the surface wave interaction with coastal structures (Zhao et al., 2016), free surface flows past irregular geometries (Huang et al., 2015), flapping dynamics of inverted flags (Ryu et al., 2015), insect flight (Pradeep Kumar et al., 2015) and energy-harvesting from flow-induced motion (Griffith et al., 2016).

For sharp-interface methods in particular, the ability to handle moving boundaries while retaining a sharply-resolved representation of the boundary geometry is a key feature and advantage of the method. However, employing this feature presents some challenges, the most notable being the well-documented presence of spurious pressure oscillations near the boundary when the boundary is set to move in the fluid domain (Liao et al., 2010; Seo and Mittal, 2011; Lee et al., 2011; Yi et al., 2016). Although these pressure oscillations appear to have only a small effect on the velocity field, they can show up clearly in a time history of the fluid force on the immersed boundary. However, it is not clear what impact these pressure, and therefore force, oscillations have on the overall quality of a simulation when the motion of the body is driven by this fluid forcing.

* Corresponding author at: Swinburne University of Technology, Hawthorn, Victoria, 3122, Australia.
E-mail address: martin.d.griffith@gmail.com (M.D. Griffith).

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The primary cause of the oscillations has been identified as the violation of the geometric conservation law and local mass conservation near the immersed boundary as it moves through the underlying grid representing the fluid domain (Seo and Mittal, 2011). Essentially a difference in the volume of the immersed body exists between its true representation and its stair-step representation on the underlying Cartesian grid. In a flow where the immersed body traverses the underlying grid, the representation of the geometry changes abruptly as cells change from being inside the immersed body to outside, and vice versa. This leads to non-physical oscillations in the flow and in measured fluid force on the immersed body. Methods have been proposed to reduce the error associated with these small changes in the precise geometry of the boundary. With the cut-cell approach (Seo and Mittal, 2011), the geometry is more precisely maintained and spurious pressure oscillations due to violation of the geometric conservation law are mitigated, but not completely removed.

The computational method employed in the current paper follows that outlined in Mittal et al. (2008) and Seo and Mittal (2011). Although several authors have identified the problem of spurious force oscillations and proposed various methods to reduce, but not eliminate, them (see for example, the cut-cell approach (Seo and Mittal, 2011), hybrid discrete and continuous forcing immersed boundary methods (Uhlmann, 2005) and the field-extension approach (Yang and Balaras, 2006)), the literature lacks a thoroughly quantified study of the limits that the error places on the types of flows with fluid–structure interaction that the sharp interface immersed boundary method can accurately simulate. The current study investigates a canonical fluid dynamics problem featuring fluid–structure interaction, the flow past a cylinder free to oscillate in the transverse direction. This problem has been simulated using a number of methods, including finite elements (Mittal and Kumar, 1999; Singh and Mittal, 2005); two-dimensionally using spectral elements (Blackburn and Karniadakis; Shiels et al., 2001; Leontini et al., 2006); three-dimensionally using spectral elements with a Fourier expansion in the spanwise direction (Blackburn et al., 2001; Newman and Karniadakis, 1997; Lucor et al., 2005; Bourguet et al., 2011); sharp interface immersed-boundary techniques (Bozkurttas et al., 2005; Borazjani et al., 2008); discrete-forcing immersed boundary techniques (Yang et al., 2008; Ilinca and Hétu, 2012; Su et al., 2007; Yang and Stern, 2015; Lee and Choi, 2015); and discrete-forcing immersed-boundary techniques in a non-inertial reference frame (Kim and Choi, 2006). A more general description of the issues faced in simulating fluid–structure interaction using immersed-boundary methods can be found in the in-depth review of Sotiropoulos and Yang (2014), and the challenges of simulating fluid–structure interaction with any method in Hou et al. (2012).

Effective simulation of this problem relies on effective coupling of the motion of the cylinder to the fluid forces and thus provides a strong test for the immersed boundary method. To quantify the performance, results are compared with a validated and highly-accurate spectral-element method, which models the motion of the cylinder in the non-inertial reference frame attached to the cylinder, avoiding mesh deformation (Leontini et al., 2006). Every effort is made to reduce errors from sources other than the spurious pressure oscillations in the immersed boundary code, including the use of a strongly-coupled time integration scheme for the fluid–structure interaction (Yang et al., 2008; Borazjani et al., 2008).

While the particular problem is well understood, and fluid–structure problems have been simulated using the method in question, here the focus is on how any error induced by the spurious pressure oscillations affects the subsequent motion of the body. The robustness of the method for fluid–structure interaction problems is investigated and practical suggestions on how to minimize the potential impact of this error are provided, based primarily on ensuring separation of the frequencies of the spurious force oscillations and the frequencies of the physical system.

The paper is organized as follows: Section 2 presents details of the method used as well as the numerical details of the simulations. In the results section, data obtained using the method and showing the dependence of spurious force oscillations on spatial and temporal resolution are presented. Section 3.2 presents an heuristic model of the error, detailing possible interactions of the error frequency with the system, or physical frequencies. Section 3.3 investigates the effect of error amplitude, while Sections 3.4 and 3.5 investigate the effect of the error in the contexts of more disordered, complex oscillations and of higher body accelerations. Section 4 details the conclusions from the study.

2. Method

2.1. Immersed boundary method

The immersed boundary method functions by defining a boundary as a Lagrangian entity and immersing it in a regular Cartesian grid. The method employed in this study closely follows that presented in Mittal et al. (2008), and as such is an example of the sharp interface immersed-boundary technique. A summary of the main details of the method is provided here.

2.1.1. Governing equations

The three-dimensional unsteady Navier–Stokes equations for incompressible flow are given by

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}\right), \tag{2}$$