Water Science and Engineering 2017, 10(2): 143−153

HOSTED BY
ELSEVIER
CrossMark
Available online at www.sciencedirect.com
Water Science and Engineering
journal homepage: http://www.waterjournal.cn

Parametric study on smoothed particle hydrodynamics for accurate determination of drag coefficient for a circular cylinder

Maziar Gholami Korzani [a,*], Sergio A. Galindo-Torres [a,b], Alexander Scheuermann [a], David J. Williams [a]

[a] School of Civil Engineering, The University of Queensland, St Lucia, Brisbane, QLD 4072, Australia
[b] School of Mathematics and Physics, The University of Queensland, St Lucia, Brisbane, QLD 4072, Australia

Received 16 November 2016; accepted 21 March 2017
Available online 13 June 2017

Abstract

Simulations of two-dimensional (2D) flow past a circular cylinder with the smoothed particle hydrodynamics (SPH) method were conducted in order to accurately determine the drag coefficient. The fluid was modeled as a viscous liquid with weak compressibility. Boundary conditions, such as a no-slip solid wall, inflow and outflow, and periodic boundaries, were employed to resemble the physical problem. A sensitivity analysis, which has been rarely addressed in previous studies, was conducted on several SPH parameters. Hence, the effects of distinct parameters, such as the kernel choices and the domain dimensions, were investigated with the goal of obtaining highly accurate results. A range of Reynolds numbers (1−500) was simulated, and the results were compared with existing experimental data. It was observed that the domain dimensions and the resolution of SPH particles, in comparison to the obstacle size, affected the obtained drag coefficient significantly. Other parameters, such as the background pressure, influenced the transient condition, but did not influence the steady state at which the drag coefficient was determined.

Keywords: Smoothed particle hydrodynamics; Drag coefficient; Reynolds number; Sensitivity analysis; Viscous flow

1. Introduction

Recent advancements in high-performance computing technologies have had significant impacts on mesh-free methods such as smoothed particle hydrodynamics (SPH) in computational fluid dynamics (CFD). Although SPH is computationally expensive due to intensive interactions between integration points (in a misleading manner also denoted as particles), it may be advantageous in several situations, including moving boundaries (e.g., free-surface flow), complex boundary geometries, and shock wave simulations. Consequently, SPH has grown in popularity since its inception in 1977 for astrophysics purposes (Gingold and Monaghan, 1977; Lucy, 1977). Furthermore, recent developments in this method have extended its applicability to several engineering and scientific areas (Liu and Liu, 2005; Monaghan and Gingold, 1983) including fluid and solid dynamics (Gray et al., 2001), coastal management (Mirmohammadi and Ketabdari, 2011), and geotechnical engineering (Bui et al., 2007). In order to ensure the best performance, the accuracy, stability, and validity of SPH still need to be investigated thoroughly, since it is rather a new numerical approach.

Despite the growing popularity of SPH, there have been few studies on the sensitivity of results to SPH parameters and the influence of SPH variables on the accuracy of results. On the other hand, this method is better known for simulating

This work was supported by the Australian Research Council Discovery Project (Grant No. DP120102188).
* Corresponding author.
E-mail address: m.gholamikorzani@uq.edu.au (Maziar Gholami Korzani).
Peer review under responsibility of Hohai University.

http://dx.doi.org/10.1016/j.wse.2017.06.001

fluid motion in games (Gourlay, 2014; Nie et al., 2015). As a result, the qualitative visualization of fluid flow has almost always been the main concern, rather than the accuracy in fluid simulations in engineering applications. Takeda et al. (1994) simulated flow past a circular cylinder for Reynolds numbers less than 55, and their results perfectly matched the results from the finite difference method (FDM) and experimental data. Although they developed a no-slip boundary and a new viscosity equation, they carried out sensitivity analyses only on the smoothing length and domain shape. Morris et al. (1997) used SPH to simulate the same problem for very low Reynolds numbers ($Re \leq 1$). They proposed an artificial velocity for boundary particles to fulfill the no-slip boundary condition. They also used a simplified viscosity equation based on a finite difference approximation for very low Reynolds numbers. Marrone et al. (2013) obtained good results for the same problem using the δ-SPH method (Antoci et al., 2007). They also compared results for circular and square shapes with those obtained from FDM, and mostly studied the effects of obstacle shape and vortices geometries. Nonetheless, a series of questions, including selection of a smoothing function, smoothing length, and different viscosity equations, as well as impacts of background pressure and the speed of sound, have remained unsolved.

The capability of this method should be examined quantitatively in relation to a well-documented problem such as flow over a bluff body (Anderson, 2007), to provide an appropriate benchmark to verify the accuracy and validity of a numerical method as well as a newly developed code. In this study, a weakly compressible SPH method was adopted (Monaghan, 2005). The drag coefficient, as the main output, was studied for different SPH variables, including viscosity equations, kernels, smoothing lengths, speed of sound, and background pressures, as well as the domain parameters, including dimensions and resolution numbers. This study provides a practical approach to increasing the accuracy of future SPH simulations.

This paper is structured as follows: the SPH method is described in the subsequent section, the third section briefly explains the developed code, flow past a circular cylinder is discussed intensively in the fourth section, and the paper closes with a discussion of this work as well as planned extensions of it.

2. SPH method

The SPH method, originally developed for astrophysical purposes (Gingold and Monaghan, 1977; Lucy, 1977), is basically an interpolation technique. A comprehensive review of this method is presented in Liu and Liu (2005) and Monaghan (1994). In SPH, the computational domain is discretized into a finite number of particles (or integration points). These particles carry material properties such as velocity, density, and stress, and move with the material velocity according to the governing equations. The material properties of each particle are then calculated through the use of an interpolation process over its neighboring particles (integration domain) (Bui and Fukagawa, 2013). The interpolation process is based on the integral representation of a field function. Numerous scientists have recently shown interest in this method and introduced details on the derivation and formulation of SPH (Li and Liu, 2004; Liu and Liu, 2005, 2010). Below, the SPH method is introduced in detail against the background of this study. As is generally known, fluid motion is governed by the continuity and momentum (Navier-Stokes) equations, which are formulated in SPH as follows:

The continuity equation:

$$\frac{\mathrm{d}\rho_{\mathrm{a}}}{\mathrm{d}t} = \rho_{\mathrm{a}} \sum_{\mathrm{b}} \frac{m_{\mathrm{b}}}{\rho_{\mathrm{b}}} (\boldsymbol{v}_{\mathrm{a}} - \boldsymbol{v}_{\mathrm{b}}) \cdot \nabla_{\mathrm{a}} W_{\mathrm{ab}} \tag{1}$$

The momentum equation:

$$\frac{\mathrm{d}\boldsymbol{v}_{\mathrm{a}}}{\mathrm{d}t} = -\sum_{\mathrm{b}} m_{\mathrm{b}} \left(\frac{P_{\mathrm{a}}}{\rho_{\mathrm{a}}^2} + \frac{P_{\mathrm{b}}}{\rho_{\mathrm{b}}^2} \right) \nabla_{\mathrm{a}} W_{\mathrm{ab}} + \left\{ \frac{\mu}{\rho} \nabla^2 \boldsymbol{v} \right\}_{\mathrm{a}} \tag{2}$$

where t is time; W_{ab} is the kernel (smoothing function), which should have particular characteristics in order to approximate Dirac's delta function (Li and Liu, 2004); ∇_{a} denotes the gradient with respect to the coordinates of particle a; the subscripts a and b denote the integration point and particles in the neighborhood of particle a, respectively; and the particle field variables are $\boldsymbol{v}$, P, m, μ, and ρ, which represent the velocity, pressure, mass, dynamic viscosity, and density, respectively. The last term in the momentum equation denotes the viscosity, which will be discussed in Section 2.2.

2.1. Equation of state

In a weakly compressible SPH (WCSPH) method, an equation of state (EOS) must be used to correlate density and pressure. As shown in Eq. (2), the pressure plays an essential role, so the estimation of pressure from the density field is of paramount importance in the WCSPH method. Three options are available:

$$P = C_{\mathrm{s}}^2 \rho \tag{3}$$

$$P = C_{\mathrm{s}}^2 (\rho - \rho_0) \tag{4}$$

$$P = P_0 + C_{\mathrm{s}}^2 (\rho - \rho_0) \tag{5}$$

where C_{s} is the speed of sound and should be greater than $10U$, with U being the upstream velocity of the flow (Monaghan, 1988); and ρ_0 and P_0 are the density and background pressure at rest (initial condition), respectively.

EOS also has a significant effect on tensile instability, which is a well-documented issue in SPH, by maintaining a persistent positive pressure. SPH particles repel each other when the pressure is positive, similarly to atoms, and attract each other in the case of negative pressure, unlike atoms. However, the attraction causes SPH particles to form clumps, resulting in tensile instability (Monaghan, 2000; Swegle et al., 1995).