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Numerical simulation of circular cylinders in free-fall

Pedro Romero-Gomez, Marshall C. Richmond *

Hydrology Group, Pacific Northwest National Laboratory, Richland, WA, 99352, USA

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ABSTRACT

In this work, we combined the use of (i) overset meshes, (ii) a 6 degree-of-freedom (6-DOF) motion solver, and (iii) an eddy-resolving flow simulation approach to resolve the drag and secondary movement of large-sized cylinders settling in a quiescent fluid at moderate terminal Reynolds numbers ($1500 < \mathrm{Re} < 28{,}000$). These three strategies were implemented in a series of computational fluid dynamics (CFD) solutions to describe the fluid-structure interactions and the resulting effects on the cylinder motion. Using the drag coefficient, oscillation period, and maximum angular displacement as baselines, the findings show good agreement between the present CFD results and corresponding data of published laboratory experiments. We discussed the computational expense incurred in using the present modeling approach. We also conducted a preceding simulation of flow past a fixed cylinder at $\mathrm{Re} = 3900$, which tested the influence of the turbulence approach (time-averaging vs. eddy-resolving) and the meshing strategy (continuous vs. overset) on the numerical results. The outputs indicated a strong effect of the former and an insignificant influence of the latter. The long-term motivation for the present study is the need to understand the motion of an autonomous sensor of cylindrical shape used to measure responses to the hydraulic conditions occurring in operating hydropower turbines.

1. Introduction

The motion of particles in fluid flow is important in a wide variety of phenomena involving particle movement in nature, machinery, chemical processing, and civil infrastructure. Studies have examined a wide variety of particle shapes (spheres, ellipsoids, and cylinders) in various flow conditions (quiescent fluid, laminar, or turbulent flows). From the perspective of applied technology, the interest in examining fluid dynamic forces and the resulting motion of falling cylinders has come from various fields. Seminal work can be found in McNown and Malaika (1950). A brief list of applications includes chemical process devices such as classifiers, dust collectors, and conveyors (Christiansen and Barker, 1965); environmental studies of erodibility, movement, suspension, and deposition of earth material (Dietrich, 1982); biomass particles transforming into fuel and chemicals (Ren et al., 2011); and carbon sequestration in deep waters using field hydrate particles (Chow and Adams, 2011). The present work is motivated by the long-term goal of simulating the motion of an autonomous sensor device of cylindrical shape used in hydropower turbine investigations (Carlson et al., 2003; Deng et al., 2007) to record the device response to hydraulic conditions. This work reports the first stage towards our ultimate goal, and consisted of a numerical study of the motion of cylinders in quiescent fluid conditions, a canonical test case that minimized the

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* Corresponding author.
E-mail address: marshall.richmond@pnnl.gov (M.C. Richmond).

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complexities associated with highly turbulent flows in hydro-turbines. For that reason, the literature, simulations and discussions herein focused on cylinders of large length-to-diameter ratio, rather than on disks or oblate ellipsoidal particles, which can exhibit fundamentally different patterns of motion.

Laboratory studies have long demonstrated that the parameters characterizing the free-falling cylinder motion depended on the motion regime itself. For instance, early authors carried over the knowledge basis from fluid flows past fixed cylinders, and for the most part characterized the particle motion regimes and surrounding flow conditions as a function of Reynolds number (Re, defined in terms of the cylinder diameter and terminal velocity). Settling cylinders were therefore observed to maintain their release orientation and to lack oscillatory motion in the Stokes regime ($\text{Re} < 0.01$) (Jayaweera and Mason, 1965), but showed preferential orientation exposing the largest projected area to the direction of the motion (e.g., cylinder axis in horizontal position for ratios length-to-diameter > 1) in the so-called transition range ($0.01 < \text{Re} < 100$) (Marchildon et al., 1964). Although eddies appeared in the wake flow at $\text{Re} > 1$ and a Kármán vortex shedding developed at $\text{Re} > 50$, no oscillatory motion of the body was observed. Values of $\text{Re} > 100$ triggered a secondary motion characterized by the cylinder's main axis oscillating in the vertical plane, and the centroid's trajectory oscillating around the mean falling path (Clift et al., 2005). The onset of secondary motion was also reported at $\text{Re} > 400$ in an extensive laboratory work with cylindrical and irregular-shaped particles (Stringham et al., 1969). Within moderate Reynolds number ($100 < \text{Re} < 2400$), the particle oscillations were very regular and allowed for determining the oscillation time and maximum angular deflection as a function of the length-to-diameter and particle-to-fluid density ratios (Marchildon et al., 1964; Isaacs and Thodos, 1967; Chow and Adams, 2011), i.e. Reynolds number alone cannot characterize secondary particle motion. The motion regularity was found to be valid for an extended range ($200 < \text{Re} < 6000$) (Chow and Adams, 2011). The present study focused on this moderate Re range and on body length-to-diameter ratios greater than one. For larger Reynolds numbers, the oscillations became three-dimensional, and this complexity precluded the development of empirical relationships for secondary motion. Drag coefficients showed no correlation with Reynolds numbers as high as 300000 (Christiansen and Barker, 1965; Isaacs and Thodos, 1967), which suggested the need for other dimensionless parameters such as the aspect ratio and specific gravity of the cylinders to characterize the terminal velocity (Marchildon et al., 1964; Chow and Adams, 2011).

Further studies have sought to gain understanding of particle motion in more complex flow configurations. For instance, falling cylinders subject to an upward gas flow have also been examined (Ren et al., 2011), and the influence of both the initial drop conditions and center-of-mass location has been tested (Chu et al., 2005). Other works have analyzed the secondary motion from an analytical perspective, suggesting that the oscillations depend on the non-coincidence between the center of pressure and center of gravity of the particle (Mandø and Rosendahl, 2010). Computational fluid dynamics (CFD) runs simulated the flow fields of horizontal and inclined particles of cylindrical shape, but orientations were fixed (Hashino et al., 2014).

The present study of the motion of a cylinder in free-fall will support subsequent studies to determine how an autonomous sensor device moves through and responds to hydro-turbine flows (Carlson et al., 2003; Deng et al., 2007). Because these responses can be related to injuries of fish passing through hydropower turbines in operation, the environmental performance of new and replacement turbines can be both evaluated and improved (Richmond et al., 2009). The present work represents a canonical test case that allows us to perform an initial validation of a virtual version of the autonomous sensor where the complicating factors present in hydropower turbine systems are not present, and one for which experimental data are readily available. We envision a future modeling approach that consists of using an overset moving mesh to represent the autonomous sensor traveling through the rapidly changing hydropower turbine flows, thereby improving the state-of-art design tools described by Richmond et al. (2014). The present work constitutes the first step for determining the accuracy of simulating the drag and secondary motion of an equivalent cylinder in a quiescent fluid environment.

In this work we use a moving overset mesh scheme containing the cylinder as a means to simulate the dynamic flow fields arising around the settling cylinder. We present a general description of the overset mesh approach and its implementation in the commercial CFD code used to conduct this study. Before simulating cylinders in free-fall, we tested the overset mesh capability in a fixed cylinder at a condition relevant to the cases in motion ($\text{Re}=3900$). These initial numerical tests helped to quantify the effect of using an overset, discontinuous mesh, instead of a single continuous grid as con-conventionally done. The eddy-resolving turbulence model is briefly described, as well as its performance in comparison to conventional two-equation turbulence modeling. Then, the simulations of freely settling cylinders are described, and results for drag coefficients and secondary motion are presented. We also discuss the computational effort required to accomplish the task, which still remains an issue when considering using the overset mesh approach for this and other similar engineering applications for moving bodies. We particularly emphasize the relevance of the selected cases to the target application, i.e., to understand the hydrodynamics of the moving autonomous sensor.

2. Methods

2.1. The overset mesh scheme

The use of overset meshes—also known as chimera or overlapping grids—in CFD simulations has gradually evolved since its introduction to solve simple benchmarking flow cases (Dougherty, 1985; Hinatsu and Ferziger, 1991). Conceptually, this