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Direct numerical simulations of a freely falling sphere using fictitious domain method: Breaking of axisymmetric wake

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A B S T R A C T

In the present paper, numerical simulations of the wake generated by a freely falling sphere, under the action of gravity, are performed. Simulations have been carried out in the range of Reynolds numbers from 1 to 210 for understanding the formation, growth and breakup of the axisymmetric wake. The in-house code used is based on a non-Lagrange multiplier fictitious-domain method, which has been developed and validated by Veeramani et al. (2007). The onset of instability in the wake and its growth along with the dynamic behavior of a settling sphere is examined at Reynolds number (*Re*) of 210. It is found that at the onset of instability the sphere starts to rotate and gives rise to a lift force due to the break of the axisymmetry in the wake which in turns triggers a lateral migration of the sphere. The lift coefficient of a freely falling sphere is 1.8 times that of a fixed sphere at a given sphere density of 4000 kg m^{-3} and sphere to fluid density ratio of 4. This is attributed to the Robin's force which arises due to the rotation of the sphere. At this Reynolds number (*Re*=210) a double threaded wake is observed, which resembles the experimental observations of Magarvey and MacLatchy (1965).

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1. Introduction

Wakes generated by the bubbles, drops and particles in a fluid are important fundamental features in multiphase flows like sedimentation and fluidization (adsorption, leaching, particle classification and backwashing of down flow granular filters, slurry transport (water lubricated transport of heavy crude and coal slurries) and hydraulic fracturing (oil and natural gas production). The direct computation of such possibly unsteady flows became possible in the recent years due to the increase in the computational power and the development of advanced parallel numerical techniques. In the present work, the onset of the instability in the wake behind a freely falling sphere, its growth and saturation which leads to the breakup of the axisymmetric toroidal vortex, is simulated by using an in-house code. The code which is based on a non-Lagrange multiplier fictitious-domain method, that has been developed and validated by Veeramani et al. (2007). In this method, the fluid flow is governed by the continuity and momentum equations and the particle motion is governed by the equations of motion of a rigid body. The flow field around the particle is resolved and the resultant hydrodynamic force between the particle and the fluid is computed from the solution itself rather than being modeled by any drag law.

The behavior of the wake behind a sphere has been studied by a number of researchers over a wide range of Reynolds number. The earlier flow visualization experiments have been carried out by Taneda (1956) using a string mounted sphere moving at a constant velocity in a water tank. He measured the size, separation angle and the center of the steady axisymmetric wake behind the sphere. He has reported that the size of the vortex ring is proportional to the logarithm of the Reynolds number. He found that the Reynolds number at which the axisymmetric toroidal vortex ring begins to form in the rear end of a sphere is *Re*=24 and a faint periodic motion at the rear end of the vortex ring was found to begin at *Re*=130. The wake generated by liquid drops (carbon tetrachloride and chlorobenzene) in water has been studied by Magarvey and Bishop (1961) who also classified the wake, based upon the nature of the tail of the vortex and Reynolds number. Up to *Re*=210 the wake is steady and axisymmetric and is referred to as a single thread wake. For $210<Re<270$ the vortex becomes non-axisymmetric and was classified as a double threaded wake. In the range of $270<Re<290$ the double threaded wake becomes unstable which leads to a wavy vortex tail. Above *Re*=290, vortex loops begin to shed into the free stream. The formation and structure of the vortices due to accelerating liquid drops at different intervals of time, at *Re*=340,

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has been shown experimentally by Magarvey and MacLatchy (1965). They observed that the liquid drops follow a spiral path while settling. As pointed out by Winnikow and Chao (1966) and Natarajan and Acrivos (1993) these experiments with falling liquid drops in immiscible liquids could be compared with the standard solid rigid sphere wakes due to the presence of the surfactants at the liquid–liquid interface which hold the drops in a spherical shape.

Masliyah (1972) has shown the recirculating wakes behind a sphere and three oblate spheroids by using flow visualization technique over a Re range from 15 to 100. He analyzed the variation of the wake length and angle of separation of the stable wake with respect to the Reynolds number. Achenbach (1974) has studied the fixed sphere wakes for the range $400 < Re < 5 \times 10^6$. With a help of a sketch, he has explained the periodic formation and release of vortex loops in the free stream, and determined the shedding frequency at Re=3000. The characteristics of the steady wake behind liquid filled spheres have been studied experimentally by Nakamura (1976), using dyed water for flow visualization experiments. From these experiments he observed that a stable and steady accumulation of dyed water at the rear end of the sphere begins at Re=7.3 and that the shape of the wake changes from concave to convex as the Reynolds number increases. He pointed out that the tracer, aluminum dust, used by Taneda (1956) is not fine enough to seamlessly drift along with the slow fluid stream when $Re < 30$. He also found that the maximum Reynolds number at which the toroidal vortex is steady is about 190, which is in contrast with the Magarvey and Bishop's (1961) observation. This early instability in the wake at a Reynolds number of 190 can be attributed to the use of liquid filled spheres where the fluid inside is free to move around, thus potentially affecting the sphere's motion and the wake development. Sakamoto and Haniu (1990) have measured the vortex shedding frequencies of a fixed sphere for Reynolds numbers from 300 to 40,000 using hotwire anemometry and flow visualization experiments. The onset of a hairpin vortex shedding takes place at Re=300. The wake behind a fixed sphere from Re=30 to 4000 has been visualized by using tracers illuminated by laser sheet by Wu and Faeth (1993). They also measured the streamwise velocities using laser velocimetry. Ormieres and Provansal (1999) qualitatively showed that the double threaded wake of a sphere held by a thin metallic pipe was formed at Re=220 and a periodic vortex shedding occurred at Re=300. They also made quantitative measurements of the free-stream velocity in a wind tunnel by using laser Doppler velocimetry (LDV) and hotwire anemometry. Visualizations of the vortex structures and measurements of the streamwise velocity of a fixed sphere in the range of Reynolds numbers from 270 to 500 in a uniform flow channel have been performed by Schouveiler and Provansal (2002). Flow visualization experiments capturing the wake structure behind the rising and falling solid spheres in water have been also performed by Veldhuis et al. (2005) using the Schlieren technique. From these experiments they concluded that the wake generated by a moving sphere is different from the wake generated by a fixed sphere. They have demonstrated the formation of a pair of opposite signed vortex threads and kinks on these threads which cause the formation of the hairpin vortices.

One of the first theoretical stability studies is performed by Kim and Pearlstein (1990) who have carried out a two dimensional linear stability analyses by using a pseudo spectral method for discretization of the Navier–Stokes equation. They predicted that the primary bifurcation occurs at Re=175 which is significantly lower than the experimentally observed by Magarvey and Bishop (1961) value of 210. Using a modified linear stability analysis, Natarajan and Acrivos (1993) carried out two-dimensional simulations of a sphere and a circular disk. They predicted that the primary bifurcation in case of a sphere occurs at Re=210 which is in a perfect agreement with the experimental observation and they reported that the secondary (Hopf type) bifurcation and shedding of vortices occurs at Re=278. Tomboulides (1993) has performed three dimensional numerical simulations of a fixed sphere from Re=20 to Re=1000. He used a numerical method in which spectral element decomposition in the axial and radial direction is combined with a spectral expansion in the tangential direction. He observed initial flow separation at Re=20 and a steady non-axisymmetric flow at Re=212. The vorticity of the non-axisymmetric flow field resembled the double-thread wake as observed by Magarvey and Bishop (1965) at Re=210. The wake structure behind a fixed sphere in the range of Reynolds number from 20 to 300 has been studied both, numerically and experimentally, by Johnson and Patel (1999). They used a fourth order Runge–Kutta method for the integration of the momentum equations along with a pressure Poisson equation to satisfy the continuity equation. They reported that the flow separation and formation of a vortex behind the sphere begins at Re=20 and computed the separation angle, length and the position of the vortex. They observed that the axisymmetry is broken at Re=210 and explained this phenomenon by presenting three-dimensional interactions of the stream lines. They also calculated the values of the lift force, which arises after the breakage of symmetry. In addition, these authors reported that a periodic vortex shedding begins at Re=270 and explained it with the help of vorticity diagrams. The variations in the drag and lift forces due to vortex shedding were also presented.

Numerical simulations of the flow past fixed oblate spheroidal bubbles at Re ranging from 100 to 1000 has been simulated by Magnaudet and Mougin (2007). Their numerical method is based on a finite volume discretization on a staggered grid and a third order Runge–Kutta algorithm for solving the velocity field combined with a semi implicit algorithm for the viscous terms. At Re=180 they observed a non-axisymmetric wake, using 3D particle paths. They also presented the vorticity isosurfaces at Re=180, 300 and 700. The wake instability of a fixed sphere has been studied by Ghidersa and Dusek (2000) who used a spectral element method and reported that the primary bifurcation occurs at Re=215. A vortex method for numerical simulation of flows past spheres have been developed by Ploumhans et al. (2002). They presented the isosurfaces of the streamwise vorticity at Re=300, 500 and 1000. The hydrodynamic forces acting on a rigid fixed sphere at the range of Reynolds numbers from 10 to 320 have been computed by Bouchet et al. (2006) using spectral element method. They presented the vortex shedding frequencies and oscillation amplitude of the drag and lift forces from Re=280 to 320.

All these numerical studies throw light on the flow separation, wake instability and vortex shedding of a fixed sphere. However, the lateral migration and rotation of the sphere after axisymmetry breaking have not been explained by these fixed sphere simulations. Understanding of such fundamental dynamic instabilities is possible only by simulating the settling or fluidizing of a free sphere. Further, there are relatively few theoretical studies of such phenomena available in the literature. A finite element based distributed Lagrange multiplier (DLM) fictitious domain method for solid–liquid flows has been introduced by Glowinski et al. (1999 and 2001). This numerical technique is based on the extension of the Navier–Stokes equations into the "fictitious" domain occupied by the particles. The no-slip boundary conditions on the particle boundaries are enforced by means of distributed Lagrange multipliers. These multipliers represent the additional body force per unit volume needed to maintain the rigid-body motion inside the particle boundary. By using this method they simulated the sedimentation of 504 and 6400

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