DYNAMICS OF THE FLOW AROUND AN IMPACTING SPHERE

Thomas Leweke*, Mark C. Thompson**, Kerry Hourigan**
*IRPHE-CNRS, B.P. 146, F-13884 Marseille Cedex 13, France
**Monash University, Dept. of Mechanical Engineering, Melbourne, VIC 3800, Australia

Summary Results from an experimental and numerical study of the flow generated by a sphere impacting without rebound on a solid wall are presented. The parameters are the running distance before impact, the sphere Reynolds number, and the stopping distance away from the wall. For running lengths less than 7.5 diameters, the sphere wake remains axisymmetric in the form of an attached vortex ring. After impact, this ring overtakes the sphere and spreads out along the wall. For Reynolds numbers above 1000, perturbations of azimuthal wave numbers 20-25 are observed on the vortex ring, which appear to be the result of a centrifugal instability.

INTRODUCTION

This presentation deals with the flow generated by a sphere impacting a solid wall without a rebound. Such a configuration has potential relevance for the determination of wall heat exchange properties in the presence of particles, due to the convection of fluid towards and way from the surface by the flow generated by the impact, as well as for the problem of resuspension of dust from the surface. For spherical solid bodies impacting on a wall, the wake flow following body overtakes it on impact, and resultant ring vortex structure(s) can cause significant fluid exchange near the surface. Eames & Dalziel [1] have examined this behaviour in detail, as the Reynolds number was varied between 300 and 3500. In that study, the analysis was primarily directed towards resuspension characteristics of different dust types and layer thicknesses, rather than the fluid dynamics, which is of primary concern in the present study. Joseph *et al.* [2] experimentally examined particle-wall collisions for Reynolds numbers between 10 and 3000, and showed that the rebound was primarily a function of the Stokes number. Both Joseph *et al.* [2] and Gondret *et al.* [3] determined the coefficient of restitution as a function of Stokes number and showed that it reaches an asymptotic value for high Stokes numbers, corresponding to the value for dry collisions. The vortex ring system generated after the impact of a solid body shows similarities to that produced from the collision of a vortex ring with a wall, examined by a number of authors including, *e.g.*, Orlandi & Verzicco [4] and Swearingen *et al.* [5]. This presentation focuses mainly on two aspects of the particle-wall interaction: the formation and evolution of the vortex system associated with the impact, and the interpretation of a three-dimensional instability which appears above a critical Reynolds number and leads to the rapid diffusion of the main vortex.

TECHNICAL DETAILS

The experiments were carried out in a 50 × 50 × 60 cm^3 water tank with a Plexiglas bottom, using a bronze sphere of diameter D = 3/4” attached to an inelastic string, and whose vertical motion was imposed by a computer-controlled stepper motor. Visualization was achieved using fluorescent dye and light from an Argon laser. The sphere was impulsively started from rest at a distance L from the bottom surface. It moved downward with constant speed U until it hit the surface, where its motion was stopped (see Fig. 1).

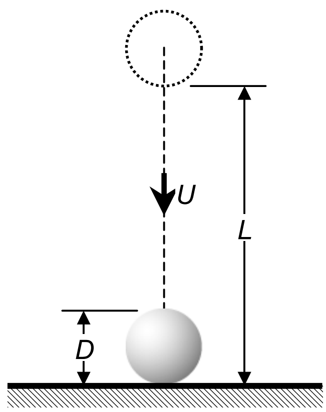

Figure 1. Geometry and parameters.

In parallel, existing spectral-element software (see, *e.g.*, Sheard *et al.* [6]) was modified to perform Direct Numerical Simulations. The movement of the sphere relative to the wall was treated using the Arbitrary Lagrangian Eulerian (ALE) approach [7]. As the sphere moves towards the surface, the vertices of the mesh move with predetermined specified velocities so that the semi-circular boundary of the sphere (in the axisymmetric coordinate system) is maintained and the distortion of the mesh is controlled. The sphere was stopped at 0.005D away from the wall to avoid the development of a mesh singularity over the final few time steps before impact.

The parameters controlling the interaction are L/D, where L is the initial distance between the bottom of the sphere and the wall, and the Reynolds number, $Re = UD/\nu$, where ν the kinematic viscosity.

RESULTS

Figure 2 shows the evolution of the flow for Re = 800 and L/D = 5. For this parameter set, the flow remains axisymmetric throughout the evolution, yet the Reynolds number is sufficiently large to allow a complex vortex ring system to develop. The left-hand images are experimental dye visualizations obtained by coating the surface of the sphere with fluorescent dye. The right-hand images show instantaneous fields of azimuthal vorticity, obtained from DNS simulations, together with positions of tracer particles placed initially in a layer near the wall. $\tau = tU/D$ is the non-dimensional time. The visualizations clearly show the wake vortex behind the sphere at impact. A small secondary vortex develops from the opposite-signed vorticity generated on, and shedding from, the sphere surface as the wake vortex ring threads over the

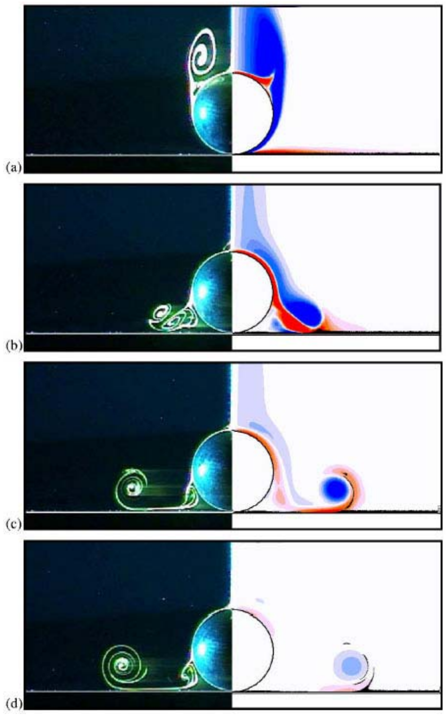

Figure 2. Flow after impact of the sphere for Re=800, L/D =5. Left: dye visualization; right: vorticity and tracer particles from DNS. (a) τ = 0, (b) τ = 2, (c) τ = 5, (d) τ = 10.

sphere. The simulations further show the presence of considerable secondary vorticity induced at the wall when the primary vortex ring strikes it. This secondary vorticity wraps around the wake vortex ring, which reduces the total circulation of the structure to very low values, and results in a considerable slowing down of the radial spreading of the ring through induction by its image. The primary vortex reaches a final diameter of around $3D$, which varies little with L and Re.

When the running distance L of the sphere is varied at constant Reynolds number Re = 800, it is found that the wake before impact, and subsequently the flow throughout the entire evolution, is axisymmetric up to L = 7.5. For larger distances, the wake vortex ring becomes tilted before the impact, resulting in large-scale perturbations of the later flow. For L < 2, the wake of the sphere does not have enough time to roll up into a vortex ring, and no coherent structures are observed after impact.

When the Reynolds number is increased above a critical value of around 1000, the flow loses its axisymmetry through an instability occurring after the sphere impact, when the primary wake vortex ring starts spreading out at the wall. Figure 3 shows this phenomenon in a view from below. These images reveal that the perturbation first appears in the outer parts of the primary vortex ring, whereas the centreline still remains relatively unperturbed at this stage. The azimuthal wavenumber of the unstable mode is between 21 and 24. Similar observations were made in the dust resuspension study by Eames & Dalziel [1]. They suggested that the origin of this instability is the same as the one responsible for the 3D instability of the flow generated by a vortex ring impinging on a wall, as explained by Swearingen *et al.* [5], namely a combination self- and mutual induction between the primary ring and a secondary vortex ring of opposite circulation rolling up from the wall vorticity. However, the wave numbers predicted from this analysis are significantly lower (around 6) than observed in the present study, and the visualisations in Fig.1 show no coherent secondary vortex forming from the wall vorticity for the chosen parameter set (the qualitative features of the base flow vary little with Reynolds number, even above 1000). Instead, the negative vorticity wrapping around the positive-vorticity primary wake vortex creates a flow which is centrifugally unstable. This feature is also consistent with the observation that the main perturbations are found in the outer part of the vortex. Further evidence is found when performing a stability analysis of an axisymmetric vortex whose velocity profile is given by the azimuthally averaged profile of the primary wake vortex at τ = 4, *i.e.*, at a time from whereon its position and structure is only slowly changing. The growth rate and most unstable wavelengths determined in this way are close to the values found for the instability of the fully time-dependent flow, as calculated by DNS. This further supports the conclusion that the 3D instability observed in the flow generated by the collision of a sphere with a wall is due to a centrifugal instability of the primary wake vortex ring.

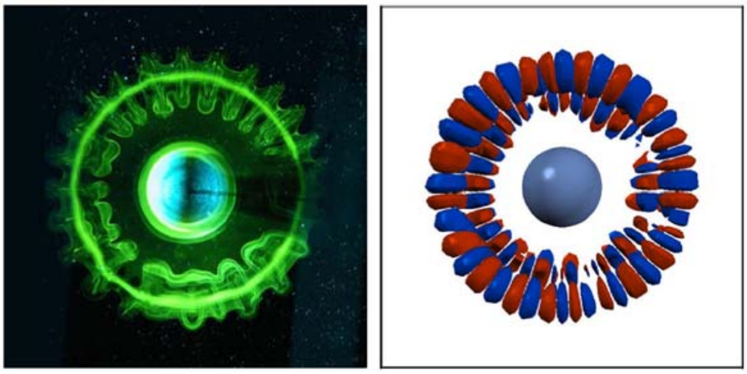

Figure 3. Instability of the axisymmetric flow. Left: experiment at Re = 1200; right: perturbation vorticity from DNS at Re = 1500. L/D = 5, τ = 9.

Further details on this instability, as well as results concerning the trajectories of the vortex ring(s) as function of Reynolds number and running distance for the axisymmetric flows, and the effect of a rebound of the sphere, will be presented at the Conference.

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