OBLIQUE IMPACTS OF NON-ROTATING SPHERES

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The paper deals with an experimental investigation of impacts of non-rotating spherical bodies on a flat, solid surface in water. The aim of the investigation was, using the PIV (Particle Image Velocimetry), method to analyze the velocity fields around the falling sphere which falls in an oblique direction. The experiments showed that the wake that forms behind the sphere is asymmetrical and that after the impact it continues its motion to the bottom, only along one side of the sphere, though. This non-symmetrical velocity field results in additional forces which push the sphere to the opposite direction than is the direction of the sphere motion just after the impact.

Keywords: *wake, particle trajectory, velocity field*

1. Introduction

A large number of experimental and numerical studies of the wake behind the sphere have been performed. Thompson et al. [1] investigated the flow dynamics associated with the normal impact of a sphere on a wall, for Reynolds numbers $100 < \mathrm{Re} < 2000$, both numerically and experimentally. The experiments were carried out in a glass tank. A brass sphere of 19.02 mm in diameter was attached to a fine, thermally fused, twisted, stretch-resistant thread. During the experiments there was taken special care to ensure maximal purity of the attachment to avoid causing extraneous disturbances to the flow. The thread passed over a pulley and was wound on a threaded reel driven by a high-resolution computer-controlled stepper motor. This mechanism allowed the sphere to be lowered through the water at a specified uniform speed and thus allowed the selection of the Reynolds number. During the experiments, there were observed no noticeable oscillations of either the sphere or supporting thread. Their experiments indicated that the collision remains essentially axisymmetric for $\mathrm{Re} < 1000$. Eames and Dalziel, [2], experimentally investigated the hydrodynamic mechanism of dust re-suspension as a function of Reynolds number for $300 < \mathrm{Re} < 3500$. The study has shown that when a sphere collides with a wall, the wake vortex, which is initially behind the body, threads over the sphere's surface, generating a secondary vortex. The coherent structure, composed of the wake vortex and secondary vortex, collides with the wall, pushing fluid adjacent to the wall to one side, which is subsequently entrained by the wake vortex.

This study is focused on how spherical particles rebound from the flat bottom when they reach the surface in non-normal direction.

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2. Experimental arrangements

The experiments were carried out in a water tank of dimensions 400×200×280 mm. The tank was filled with water up to the level of 230 mm above the flat bottom formed by a 19 mm thick glass plate. In the experiment there were used two types of spherical bodies:

– plastic sphere of diameter 37.5 mm and density 1028 kg/m^3,
– golf ball of diameter 42.8 mm and density 1120 kg/m^3.

Spheres of such physical properties were used in the experiments because the densities of both types of spheres were close to the density of water. To record the sphere movements in water there was employed a digital video camera NanoSence III+ with a specific frequency – 700 frames per second for the plastic sphere, and 1000 frames per second for the golf ball. The flow field was visualized by aluminum seeding particles and a light sheet, immersed in the water tank on the left side. The PIV analysis was performed using a time-resolved digital particle image velocimetry application, developed for Matlab. The sphere trajectories were captured by functions implemented in the Matlab Image Processing Toolbox. Details of image capture and subsequent analysis were published in Chara et al., [3]. The important parameter, controlling the impact process, is the dimensionless quantity L/D, where L is the initial distance between the bottom of the sphere and the bottom of the tank, and D is the sphere diameter. In the experiments the dimensionless ratio L/D was 4–5 and the Reynolds numbers varied from 5000 to 13000. The spheres were kept between cups below the water level and when the trigger was released, the springs pulled the cups apart, allowing the ball to fall freely in the water.

3. Discussion of the results

Fig. 1 shows trajectories of the rebounding plastic sphere in different experimental runs. As the density ratio of the used spheres to water is close to one for both types of spheres, the spheres have a tendency to fall, not downwards, but more likely along a curved line, Horowitz and Williamson, [4].

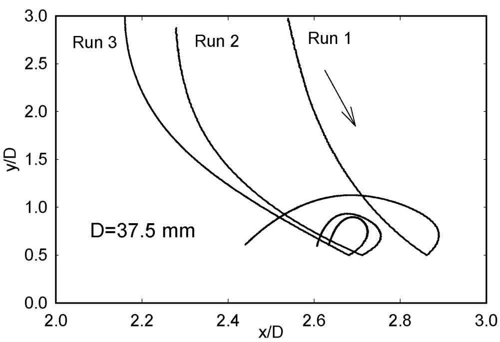

Fig.1: Dimensionless trajectories of the plastic sphere

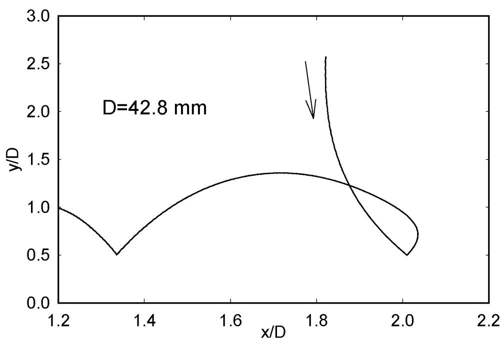

Fig.2: Dimensionless trajectory of the golf ball

The sphere impacts the bottom at an oblique angle and after the rebounding, the sphere seems to follow a path respecting the law of reflection. However, after a while the sphere suddenly changes its direction and moves to the opposite side. Such behavior was also observed for the golf ball, see Fig. 2. In order to explain this behavior there was analyzed

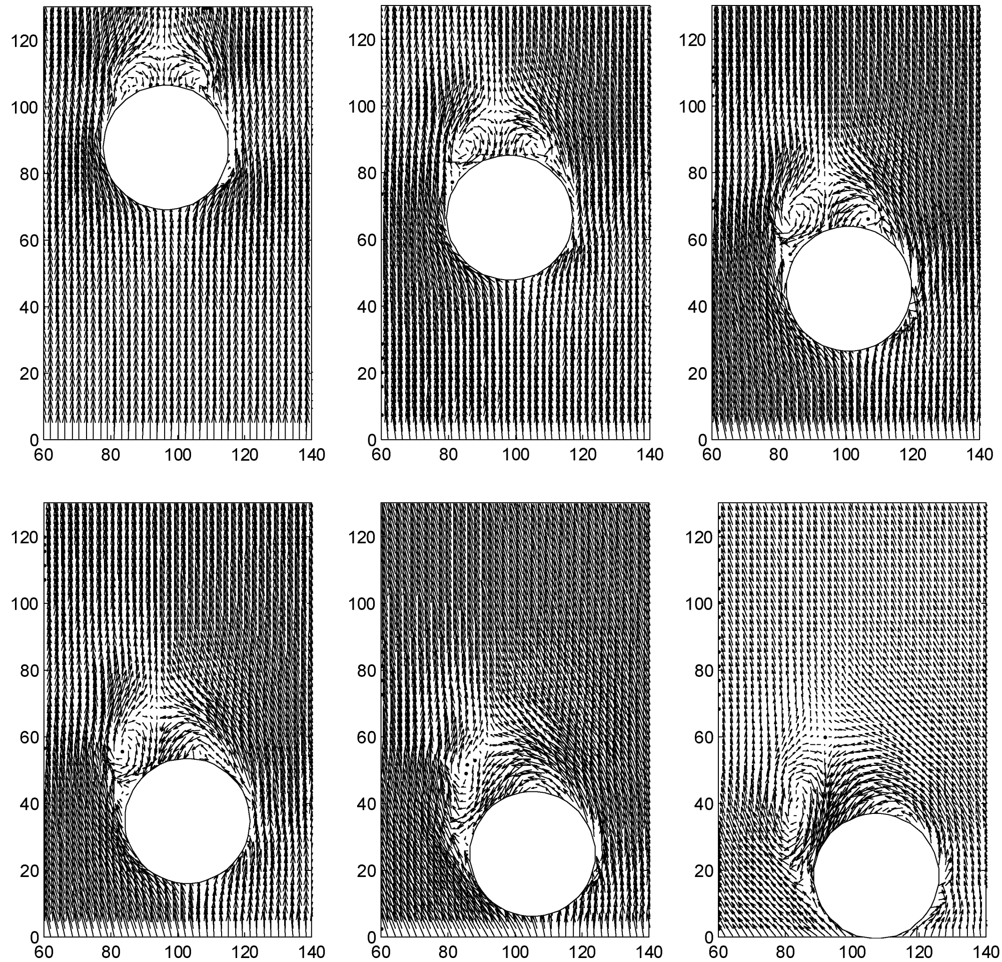

Fig.3: Wake development trailing the plastic sphere (Run 1), $D = 37.5\,mm$

the wake formation during the falling and the rebounding periods. Fig. 3 shows the velocity vectors measured by the PIV method in the plane leading through the centre of the plastic sphere. The velocities are related to the instantaneous sphere velocities. The dimensions in Fig. 3 are given in millimeters. In Fig. 3 it is obvious that during the falling period, the wake behind the sphere is shifted to the left side. When the sphere rebounds from the wall, the wake shifts towards the wall, mainly along the left side of the sphere, and the velocity field around the sphere is asymmetrical. The relative velocities in the wake before the impact are practically the same as is the falling velocity of the sphere. After the impact the sphere moves up but the wake keeps moving towards the wall and the relative velocities are approximately double the falling velocity. According to the Bernoulli principle an increase in the velocity of the fluid causes a decrease in pressure. In other words, the pressure on the left side of the sphere is lower than the pressure on the right side. Therefore, this difference in pressure probably causes an additional force, pushing the sphere to the left. Similar behavior was also observed for the other experimental runs, both with the plastic sphere and the golf ball.

The instantaneous sphere velocities were calculated from experimentally captured sphere trajectories, which allowed to determine the time derivations of the velocities, in other words

– accelerations. According to Newton's second law 'the acceleration of the body is directly proportional to the total force acting on the body'. Fig. 4 shows the time series of the golf ball's accelerations in the horizontal as well as in the vertical directions. The zero time on the time axis is set at the time of the impact. The negative maximum of the acceleration of the horizontal velocity occurs approximately at the time of 0.038 s (after the impact), negative maximum of acceleration of the vertical velocity occurs at the time of 0.077 sec. It means that the maximal forces that affect the golf ball in the horizontal and the vertical directions after the impact do not act simultaneously. It is caused by the uneven, developing velocity field in the vicinity of the rebounding sphere. The wake, formed behind the sphere during the falling period, moves towards the bottom even after the sphere-bottom collision and passes the rebounding sphere vertically downwards, along its left side. After the collision part of the wake moves into the gap between the sphere and the bottom and in the horizontal direction it forms an asymmetrical velocity field.

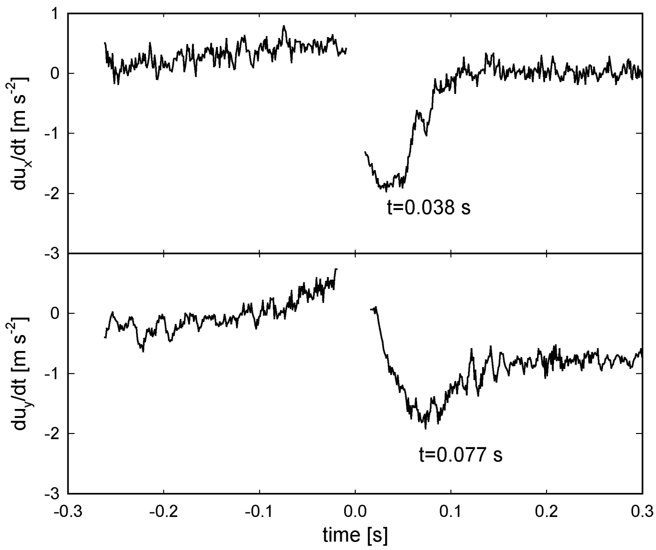

Fig.4: Acceleration of the golf ball in horizontal (upper plot) and vertical (lower plot) directions

Fig. 5 shows the profile of the vertical relative velocity component (fluid velocity minus sphere velocity) measured at the time of 0.038 s after the impact. The profile was measured on the horizontal axis of the golf ball. The data in Fig. 5 indicate that the relative vertical velocity is maximal on the left side of the sphere where the wake and the sphere pass each other. Similar asymmetrical velocity profiles were observed for the horizontal relative velocity component. Fig. 6 shows the results of the horizontal relative velocities measured on the vertical axis of the golf ball at the time of 0.077 s after the impact. The maximal velocity was observed below the sphere where a part of the wake was coming from the left side.

The next section is aimed on comparison between the accelerations of the golf ball and the maximal fluid relative velocities. The data were measured on the vertical and horizontal axes of the golf ball in short-time intervals. Subsequently, both the accelerations of the ball and the fluid velocities were normalized by their maximal values within the particular interval. For the results see Fig. 7. The left part of Fig. 7 shows time series of the dimensionless

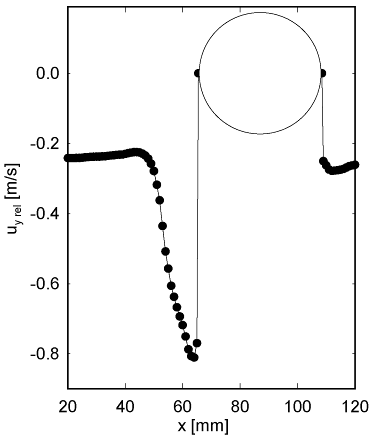

Fig.5: Vertical relative velocity component of the golf ball measured at the time of 0.038 s

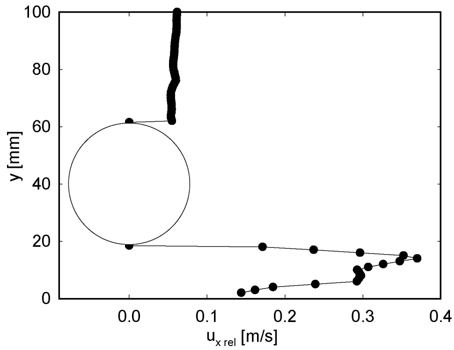

Fig.6: Horizontal relative velocity component of the golf ball measured at the time of 0.077 s

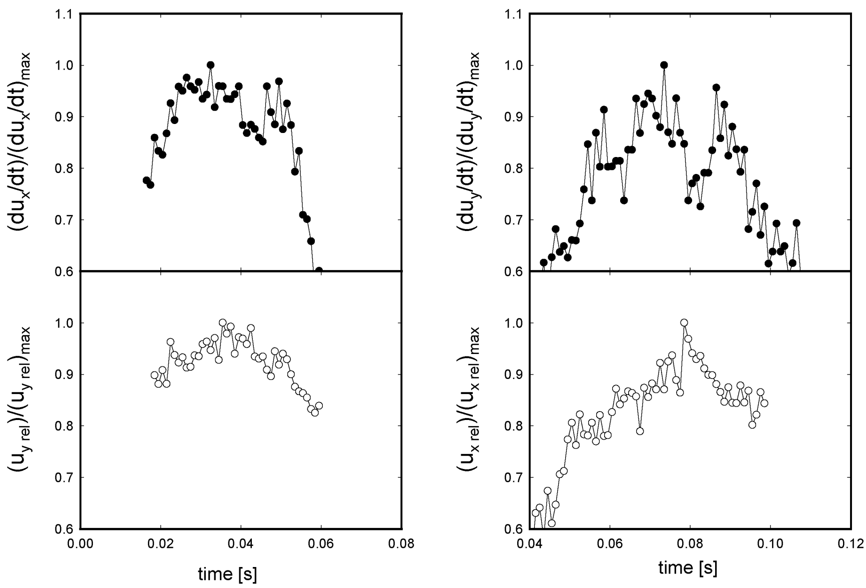

Fig.7: Dimensionless accelerations and dimensionless velocity of the golf ball

horizontal acceleration of the golf ball (upper figure) and the dimensionless relative vertical velocity component measured on the horizontal axis of the ball (lower figure). The right part of Fig. 7 shows the plots of dimensionless acceleration of the ball in the vertical direction and dimensionless horizontal relative velocity component. From the Fig. 7 it is apparent that both the maximal values of the acceleration and the fluid velocity correspond to each other and thus the changes of the golf ball acceleration in the horizontal direction are caused by non-symmetrical velocity field of the vertical component. Similarly to the left part of Fig. 7, the position of the maximal acceleration of the ball in the vertical direction corresponds very well with the position of the maximal relative horizontal velocity. These observations confirm the assumption that after the impact, the sphere movement is affected by the asymmetrical wake, formed during the falling period, and by the Bernoulli principle. Similar results were also obtained for the plastic sphere.

4. Conclusions

The movements of non-rotating spherical bodies, falling in water and their oblique impacts on the flat bottom were analyzed. There seem to exist additional forces which act on the bodies for a short time after the impact both in the horizontal and the vertical directions. These forces result from the Bernoulli principle and from a non- symmetrical motion of the wake after the oblique impact.

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