Wake formation behind a rolling sphere

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Experimental flow visualizations are presented depicting the flow behind a spherical body moving on a plane wall. In the Reynolds number range of $100<\mathrm{Re}<350$, four distinct wake modes occur which are dependent on the imposed rotation rate of the body. Five different rotation rates are examined: two with forward rolling, one with pure translation (zero rotation), and two with reversed rolling. As the sphere undergoes forward rolling, steady and unsteady wake modes are observed which bear similarities to the flow behind an isolated sphere in a free stream. However, for cases with reversed and zero rotation of the sphere, a new antisymmetric wake mode is discovered.
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Sedimenting particles near a wall experience fluid forces that exert a moment on the body, thus causing a rotation.[1–3] This phenomenon has been studied and the wake flows reported for a cylinder moving along a wall[4,5] but information on the resulting flows is still lacking for the case of the sphere. Experimental work by Liu *et al.*[6] found that small spheres dropped down an inclined plane could be forced into a reversed rotation by the hydrodynamic forces acting on the body. Similarly, three-dimensional numerical simulations by Zeng *et al.*[7] observed a net rotation when a particle moving through a still fluid at various distances from a wall was free to spin. In the latter study, a limited number of flow visualizations were presented, when the displacement between the sphere and the wall was equal to $0.5D$, where D is the sphere diameter. Both steady and unsteady modes were observed. In order to understand more fully the flow structures that form in this configuration, the present study examines the wake of a sphere as it is undergoing various rates of rotation, while adjacent to a plane wall.

Experiments were carried out in a recirculating water channel with a closed test section of dimensions of $12\times 15\times 80\ \mathrm{cm}^3$, equipped with a moving floor. The test section diverged slightly to compensate for increases in the free-stream velocity due to boundary layer growth on the upper and side walls. Boundary layer suction took place at the start of the working section to remove the boundary layer that developed upstream. This configuration allowed the sphere position to be fixed, while the adjacent tunnel floor moved past the body at the same velocity as the free stream flow. This is analogous to a sphere moving along a fixed wall through a quiescent fluid when a change of reference frame is taken into consideration.

A 9 mm diameter sphere was mounted midstream on a supporting rod with 1.5 mm diameter, as shown in Fig. 1. From previous experimental studies of the isolated sphere in a free stream, it has been found that the presence of similar supporting structures has negligible effect on the qualitative properties of the wake, when compared to the predicted numerical results.[8–11] Wherever possible, the sphere was positioned in contact with the floor. For the cases of $\alpha=-0.5$ and -1, when the relative motions of sphere and floor were in opposite directions, a small gap (approximately 5% of the diameter) was present. This distance was carefully minimized to prevent the moving floor from interfering with the sphere motion.

The rotation rate of the sphere α is defined as $D\omega/2\mathcal{U}$, where ω is the angular velocity of the sphere and $\mathcal{U}$ is the free stream/floor velocity. For a sphere moving in a still fluid, this equates to the ratio of the tangential velocity on the surface of the sphere to its translational velocity. Positive α is in the direction shown in Fig. 1 (representing forward rolling) and experiments were carried out for $\alpha=1$, 0.5, 0, -0.5, and -1. This covers the range of "normal" rolling with no slip, as would occur with a ball rolling along the ground, to the reversed rotation that has been observed in experi-

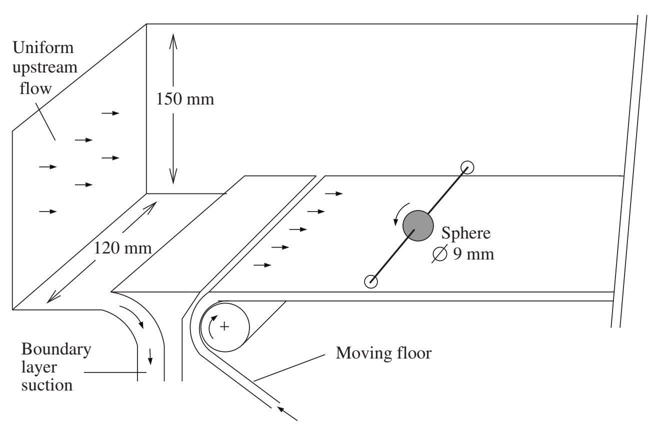

FIG. 1. Schematic showing the start of the working section in the water tunnel.

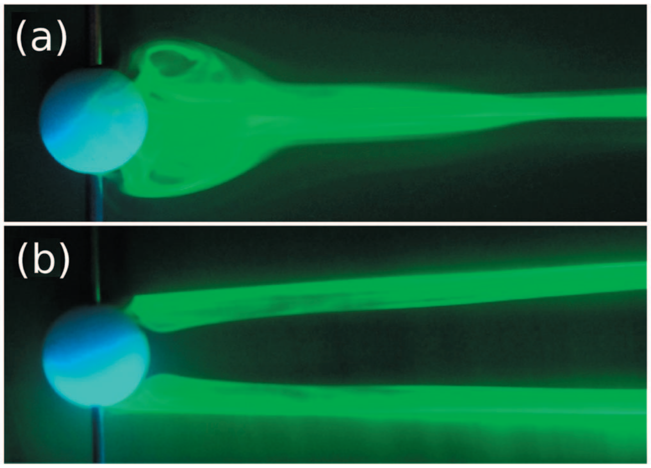

FIG. 2. (Color) Steady wake flows at Re=100 behind (a) the forward rolling sphere with α=0.5 and (b) reversed rotation with α=−0.5.

ments, such as those of Liu *et al.*[6] mentioned above. The Reynolds number Re was based on $\mathcal{U}$ and the sphere diameter and varied from 75 to 350. Visualizations of the flow were obtained using fluorescein dye, illuminated with light from an argon laser.

At the values of α and Re stated above, two steady wake modes are observed, which are dependent on the sense of rotation of the sphere. When α=1 and 0.5 (forward rolling), the motion on the upper half of the sphere opposes the direction of the free-stream flow. This opposing motion creates a zone of recirculating fluid. In addition, the fluid passing around the sides of the sphere moves into the low pressure region behind the body and into this recirculation zone. The resulting compact region of recirculating fluid is seen from above in Fig. 2(a). The dye escapes this recirculation zone via a single "tail," along the centerline of the body. The flow image shown in Fig. 2(a) bears similarities to the symmetry-breaking wake observed for the isolated sphere that occurs for Re>210.[9,10] However, in this case the presence of the wall appears to suppress the double-tailed wake that is generally observed in unbounded flow.

For α=−0.5 and −1 (reversed rolling), the upper surface of the sphere is moving in the same direction as the free-stream fluid. When one considers flow in the vertical centerplane of the sphere, the upstream fluid is free to move over the sphere surface and reattach to the moving floor in a relatively undisturbed fashion, thus preventing the formation of a recirculation zone. Instead, the reversed rotation wake shows a markedly different structure, in which the curvature of the sphere and the nearby moving wall cause the roll-up of fluid around the sides of the body, which forms a counter-rotating, streamwise vortex pair. For the wake shown in Fig. 2(b), the vorticity in the streamwise direction of the lower vortex is negative and that of the upper vortex is positive. This pair of vortices has an induced motion toward the wall (as described by Ersoy and Walker[12]) and once there, the distance between the two vortices increases as they progress downstream. For the case of α=0 (sliding), a similar wake is observed, with two distinct vortices forming a double tail behind the body.

As Re is increased and for all values of α, the wake experiences a transition to unsteady flow. For the cases of α=0.5 and 1, the shedding takes the form of hairpin vortices, as for the isolated sphere. This is shown in Fig. 3(a). In this instance, the proximity of the moving wall fixes the orientation of the wake, with the hairpin vortices forming over the top of the sphere and tilting away from the wall as they move downstream. The sense of rotation of the hairpin vortices is the same as that described by Achenbach[13] for the vortex shedding from an isolated sphere.

For $\alpha \leqslant 0$, the wake experiences a very different transition [as shown in Fig. 3(b)]. Here, the counter-rotating streamwise vortices maintain the same sense of rotation as for the steady flow but as they increase in size and strength, they begin to interact behind the body, causing an antisymmetric oscillation of the wake in the transverse direction. For α=0, the circulation of these vortices is much weaker than for the negative rotation rates, and the steady mode extends to much higher Re before the vortices begin to interact. Only at the upper range of Re considered in this investigation was an unsteadiness observed for α=0. This takes the form of a sinuous oscillation of the wake as it travels downstream and bears similarities to the initial onset of unsteady flow for $\alpha < 0$. Consequently, it is assumed that the same type of instability is observed for all $\alpha \leqslant 0$.

Initially, the sinuous oscillation appears to remain in a plane parallel to the moving floor, but as Re is increased further beyond the transition, an out of plane component becomes visible. The arrows in Fig. 3(b) indicate the points in the wake at which the vortices have lifted away from the floor. As one of these streamwise vortices is lifted away from the floor, a motion is induced in the opposite vortex, pulling it along the floor and toward the wake centerline. This motion produces an apparent narrowing of the wake (when viewed from above) at the indicated points, which corre-

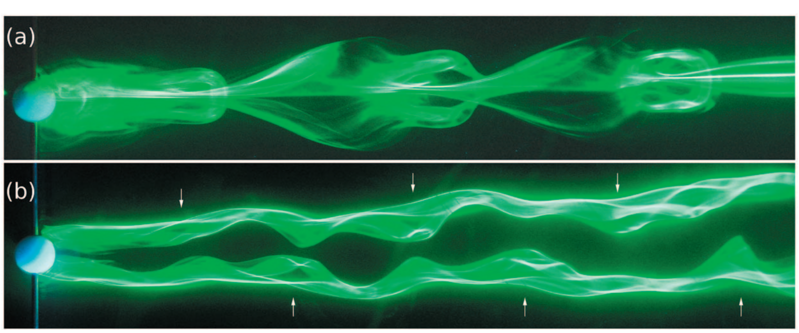

FIG. 3. (Color) Unsteady wake flows at Re=200 behind (a) the forward rolling sphere with α=1 and (b) reversed rotation with α=−1. The arrows indicate points of "lift-off" of the streamwise vortex from the floor.

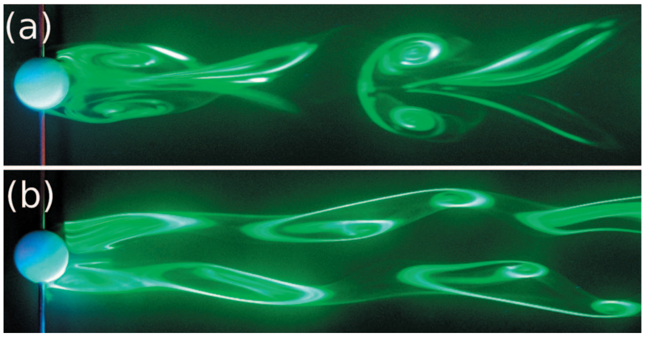

FIG. 4. (Color) The symmetry modes obtained by cutting the wake with a laser sheet positioned parallel to the moving floor at a height of $0.5D$. Images are given at Re=200 for (a) $\alpha=1$ and (b) $\alpha=-1$.

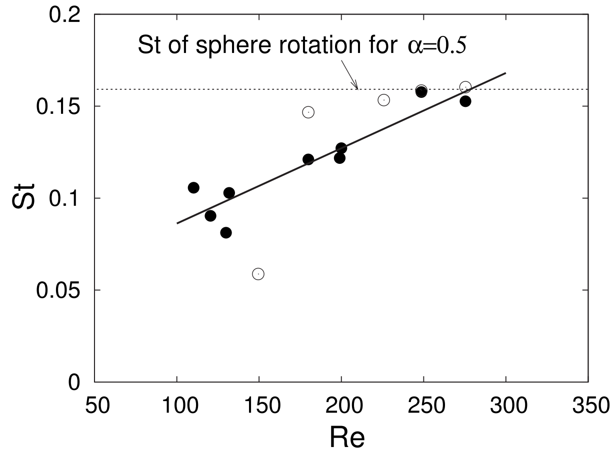

FIG. 6. Strouhal number variation for $\alpha=1$ (●) (with solid line indicating the linear best fit) and $\alpha=0.5$ (○).

sponds to an increased vertical displacement between the two vortices.

In order to better illustrate the symmetry of these different modes, Fig. 4 shows the wake pattern obtained by positioning a thin laser sheet parallel to the moving floor at a height of $0.5D$. The planar symmetry of Fig. 4(a), with $\alpha=1$, is clearly broken when $\alpha=-1$ [Fig. 4(b)] and a different mode is present. This image also helps to emphasize the three-dimensional structure that has arisen in the asymmetric mode of Fig. 3(b).

From the five different values of α under investigation, an indication can be given of the parameter space in which the four observed wake modes occur. The transition diagram is shown in Fig. 5, with the steady modes shown as open symbols. The transition to unsteady flow (closed symbols) is shown as Re is increased. It is expected that the Re thresholds for instability experience slight variations due to the presence of the supporting rod. The solid lines of Fig. 5 represent the mode limits determined visually from recordings of the dye patterns such as those shown above in Figs. 2 and 3. The dashed vertical line in Fig. 5 indicates a generalized boundary between the modes observed for $\alpha \leqslant 0$ and $\alpha > 0$.

The mode occurring for $\alpha > 0$ was the least stable, with a transition to unsteady flow occurring at Re $\approx$ 100 for $\alpha=1$. A change in the wake mode occurs for $0 < \alpha < 0.5$, and the antisymmetric mode of Fig. 3(b) becomes apparent. This mode appears to be less sensitive to small perturbations, indicating that a different mechanism brings about the transition to unsteady flow. As yet, the mechanism responsible for this transition to unsteady flow has not been clearly identified and is a topic of ongoing research.

For the sliding sphere with $\alpha=0$, the transition to unsteady flow occurs at Re just above 300. This is in agreement with the work of Zeng *et al.*,[7] who found that steady flow occurs at Re=300 for a wall distance of $0.25D$. In contrast, the sphere in a free-stream flow undergoes a transition to unsteady flow at Re $\approx$ 270.[11] For the larger, negative values of α, the transition Re reduces to Re $\approx$ 185 for $\alpha=-1$.

From the experimental data, the frequency of vortex shedding was obtained, and is shown in Figs. 6 and 7. The

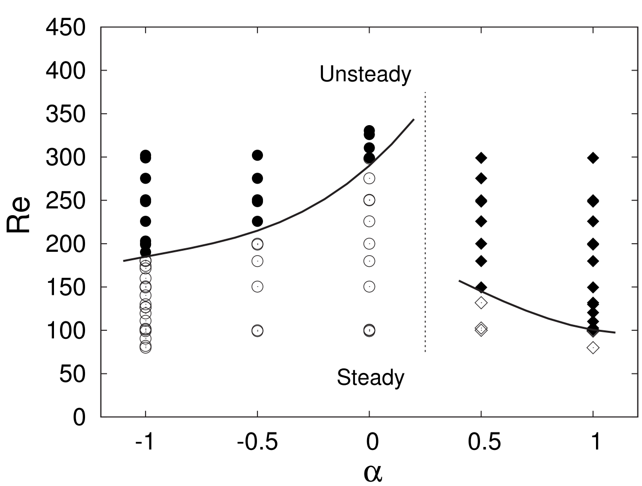

FIG. 5. Position in the parameter space of the four different wake modes observed. The closed symbols indicate unsteady modes and open symbols denote steady modes. The steady wake mode for $\alpha > 0$, and the corresponding unsteady mode displaying the shedding of hairpin vortices, are given by ◇ and ◆, respectively. Alternatively, the steady mode for $\alpha \leqslant 0$ comprising of counter-rotating streamwise vortices and the associated, antisymmetric mode, are given by ○ and ●, respectively.

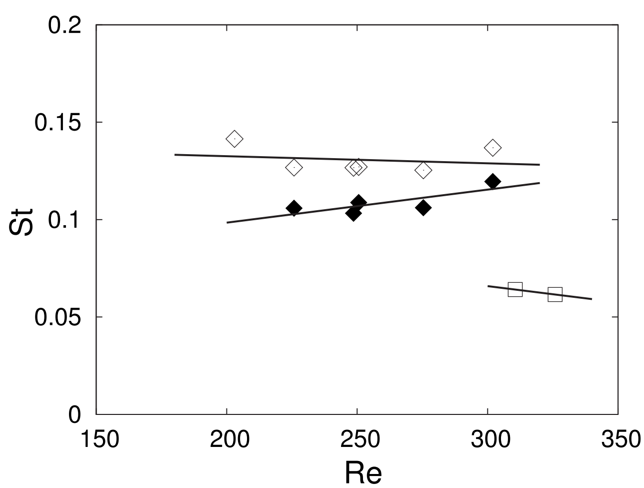

FIG. 7. Strouhal number variation for $\alpha=0$ (□), $\alpha=-0.5$ (◆) and $\alpha=-1$ (◇). The solid lines indicate the linear trends for each α.

Strouhal number (defined as $\mathrm{St}=fD/\mathcal{U}$, where f is the frequency of the instability) is shown as a function of the Reynolds number. For positive α (Fig. 6), the Strouhal number shows greater variation and the increasing linear trend for $\alpha=1$ is shown by the solid line in Fig. 6. It should be noted here that a possible synchronization of the shedding frequency and the sphere rotation was observed for $\alpha=0.5$. In this case, the values of the shedding frequency are close to the frequency of the sphere rotation. In such cases it is known that small perturbations in the body motion can cause a synchronization of the wake to the body frequency.[14] In Fig. 6, the value of St associated with the sphere motion is given by the dashed horizontal line. As Re increases, the frequency of vortex shedding experiences a sudden jump at $\mathrm{Re}>160$ to values much nearer this line, indicating that synchronization may have occurred. Such a discontinuity is not observed for any of the other rotation rates, and the values of St in other cases differ significantly from the frequency of the sphere motion.

For $\alpha=0$, -0.5, and -1, the antisymmetric flow shows little variation in frequency with Re. Instead, the average St decreases slightly as the magnitude of rotation is reduced. These values are in reasonable agreement with those of Zeng *et al.* who found values of $\mathrm{St}\approx 0.15$ for the sphere positioned $0.5D$ from the wall.

As a result of this study, a previously unobserved wake mode has been reported in which an antisymmetric mode is observed. This wake flow arises when a spherical particle is moving adjacent to a wall with reversed rotation. The steady mode which occurs at lower Re is characterized by two counter-rotating vortices with a region of largely undisturbed fluid along the wake centerline. As Re increases, this wake undergoes a transition to unsteady flow which displays a near-constant frequency. For the cases of positive rotation, the wake structures show many similarities to the flows reported behind a sphere in a free stream.

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