WAKE STRUCTURES BEHIND A ROLLING SPHERE ON A WALL

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Summary Flow visualizations are presented for the wake behind a spherical body moving along a plane wall in the Reynolds number range $100 < Re < 350$. Five different rotation rates are examined and as the sphere undergoes forward rolling, the observed wake modes bear similarities to the flow behind an isolated sphere in a free-stream. For cases with reversed and zero rotation of the sphere, a new anti-symmetric wake mode is observed.

EXPERIMENTAL RESULTS

Sedimenting particles near a wall experience fluid forces which exert a moment on the body, resulting in a net rotation [1]. The present study aims to understand more fully the flow structures that form in the wake of such a body. This has been examined, to a certain degree, for the cylinder moving along a wall [2, 3] but information is so far lacking for the case of the sphere.

Experiments were carried out in a closed water tunnel equipped with a moving floor. Boundary layer suction took place at the start of the working section to remove the boundary layer developing 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.

A 9mm diameter sphere was mounted mid-stream on a thin supporting rod. The rotation rate of the sphere, α, is defined as $R\omega/U$, where R is the sphere radius, ω is the angular velocity of the sphere and U is the free-stream/floor velocity. The case of $\alpha = 1$ corresponds to no-slip between the body and the wall. Experiments were carried out for $\alpha = 1, 0.5, 0, -0.5$ and -1, with Reynolds number, Re, based on the sphere diameter and varied from 100 to 350.

At the five values of α stated above, two steady wake modes are observed, which depend on the sense of rotation of the sphere. When $\alpha = 1$ and 0.5, a compact region of recirculating fluid forms around the body. This is shown from above in Fig. 1(a). This image bears similarities to the symmetry-breaking wake observed for the isolated sphere that occurs for $Re > 210$ [4]. However, in this case, the presence of the wall appears to suppress the double-tailed wake that is generally observed in unbounded flow.

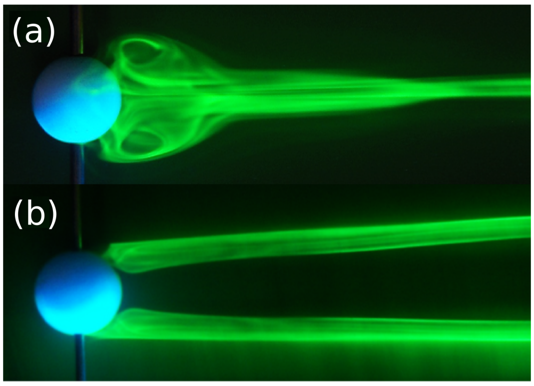

Figure 1. Steady wake flows at $Re = 100$ behind (a) the forward rolling sphere with $\alpha = 0.5$ and (b) reversed rotation with $\alpha = -0.5$.

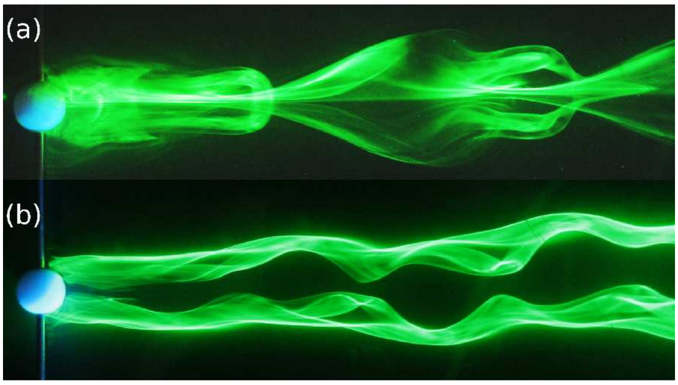

Figure 2. Unsteady wake flows at $Re = 200$ behind (a) the forward rolling sphere with $\alpha = 1$ and (b) reversed rotation with $\alpha = -1$.

For $\alpha = -0.5$ and -1, the upper surface of the sphere is moving in the same direction as the free-stream fluid, 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 form a counter-rotating, stream-wise vortex pair. This pair has an induced motion towards the wall (as described by Ersoy and Walker [5]) and once there, the vortices in the pair maintain an approximately constant distance from each other as they progress downstream. For the case of $\alpha = 0$, a similar wake is observed, with two distinct vortices forming a double tail behind the body. However, in this instance, the circulation of the vortices appears to be much weaker and the steady mode extends to much higher Re.

As Re is increased for all values of α, the wake experiences a transition to unsteady flow. For the cases of $\alpha = 0.5$ and 1, the shedding takes the form of hairpin vortices, as for the isolated sphere. This is shown in Fig. 2(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. For $\alpha \leq 0$, the wake experiences a very different transition (as shown in Fig. 2(b)). Here, the counter-rotating stream-wise vortices begin to interact behind the body, causing an anti-symmetric oscillation of the wake. Initially, this oscillation remains in a plane parallel to the moving floor, but as Re is increased beyond the transition, an out of plane component develops and the vortices lift away from the floor on alternating sides of the wake.

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. 3, with the steady modes shown as open symbols. It must be noted that the dashed lines of Fig. 3 are included as a guide only and do not precisely denote the transitions between modes.

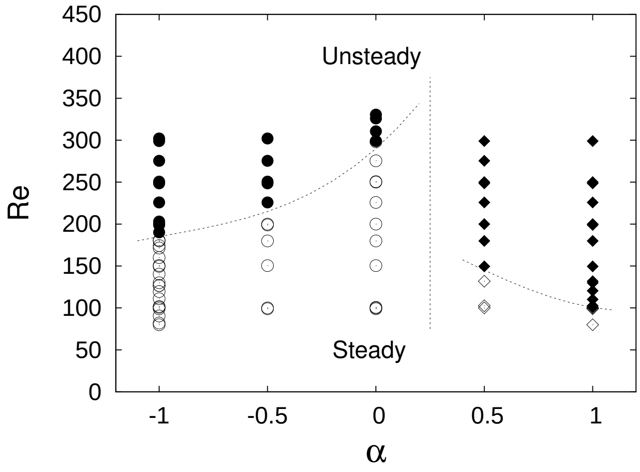

Figure 3. Position in the parameter space of the four observed wake modes. The steady wake mode for $\alpha > 0$, and the corresponding unsteady mode, displaying the shedding of hairpin vortices are given by $\diamond$ and $\blacklozenge$ respectively. Whereas, the steady and unsteady modes for $\alpha \leq 0$, consisting of two counter-rotating, streamwise vortices, are given by $\circ$ and $\bullet$ respectively.

The mode occurring for $\alpha > 0$ is 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. 2(b) becomes apparent. This mode appears to be less sensitive to small perturbations.

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.* [1], who found steady flow occurring 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 $Re \approx 270$ [6]. For the larger, negative values of α, the transition Re reduces to $Re \approx 185$ for $\alpha = -1$.

As a result of this study, a previously unobserved wake mode has been reported in which an anti-symmetric mode is observed. This mode arises when a spherical particle is moving adjacent to a wall with either zero or reversed rotation. This steady mode which occurs at lower Re is characterised by two counter-rotating vortices with a region of largely undisturbed fluid along the wake centreline. This mode undergoes a transition to an anti-symmetric, unsteady mode as Re is increased. For the case of positive rotation, the wake structures show many similarities to the flow reported behind a sphere in a free-stream.

Acknowledgments

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