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Characteristics of Flow past an Oscillating Sphere

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진동하는 구를 지나는 유동의 특성

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Abstract

Flow over a sphere under forced oscillation at Re=300 is simulated for various frequency ratios which are defined as excitation frequency over natural frequency of stationary sphere. The results of oscillating sphere are compared with those of stationary sphere and an oscillating cylinder. Detailed vortical structures, hydrodynamic forces and frequencies of the wake are prescribed as a function of frequency ratio. For oscillating sphere, planar symmetry of the wake is kept and two nearly symmetric hair pin vortices are induced by oscillation for one period of oscillation when the frequency ratio is bigger than 0.5. Modulation phenomenon which can be found in an oscillating cylinder were not seen for an oscillating sphere.

1. Introduction

Multiphase flow, particle transport and particle-laden flow have wide engineering applications such as combustion, chemical reaction and environmental control. Particles are usually modeled as a sphere and those particles translate, rotate and oscillate in the fluid. While there are lots of studies on the translating and rotating sphere, an oscillating sphere has been outside of researchers' interests. To the best of author' knowledge, only a few studies on oscillating sphere can be found. Govardhan & Williamson [1][2] investigated vortex induced motions of tethered sphere. Tethered sphere is applicable to marine buoys and underwater mines. They constrained free motions of sphere in one or two directions. Within a particular range of flow speeds, where the oscillation frequency is of the order of the static-body vortex shedding frequency, there exist two modes of periodic large-amplitude oscillation, defined as modes I and II, separated by a transition regime exhibiting non-periodic vibration. The dominant wake structure for both modes is a chain of streamwise vortex loops on alternating sides of the wake. Further downstream, the heads of the vortex loops pinch off to form a sequence of vortex rings.

2. Numerical method

2.1 Governing equations

The governing equations describing instantaneous incompressible viscous flow in a dimensionless form are given by the continuity and the momentum equations as follows;

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j \partial x_j} + f_i, \quad (1)$$

$$\frac{\partial u_i}{\partial x_i} - q = 0, \quad (2)$$

where f_i is momentum forcing for both of direct and feedback IBM and q is mass sink/source for immersed boundary method [3].

The equations are discretized on non-staggered Cartesian grids. A second-order accurate finite volume method is used in the present study where the second-order two-step fractional step method is employed for time advancement. The convection terms are treated explicitly using third-order Adams-Bashforth scheme and diffusion terms are treated implicitly using Crank-Nicolson scheme.

2.2 Computational details

Fig. 1 shows computational domain and boundary conditions for both of stationary and oscillatory sphere. Dirichlet conditions are used for the inlet, top and bottom walls. And convective outflow is applied to the outlet.

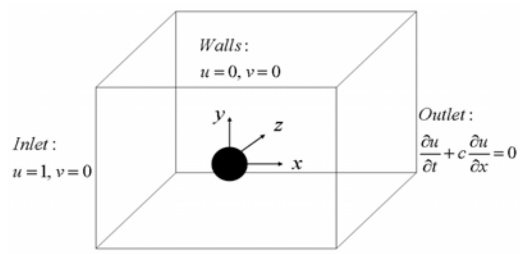

Figure 1. Computational domain and boundary conditions for a stationary and oscillating sphere

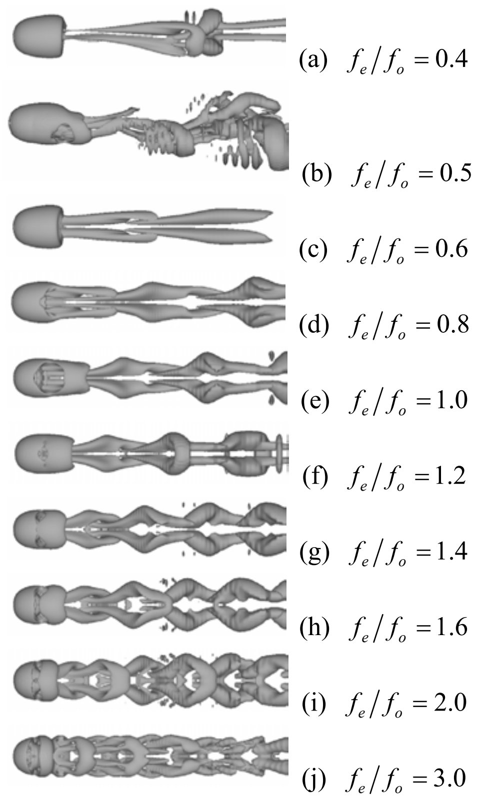

Figure 2 Instantaneous vortical structures at $x-z$ plane.

Domain size are $-15 \le x \le 25$, $-20 \le y \le 20$ and $-20 \le z \le 20$ and grid numbers are 300, 192 and 192 for x, y and z direction. Near the sphere, uniform grid ($\Delta x = \Delta y = 0.01666$) is used.

3. Results

Natural vortex shedding frequency of stationary sphere at $\mathrm{Re} = 300$ is 0.134 from present simulation and this frequency is designated as a reference frequency, f_o for the sphere oscillation. Amplitude is fixed as 0.2 same as the cylinder oscillation and frequencies are between 0.3 and 3.0

3.1 Planar symmetry

Stationary sphere has planar symmetric wake at $210 \le \mathrm{Re} \le 375$.[4] It seems natural that a sphere which is oscillating in one direction has planar symmetry about $x-y$ plane at $\mathrm{Re} = 300$ as oscillation strengthens the spanwise coherence.

Fig. 2 shows instantaneous vortical structures of oscillating sphere at various frequency ratios and Reynolds numbers at $x-z$ plane. The oscillating sphere shows planar symmetry for $f_e/f_o \ge 0.6$. For rather low frequency ratios, f_e/f_o =0.5 and 0.4 at $\mathrm{Re} = 300$, the wake is not planar symmetric anymore. At f_e/f_o =0.4 shown in Fig. 2(a), the vortical structures are similar to that of stationary sphere as they look like near planar symmetric about arbitrary $x-Y$ plane. But, the vortical legs are twisted. For f_e/f_o =0.5, the vortical structure is very complicated and shedding is not clear. From $f_e/f_o = 0.6$, the planar symmetry becomes clear and the streamwise vortex length that is attached to the sphere decreases and envelopes that are surrounding the oscillating sphere tend to be smaller as the frequency ratio is increased. The shape of rupture at low frequency ratios evolves from a hole and then the hole is getting bigger as the part of the envelope advected away and finally the envelope is torn into two vertical legs. But, for higher frequency ratios, the hole evolves not in streamwise but spanwise direction, so, the envelope is convected away without separation.

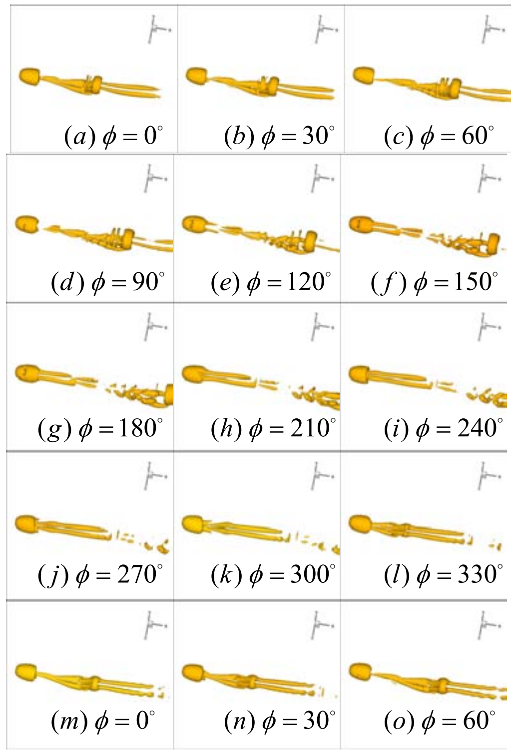

Figure 3 Time series of vortical structures of flow over a sphere at $f_e/f_o = 0.4$ and $\mathrm{Re} = 300$

3.2 Vortical structure

Fig. 3 shows time series of vortical structure of flow past an oscillating sphere at f_e/f_o =0.4. The flow is not planar symmetric as already mentioned. The flow is not periodic for one sphere oscillation ($0^\circ \le \phi \le 360^\circ$) as first three vortical structures are different from second figures for $\phi = 0^\circ, 30^\circ, 60^\circ$. As shown in Fig. 3, the hairpin vortex is at the connections of upper vortex legs and lower vortex legs as shown in Fig. 3 for second $\phi = 0^\circ, 30^\circ, 60^\circ$. As the oscillation frequency decreases to $f_e/f_o = 0.4$, vortical legs are twisted. For stationary sphere, rupture in envelop and hairpin vortex are in same direction, but for $f_e/f_o = 0.4$, they orient different directions. So, the vortical legs are twisted.

Fig. 4 shows time series of vortical structure of flow past an oscillating sphere at f_e/f_o =0.8. Generally, the vortical

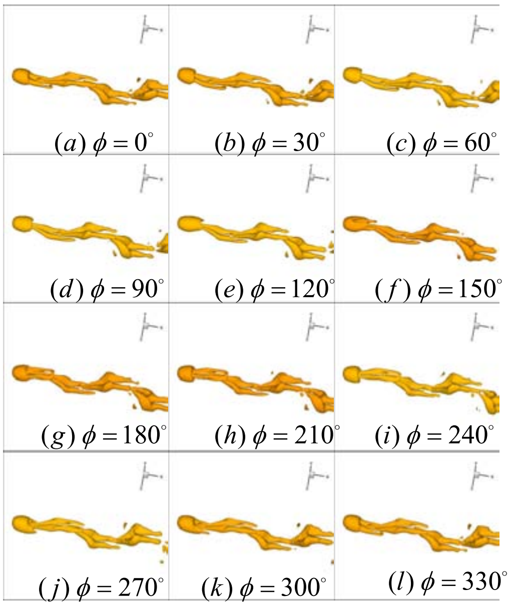

Figure 4 Time series of vortical structures of flow over a sphere at $f_e/f_o=0.8$ and $\mathrm{Re}=300$

structures for f_e/f_o =0.8 is similar to those of stationary cylinder. The lower and upper vortical structures are developing alternatively while flowing downstream. As the sphere is oscillating in y-direction, the vortical structures are elongated in y-direction comparing with those of stationary sphere. Instantaneous vortical structure for $\phi=0$ is shown in Fig. 4(a). Lower vortical legs are developing attached to the vortical structure enveloping the sphere. The lower legs are elongated more as the sphere goes up while upper legs advect with nearly unchanged length for $\phi=30^\circ \sim 90^\circ$ as shown in Fig. 4(b), (c) and (d). After sphere past an extreme upper position, $\phi=90^\circ$, the enveloping structure is developing in the upper side, flat envelop experiences rupture and separation into new upper vortical legs. These processes occur for $\phi=120 \sim 180$ as shown in Fig. 4(e), (f) and (g). The developing process looks similar to that of the upper legs of stationary sphere. The shape of torn envelope differs from that of stationary sphere and this results in different head shapes. Now the upper structure is developing as the sphere goes down for $\phi=180^\circ$ and 210°. In Fig. 4(j), the lower part of the envelope is now extending as happened at the upper side of the sphere in Fig. 4(e). While the stationary sphere has only one rupture of the envelope in one natural vortex shedding period, oscillating sphere experiences twice in one oscillation period. That means ruptures occur at the top side and bottom side alternatively. Also, Fig. 4(k) and (l) are similar to the upside-down structures of Fig. 4(f) and (g).

Fig. 5 shows time series of vortical structure of flow past an oscillating sphere at f_e/f_o =1.0. General patterns are similar to those of the case for f_e/f_o =0.8. The hairpin vortex can be seen clearly in Fig. 5(h). The rupture of the enveloping structure is similar to that of stationary sphere. A hole is growing in the mid of the envelope and torn envelope develops as vortical legs in Fig. 5(f), (g) and (h).

Fig. 6 shows time series of vortical structure of flow past an oscillating sphere at f_e/f_o =3.0, super harmonic frequency. The hole in the envelope for $\phi=90^\circ$ is seen and then develops in azimuthal direction for $\phi=120^\circ$. A band-shaped structure from envelope advects away from the sphere and shape is almost unchanged. As they are advected, they became hairpin-vortex-like structures. They have two pairs of vortex legs in the near wake and one pair diminishes as they flow downstream. The head of vortex loop is curved backward (to sphere) unlikely stationary or other oscillating spheres at lower frequency ratios.

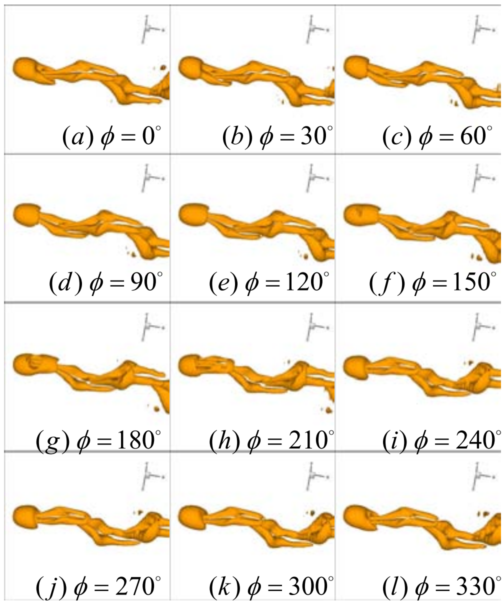

Figure 5 Time series of vortical structures of flow over a sphere at $f_e/f_o=1.0$ and $\mathrm{Re}=300$

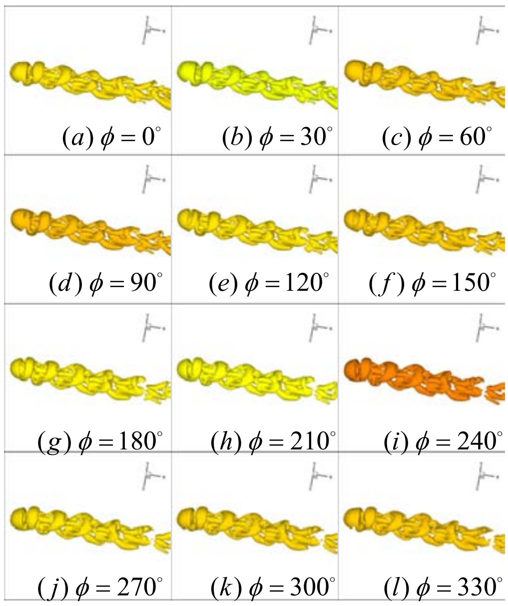

Figure 6 Time series of vortical structures of flow over a sphere at $f_e/f_o=3.0$ and $\mathrm{Re}=300$

4. Conclusions

Flow past oscillating cylinders and a sphere is simulated using immersed boundary methods.

There are several parameters to determine sphere oscillation, such as oscillation amplitude, frequency ratio and Reynolds number. In this study, amplitude is set as 0.2 and several frequency ratios near sub-harmonic and harmonic frequency and Reynolds number was selected as 300.

Although the oscillating sphere has two vortex sheddings in both directions, wake is not symmetric. Modulation phenomenon of oscillating cylinder does not appear for oscillating sphere. This may be related to the asymmetry of the wake of oscillating sphere.

At $\mathrm{Re} = 300$, stationary sphere has planar-symmetric wake. This is kept when the sphere is oscillating. But, at low frequency ratio $f_e / f_o \leq 0.5$, planar symmetry is lost..

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