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Numerical simulation of force and wake mode of an oscillating cylinder

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The turbulent flow behind a circular cylinder subjected to forced oscillation is numerically studied at a Reynolds number of 5500 by using three-dimensional Large Eddy Simulations (3-D LES) technique with the Smagorinsky model. The filtered equations are discretised using the finite volume method with an O-type structured grid and a second-order accurate method in both time and space. Firstly, the main wake parameters of a stationary cylinder are examined and compared in the different grid resolutions. Secondly, a transversely oscillating cylinder with a constant amplitude in a uniform flow is investigated. The cylinder oscillation frequency ranges between 0.75 and 0.95 of the natural Kármán frequency, and the excitation amplitude is moderate, 50% of the cylinder diameter. The flow characteristics of an oscillating cylinder are numerically examined and the corresponding wake modes are captured firstly in 3-D LES at Re=5500. A transition between different wake modes is firstly investigated in a set of numerical simulations.

1. Introduction

As the oil and gas field development activities have moved into deeper waters and areas of stronger ocean currents such as the Gulf of Mexico, the importance of Vortex-Induced Vibration (VIV) becomes more critical as it might result in serious engineering problems such as fatigue failure on offshore risers and sub-sea pipelines. Therefore, the problem of a circular cylinder oscillating in the fluid has received a great deal of attention and the prediction of the fluid forces on a circular cylinder is of the primary tasks in the design of the structures. While the experimental and numerical studies of the flow around a circular cylinder have been the centre of various investigations over many years, they still remain a challenging task due to the complexity of the flow in the wake.

One of the common approaches to study the VIV phenomenon is to force the body to oscillate with a predefined motion over a range of excitation amplitudes (A) and frequencies (f_e) that approximate VIV. Due to the large volume of literature on VIV study, the following review on both experimental and numerical studies is restricted to focus on a forced oscillating cylinder problem.

Bishop and Hassan (1964) investigated experimentally the forces exerted on an oscillating cylinder. Their experiments showed that there was an abrupt jump in the phase angle (ϕ_{Lift}) between the lift force and the cylinder motion when f_e is varied around the natural shedding frequency (f_K) for a stationary cylinder. They also observed an increase in the averaged values of drag and lift amplitude near frequency ratio $f_e/f_K \approx 1$. Sarpkaya (1978) also observed the sharp jump in the fluid force near the natural shedding frequency.

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Williamson and Roshko (1988) conducted an extensive experimental study of the different vortex shedding modes on an oscillating cylinder at various Reynolds numbers, Re = 300–1000. In their experiments, the three principal vortex-shedding modes near $f_e/f_K \approx 1$ were identified as 2S, 2P, and P+S mode. In their pioneering study, 2P mode represents two count-rotating pairs of vortices shed per oscillation cycle and 2S indicates two single vortices formed per oscillation cycle or natural Kármán mode of shedding. They found that there was a change in vortex shedding mode from 2P to 2S as f_e/f_K increased through unity. More recently, Morse and Williamson (2009) re-conducted the forced oscillation experiment to present further amplitude–response predictions and re-identify the relationship between forced oscillation and free-vibration at higher Reynolds numbers of 4000 and 12 000 with much higher resolution than in previous experiment (Williamson and Roshko, 1988). In their experiment, a high-amplitude regime in which two vortex-formation modes overlap was observed. Associated with this overlap regime, a new mode of vortex formation comprised two pairs of vortices formed per cycle, where the secondary vortex in each pair is much weaker than the primary, was identified as 2P overlap mode ($2P_o$) around the point where f_e/f_K equals unity.

Ongoren and Rockwell (1988) and Gu et al. (1994) examined the near wake structure behind an oscillating cylinder with very small amplitude ratios. Their experiments showed that there is a switch in timing of the vortex formation across the lift phase jump found by Bishop and Hassan (1964). As f_e/f_K approaches unity with a relatively low amplitude, elongated vorticity in the wake moves closer to the cylinder and forms a tight vorticity concentration in one side of cylinder. At $f_e/f_K \approx 1$ the initially formed vorticity concentration abruptly switches to the opposite side of the cylinder. This abrupt switch in the sign of the initial vortex was also observed at both laminar and sub-critical Reynolds number of 185 and 5000 respectively (Gu et al., 1994).

More recently, Carberry et al. (2001, 2003, 2005) performed controlled oscillation experiments at Re = 2300, 4100 and 9100 over small and moderate amplitude-to-cylinder diameter (A/D) ratios from 0.25 to 0.6. Their experiments showed that the low- and high-frequency wake state, which are characterised by the changes in the lift and the near wake structure, exhibited the 2P and 2S wake mode respectively. They clearly identified the intermediate wake state as a link between the low- and high-frequency wake state. Within the intermediate state, they showed that two wake modes are intrinsically linked by one-time transition from 2P to 2S wake mode, even while the amplitude and frequency were held constant. In the self-excited transition within the intermediate wake state, a new wake mode distinctly different from 2P and 2S wake mode was observed and the wake mode was characterised by the vortex lift phase ($\phi_{L\ \mathrm{vortex}}$), which is equivalent to $2P_o$ mode observed by Morse and Williamson (2009). One of the interesting aspects is that this self-excited transition was not always observed throughout their experiments at various Re and A/D, indicating that the transition is either very narrow or dependent on Re and A/D.

Several recent two- and three-dimensional (2-D and 3-D) numerical studies with particular focus on a forced oscillating cylinder problem have been performed. Lu and Dalton (1996) examined the oscillating cylinder by using a finite difference method to simulate 2-D flow. Their numerical study firstly showed good agreements with the vortex switching phenomenon observed by Gu et al. (1994). Guilmineau and Queutey (2002) also performed 2-D simulation of in-line and cross-flow oscillating cylinder at Re = 185, and their simulations are in a good agreement with both numerical results of Lu and Dalton (1996) and experimental data of Gu et al. (1994).

Blackburn and Henderson (1999) performed 2-D Direct Numerical Simulations (DNSs) of controlled oscillating cylinder at Re = 500 and validated that a change of the lift force on the oscillating cylinder was associated with a change in the timing of vortex. However, they did not observe the wake mode described by Williamson and Roshko (1988). Blackburn et al. (2000) conducted 3-D DNS study of the flow past a freely vibrating cylinder at Re = 556 and 2P wake mode was firstly captured in a set of numerical simulations. They stressed the significance of three-dimensionality in the wake and also suggested that 3-D simulation is required in order to reproduce wake response observed in experiments, even at low Reynolds number. Recently, Dong and Karniadakis (2005) conducted a 3-D DNS of an oscillating circular cylinder at a high Reynolds number of 10 000. Their direct simulation showed that the drag and lift coefficients of the forced oscillation were predicted reasonably well compared with experimental data. However, the vortex structures or wake modes were not presented in their numerical study. In spite of the limitation of 2-D simulation, 2-D simulations were widely applied to an oscillating cylinder problem. Atluri et al. (2009) performed extensive 2-D Large Eddy Simulations (LESs) of forced oscillating cylinder with a range of modulated excitation frequencies over a wide range of Re = 500–6000 and found qualitative agreement with experimental results.

While the numerical simulations with particular focus on an oscillating cylinder flow have been well investigated, the number of 3-D numerical results by using LES at moderate and high Reynolds number is very limited in literatures. Moreover, even though the numerical investigation by using 3-D DNS was successfully conducted at a high Reynolds number of 10 000 (Dong and Karniadakis, 2005), the experimental observation such as wake modes due to 3-D vortices was not covered in their study. Therefore, in this preliminary study by using the 3-D LES approach, the relation between the force and wake mode of the turbulent flow past an oscillating circular cylinder, observed in the experiment (Carberry et al., 2005) at sub-critical Reynolds numbers, is numerically examined at Re = 5500. The behaviour of time-dependent forces acting on an oscillating cylinder is numerically reproduced and transition between the wake modes is clearly presented by using 3-D LES simulation.

2. Flow modelling and computational approach

The LES method with Smagorinsky type sub-grid scale (SGS) modeling is employed for the 3-D unsteady turbulent flow in the wake using the spatially filtered Navier–Stokes equations along with continuity:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0, \tag{1}$$