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Two-dimensional and three-dimensional simulations of oscillatory flow around a circular cylinder

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ABSTRACT

Oscillatory flow around a cylinder is simulated using both two- and three-dimensional finite element models at $Re=2000$ and $KC=1$, 2, 5, 10, 17.5, 20 and 26.2. The same finite element method is used in both the two- and three-dimensional models. The purpose of this study is to investigate the feasibility of a two-dimensional model for simulating a three-dimensional flow in terms of fundamental flow characteristics and hydrodynamic forces. The vortex structures predicted by the two-dimensional model agree qualitatively with those by the three-dimensional model for the flow conditions where strong correlations exist along the span-wise direction ($KC=10$, 17.5 and 26.2). Three vortex shedding modes are reproduced by both two- and three-dimensional models at $KC=20$, which is close to the critical KC number between double-and three-pair regimes. The time histories of hydrodynamic force predicted by the two models agree with each other at $KC=20$. The predicted Morison force coefficients by the two-dimensional model are within 18% different from those predicted using the three-dimensional model for most of the cases. The two-dimensional model captures the majority of the genuine flow structures and hydrodynamic loads of a circular cylinder in an oscillatory flow.

1. Introduction

Oscillatory flow around a circular cylinder has been of significant interests in both academic and engineering communities for many years due to its rich flow features and engineering relevance. Oscillatory flow has been widely used to approximate the wave-induced water motions around cylindrical structures in offshore engineering where structures are designed against wave forces. An undisturbed oscillatory flow (far away from the structures) is often defined as $u(t)=U_m \sin(2\pi t/T)$, where U_m and T are the amplitude and the period of oscillatory velocity, respectively. It is well known that oscillatory flow characteristics around a circular cylinder is governed by KC number ($KC=U_mT/D$) and Reynolds number ($Re=U_mD/\nu$) or frequency number ($\beta=Re/KC=D^2/\nu T$), where D is the diameter of the cylinder and ν is the kinematic viscosity of fluid.

The topic of oscillatory flow around a circular cylinder can be examined through different setup of coordinate systems. In most of the experimental research, the cylinder was given an oscillatory motion in still water (Williamson, 1985; Tatsuno and Bearman, 1990; Lam and Dai, 2002), where the coordinate system was fixed with far field water. In numerical simulation works, it is more convenient to simulate an oscillating flow past a stationary cylinder (Justesen, 1991; Elston et al., 2006; An et al., 2011), where the coordinate system was fixed with the cylinder to avoid dealing with mesh deformation. The results from the two different research methods should be comparable with each other. The difference between an oscillating cylinder in a still fluid and a fixed cylinder in an oscillatory flow is that a fixed cylinder in an oscillatory flow experiences the Froude–Krylov force due to the pressure gradient along the oscillation direction, while an oscillating cylinder in a still fluid does not. Apart from this difference, the flow structures in the two cases are the same. To account for this difference, the inertial coefficient C_M that appears in the Morison equation can be written as $C_M=1+C_a$, where C_a is the added mass coefficient and 1 represents the contribution of the Froude–Krylov force. In the case of an oscillating cylinder in still water the Froude–Krylov force vanishes. In this work, it is referred to as *oscillatory flow around a circular cylinder* in the discussions.

Oscillatory flow around a circular cylinder involves many complicated flow phenomena, such as boundary layer separation, vortex shedding, and flow reversal, etc. The flow shows three-dimensional effect under most of flow conditions in practical engineering. A comprehensive review about the interaction between an oscillatory flow and a cylindrical structure is given by Sumer and Fredsøe (1997). Large amount of experimental

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investigations about oscillatory flow around a cylinder have been carried out to investigate the flow features. It was found that the transition of the flow from two-dimensional to three-dimensional is dependent on both KC and β. Oscillatory flow around a circular cylinder is two-dimensional only for very small KC numbers. The onset of three-dimensional flow structures was investigated by Honji (1981), Tatsuno and Bearman (1990) and Sarpkaya (1986). Sarpkaya (2002) proposed an empirical equation for the critical KC number based on experimental results

$$K_{cr}b^{2/5} = 12.5 \tag{1}$$

where K_{cr} represents the critical KC number above which the oscillatory flow becomes three-dimensional (Fig. 1). Williamson (1985) visualized the flow structures around an oscillatory cylinder in still water by means of particles on the free surface at $\beta=255$. Six vortex shedding regimes were found in the range of $1<KC<40$. Williamson (1985) found that the lift oscillations become less repeatable at large values of KC, suggesting the possibility of the co-existence of multiple vortex shedding regimes. Obasaju et al. (1988) measured the inline and lift forces of a circular cylinder in an oscillatory flow and found that the force coefficients were dependent on both KC and β. Lam et al. (2010) revisited the oscillatory flow in the range of $KC=8$–36 and $Re=2400$ and gave detailed description about migration, stretching, and splitting of vortices around the cylinder.

Extensive numerical simulations have been undertaken to investigate oscillatory flow around a circular cylinder during the last three decades. Most of the numerical studies conducted so far are two-dimensional (Justesen, 1991; Lin et al., 1996; Saghafian et al., 2003). Detailed discussion about the force coefficients, flow structures, pressure distribution and time histories of forces were given by Justesen (1991) in the range of $0.1<KC<26$ and $\beta=196$, 483 and 1035. Justesen (1991) also compared the numerical results of drag and inertia coefficients (C_D and C_M) with the experimental data in Obasaju et al. (1988). It was found that the numerical model tended to under-predict C_D and C_M slightly in the range of $1<KC<12$ ($\beta=196$). A good comparison was found for C_D in the range of $12<KC<26$, but C_M was under-predicted in this range. Saghafian et al. (2003) simulated oscillatory flows at high β numbers ($\beta=1035$ and 11,240) by solving two-dimensional Reynolds-Averaged Navier–Stokes (RANS) equations with a high order k–ε turbulent model. It was shown that the calculated drag and inertia coefficients agree with the experimental data reasonably well.

With the rapid increase of computational power in recent years, a number of three-dimensional numerical simulations have been carried out to investigate oscillatory flow around a circular cylinder and much improved understanding of flow mechanisms has been achieved. For examples, Honji instability (Honji, 1981) was numerically captured by Zhang and Dalton (1999) and An et al. (2011). Elston et al. (2006) simulated oscillatory flow in the range of $KC=0$–10, $\beta=0$–100 and investigated the primary and secondary instabilities of oscillatory flow around a circular cylinder. It was found that the primary instability of the oscillatory flow is three-dimensional (Honji instability) for $50<\beta<100$, which could not be captured by two-dimensional models. Zhao et al. (2011) carried out a number of three-dimensional simulations of oscillatory flow around an inclined cylinder in the range of $KC=6.75$–30 and a constant Re number of 2000. It was found the hydrodynamic forces follow the cosine law for flow incidence angle up to 45°.

Although three-dimensional simulations of various fluid flow problems have increased significantly in recent years due to the rapid increase in computing power, two-dimensional simulations are still widely used in engineering applications and will remain so for a period of time, mainly because of their low computational costs. This is especially important in front engineering phase when project schedules are tight. To use two-dimensional models with confidence, it is necessary to evaluate computational errors induced by two-dimensional simulations. So far, such an evaluation is unavailable for oscillatory flow around a circular cylinder, to the best knowledge of the authors. The present study is motivated primarily by this issue.

In this study, sinusoidal oscillatory flow past a circular cylinder is investigated using both two- and three-dimensional models at Re number of 2000 and KC number of 1, 2, 5, 10, 17.5, 20 and 26.2.

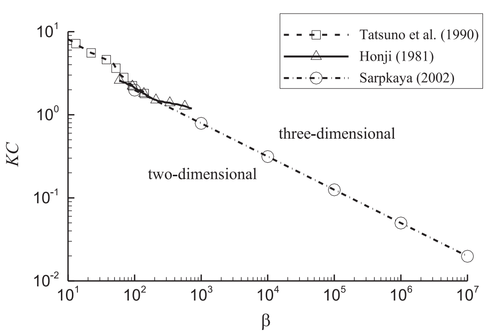

Fig. 1. The critical KC and β values for flow transition from two-dimensional to three-dimensional.

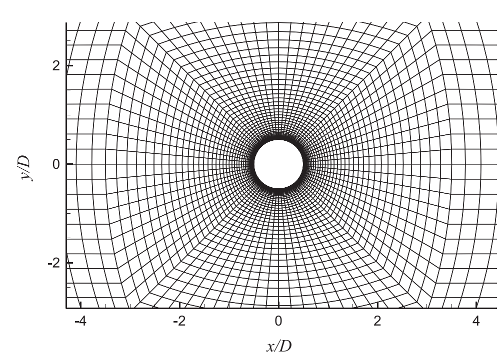

Fig. 3. The two-dimensional computational mesh around the cylinder.

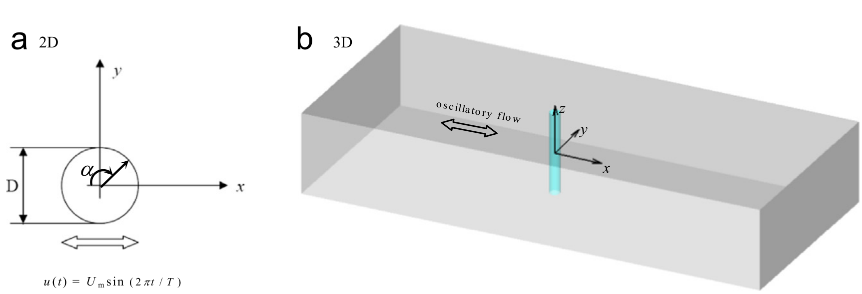

Fig. 2. A definition sketch of the computational domain.