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Numerical investigation of wake induced vibrations of cylinders in tandem arrangement at subcritical Reynolds numbers

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ABSTRACT

Wake-induced vibrations are considered distinctively different from well-known vortex induced vibrations where bluff body structures vibrate under vortex shedding in the wake of flows passing through them. Understanding characteristics of wake-induced vibrations plays an important role in design of marine-offshore structures such as platform columns, risers operating at high Reynolds number currents. This work presents an extensive study of wake-induced vibrations using a computational fluid dynamics approach. The numerical model is based on an incompressible Navier-Stokes flow solver with a hybrid detached eddy simulation (DES) approach for turbulence modelling of high Reynold number flows. The hybrid DES approach is first validated for wake-induced vibrations at subcritical Reynolds number ranging from $10^3 - 10^5$. Comparison between numerical results and experiment shows very good agreement in prediction of downstream cylinder responses including amplitudes, frequency and phase angle. Data from numerical simulations is then used to characterize and study mechanisms of wake-induced vibrations by looking at detailed force components and their frequencies in relation to cylinder responses. The effect of different Reynolds number flow conditions in tandem cylinder responses are also analysed in the present work. It is found that Reynolds number has strong influence in changing response amplitude and frequency of cylinders in wake-induced vibrations.

1. Introduction

Understanding of environment loads due to waves and currents is important in designing offshore structures such as cables, risers, mooring line systems. Apart from hydrostatic pressure forces, offshore structures under cross currents are normally subjected to dynamic load due to the well-known vortex shedding phenomena. Coupled interaction of vortex shedding from bluff bodies with its structural flexibility causes vibration responses of the structure. This vortex-induced vibration (VIV) is widely observed in various types of cylindrical structures in oceans, heat exchanger tubes, as well as chimney stacks, among others. These vibrations have been extensively studied in the literature (Williamson and Govardhan, 2004), and are modelled as resonant vibrations of elastically mounted and isolated rigid cylinders. Vibrations associated with the VIV phenomenon are known to have large amplitudes in an extended “lock-in” frequency region, where the response frequency f is maintained at near the natural frequency f_N of the structure over a range of driving frequencies f_F.

In most of offshore installations including deep sea oil-rig platforms, risers are arranged in bundles and arrays. Under array arrangement risers and similar cylindrical structures under cross flows may not only be affected by VIV but they also interfere with each other. It has been observed and noted (Paidoussis and Price, 1988) that arrays of cylinders are further subject to fluid-elastic instabilities that arise from interactions between adjacent cylinders in the array. Also termed wake-induced vibrations (WIV), these instabilities have been recognized as a distinct phenomenon from VIV and have been investigated extensively as well (Zdravkovich, 1977; Bokaian and Geoola, 1984; Brika and Laneville, 1999; Mittal and Kumar, 2001; Borazjani and Sotiropoulos, 2009; Assi et al., 2010a, 2010b; Huera-Huarte and Bearman, 2011; Assi et al., 2013; Chaplin and Batten, 2014; Assi, 2014). However, to date, no coherent theory has emerged on the WIV phenomenon, even though analyses involving nonlinear oscillators (Facchinetti et al., 2002; Armin and Srinil, 2013; Gallardo et al., 2014) and wake stiffness (Assi et al., 2010b, 2013; Assi, 2014) have been proposed. In particular, it has been suggested that WIV is not a resonant phenomenon, and that the response and driving frequencies are equivalent (Assi et al., 2010b, 2013; Assi, 2014). In addition, due to the coupling between the motion of the structure and the flow of the surrounding fluid, particularly the generation of vortices from the interaction between the fluid and the structure, it is conceivable that

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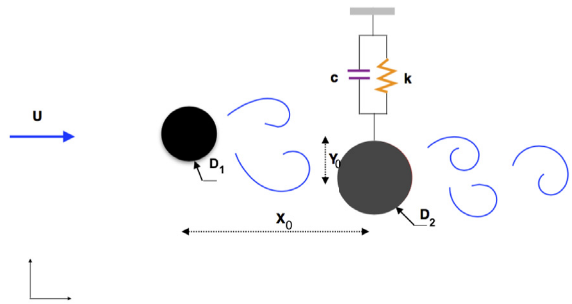

Fig. 1. Illustration of the physical setup in our model of tandem cylinders.

Table 1
List of numerical experiment conducted in the present work and their corresponding references if available. F1 is the case of fixed cylinders and all other cases are for studying of wake-induced vibrations.

Cases	Re	X/D	m^*	ζ_N	Reference
F1	2.0×10^4	4	–	–	Ljungkrona et al. (Ljungkrona et al., 1991)
W1	3.04×10^4	4.75	3.0	0.04	Hover and Triantafyllou (Hover and Triantafyllou, 2001)
W2	$0.2 - 3.0 \times 10^4$	5.0	2.6	0.007	Assi et al. (Assi et al., 2010b)
W3	1.0×10^4	4.75	3.0	0.04	–
W4	1.0×10^4	5.0	2.6	0.007	–

the frequency decomposition of the driving force is time-varying and possibly a harmonic.

Majority of earlier work on wake-induced vibrations are physical experiment listed above including many scaled model as well as full scale tests. While computational fluid dynamics (CFD) has become popular in engineering applications over the past few decades, its application in modelling and simulations of wake-induced vibrations is still limited and lacking behind experimental work. Among those limitations of CFD models for wake-induced vibration simulations is its predictive capabilities at high Reynolds number flows in the range of $\mathrm{Re} = 10^4 - 10^6$ corresponding to operational conditions of most offshore structures. Direct numerical simulations (DNS) have been attempted for vortex induced vibrations at $\mathrm{Re} = 10^4$ (Dong et al., 2006); however at the range of higher Reynolds number conditions, DNS becomes inhibited due to unrealistic computational demand even with present powerful computing infrastructures. Significance of resolving flows past cylinders at high Reynolds number has increasingly motivated the CFD community to explore various advanced turbulent modelling techniques from traditional industrial unsteady Reynolds average Navier-Stokes (URANS) (Rosetti et al., 2012) models to large eddy simulations (LES) (Feymark et al., 2012). In RANS all turbulence is modelled and it solves for ensemble average quantities. By separating flows to mean and fluctuating parts, RANS models normally require some empirical approximation to model turbulent fluctuations. In LES, larger turbulent scales are resolved while small scales called subgrid scales (SGS) are modelled. A spatial filtering is then employed to separate the resolved turbulence from its modelled counterpart. For accurate LES predictions, it requires a suitable filtering mechanism to separate large wave components from smaller ones at a cut-off frequency. Moreover it also restricts the time step and grid sizes, especially for wall bounded flows. As an attempt to strike a balance between resolving and modelling, detached eddy simulations DES (Travin et al., 2000; Spalart, 2009) was introduced as a hybrid RANS/LES approach. One can refer to those work as well as references cited therein for more details on the applications of various turbulence models for simulations of flow induced vibrations.

In this work, a fluid-structure interactions numerical model is presented as an alternative tool for investigation of wake-induced vibrations. Here, a fluid flow solver based on a DES approach (Nguyen et al., 2015) for turbulence modelling at high Reynolds number flows was used for simulations of wake-induced vibrations. The main objectives of the current work is two-fold. It is first to validate the FSI model through extensive benchmarking with experimental studies in prediction of WIV responses of tandem cylinders at the same flow conditions with physical experiment set-ups. The numerical model is capable of predicting WIV responses with pronounced agreement to earlier experimental data; thus making it a suitable alternative tool for further

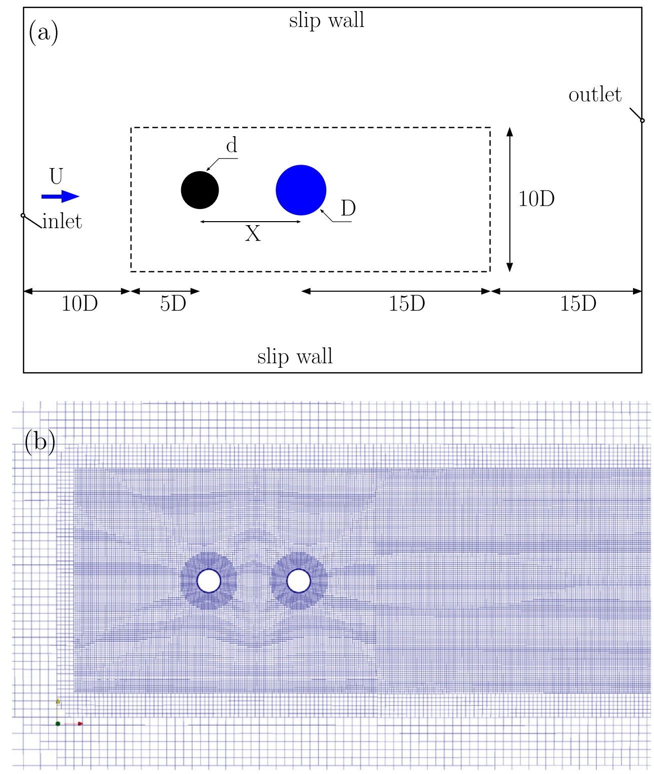

Fig. 2. Domain set up and typical grid for the current simulations of wake-induced vibration. (a) A computational domain with boundary conditions and the focus region bounded by the dash lines. A typical mesh topology used for the simulations with isotropic mesh refinemenet in the focus region. Boundary layer regions are generated around the cylinders with a-priori estimated of $y^+ \approx 1$.

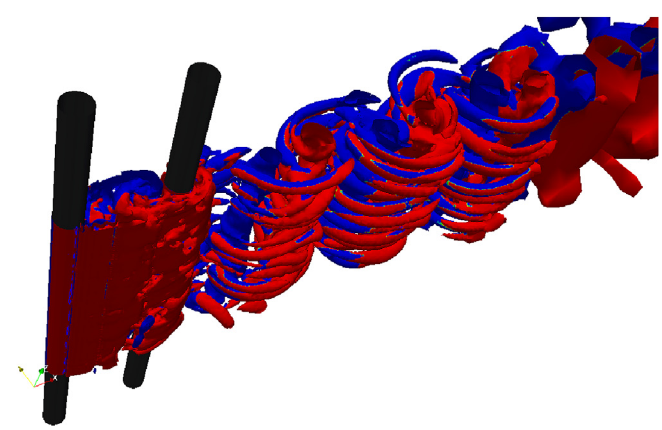

Fig. 3. Instantaneous isosurface of $Q = 1$ coloured by vorticity component in spanwise direction for flows over tandem cylinder at $X/D = 4$ and $\mathrm{Re} = 2 \times 10^4$. It shows complex three-dimensional wake structures resulted from upstream wake interacting with downstream cylinder.