Journal of Fluids and Structures 82 (2018) 101–120

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Analysis of fluctuating force acting on two cylinders in different arrangements through Lattice Boltzmann Method

H. Jiao, G.X. Wu *

Department of Mechanical Engineering, University College London, London WC1E 7JE, UK

HIGHLIGHTS

- The present work considers two circular cylinders in various arrangements and in a uniform incoming flow.
- Although there is a large amount of similar work for two bluff bodies, there has been hardly any work on systematic investigations of the fluid force components varying with alignment angles.
- Such result is extremely important for vortex-induced vibration and fatigue analysis of the cylinder.
- The problem is solved numerically by the lattice Boltzmann method coupled with the immersed boundary method. The extensive results have been provided to show the nature of the fluid force and vortex contour at different alignment angles.

ARTICLE INFO

Article history:
Received 3 July 2017
Received in revised form 4 May 2018
Accepted 15 June 2018

Keywords:
Two cylinders in different arrangements
Force components
Lattice Boltzmann method
Immersed boundary method

ABSTRACT

The force components on two circular cylinders in tandem, side-by-side and staggered arrangements and in a uniform incoming flow are investigated systematically with Reynolds number being taken $Re = 200$. The numerical simulations are undertaken using the lattice Boltzmann method and the boundary condition is imposed though the immersed boundary method. At an intermediate centre-to-centre spacing which is based on the ratio of distance between cylinder centres and the cylinder diameter, the fluid force is periodic and dominated virtually by a single frequency component in the tandem arrangement and is random with a continuous frequency spectrum in the side-by-side arrangement. Here random means that the components of the force are not in the form of discrete frequencies, but are in the form of continuous spectrum. Detailed analysis has been undertaken to show this evolution process with the alignment angle α, which is defined as the angle between the incoming flow direction and the line linking two cylinders. As α increases, the frequency component of the force on each individual cylinder changes from a single value to multiple ones, then to a large number of discrete ones and eventually to a broadband continuous spectrum. The results have important implications to vortex induced vibration and fatigue analysis of the cylinder, which has important applications, such as risers in offshore engineering.

1. Introduction

The flow past bluff bodies has been a subject of extensive interest due to its high complex physical phenomenon, the difficulty in mathematical modelling and numerical simulations, and its wide range of practical relevance. This kind of the

* Corresponding author.
E-mail address: g.wu@ucl.ac.uk (G.X. Wu).

https://doi.org/10.1016/j.jfluidstructs.2018.06.011

flow is common in engineering applications, such as oil exploration, heat exchangers, cables, bridge pilings and high-rise buildings. Compared with the flow over a single bluff body, the wake interference between multiple bluff bodies gives rise to the complete change of the flow characteristics, including the vortex shedding, which leads to a very different pattern of the force acting on the cylinder. Thus, some insightful analysis into flows in such a case is highly significant for a better understanding of physics of flow as well as better applications in many engineering practices. This paper uses the lattice Boltzmann method (LBM) together with immersed boundary method (IBM) for flow past two identical circular cylinders of equal diameter in different arrangement. The aim is to shed some further lights on the force acting on cylinders, as well as the pattern of the vortex shedding.

Flow characteristics in the two-cylinder system depend on the ratio of the centre-to-centre spacing (L) to the cylinder diameter (D), $L^* = L/D$, the alignment angle (α) between the line linking two cylinder centres and flow direction, as well as Reynolds number $Re = u_0 D/\upsilon$, where u_0 is the incoming free-stream velocity, and υ is the kinetic viscosity. Arrangements of two cylinders can be classified into three categories, including tandem ($\alpha = 0°$), staggered ($0° < \alpha < 90°$) and side-by-side ($\alpha = 90°$). Reviews of earlier work were given by Zdravkovich (1977, 1987, 2003) and more recent ones by Sumner (2010). Broadly speaking, at sufficient small L^*, the two cylinders behave like a single bluff body, while at sufficiently large L^*, they behave like two independent bodies in the free-stream and wake interaction between two cylinders vanishes. It is within certain range of L^*, the interactions between the flows past two cylinders become highly complex. Then at a given L^*, many of these interaction features are more sensitive to α than to Re when the flow is subcritical even though it may be unstable.

For cylinders in tandem arrangement, or $\alpha = 0°$, Zdravkovich (1987) discussed some essential features for this case based on experimental evidence. These features in the wake were also observed later by many numerical simulations (Slaouti and Stansby, 1992; Mittal et al., 1997; Meneghini et al., 2001). The two cylinders can be combined as a single bluff-body when $1 < L^* < 1.2 - 1.8$ (Zdravkovich, 1987). The free shear layer by the upstream body will pass by the downstream cylinder and the vortex shed from the two cylinders will be mainly in the wake behind the downstream cylinder. The oscillation of the flow is mainly periodic with period T_v. This gives the frequency $f_v = 1/T_v$, which is usually defined through the Strouhal number $St = f_v D/u_0$. Although the oscillation may have frequency components nf_v ($n = 1, 2, 3 \cdots$), $n = 1$ is usually dominant and it is usually referred as a single frequency oscillation. When $1.2 - 1.8 < L^* < 3.4 - 3.8$ (Zdravkovich, 1987), shear layer shed from the upstream body will reattach at the downstream body and a vortex street is formed only behind the downstream cylinder. The oscillation of the flow is still dominated by a single frequency. When $3 < L^* < 4$ (Zdravkovich, 2003) or $3 < L^* \leq 5$ (Xu and Zhou, 2004), the wake pattern behind the upstream cylinder or before the downstream cylinder may intermittently change between attachment on the downstream cylinder and eddy shedding from the upstream cylinder at a higher Reynolds number, say at an order around $o\left(10^4\right)$, and it is referred as " bi-stable flow" (Igarashi, 1981). The oscillation of flow has two different periods and two dominant frequency components at the bi-stable regimes. This can be understood by the fact for the upstream cylinder the incoming flow is steady and uniform. The flow behind the upstream cylinder or before the downstream body is, however, oscillatory. A new kind of oscillatory flow could be generated by the second cylinder, and hence two frequency components or bi-stable flow phenomenon. When $L^* > 3.4 - 3.8$ (Zdravkovich, 1987), the shed vortex will appear evidently behind each of the cylinders or co-shedding will occur. The oscillation is once again dominated by a single frequency. This could partly be due to the lock in effect (Xu and Zhou, 2004). Also at relatively lower Reynolds number, the oscillatory flow behind the upstream cylinder will decrease faster away from the cylinder because of the larger viscous effect. Thus as L^* increases, the flow to the downstream cylinder becomes more uniform. The value of the single frequency at this range of L^* is still different from that of an isolated cylinder. It can be expected, however, as L^* further increases, the frequency will tend to that corresponding to a single cylinder.

For the flow past two side-by-side ($\alpha = 90°$) cylinders, detailed discussions can be found in Bearman and Wadcock (1973), Williamson (1985), Kim and Durbin (1988), Sumner et al. (1999), Zhou et al. (2002), Kang (2003), Carini et al. (2014) and Singha et al. (2016). Sumner (2010) identified three flow regimes. When $1 \leq L^* \leq 1.1 - 1.2$, the flow behaves in a manner similar to that corresponding a single bluff-body, or "the single body case". The oscillation of the flow is dominated by a single frequency. The Strouhal number is not sensitive to L^* within this range and its value is lower than that of a single cylinder. When $1.1 - 1.2 \leq L^* \leq 2 - 2.2$, the gap flow between two side-by-side cylinders is asymmetrical and biased towards one cylinder. The bias may be permanent, the "deflected case" or alternate randomly, the "flip-flopping case". For deflected patterns, the developed flow is periodic and the oscillation of the flow is still dominated by a single frequency. For flip-flopping patterns, however, highly complex wake and vortex-street interaction occur. The oscillation of the flow is no longer periodic and therefore the frequency of flow oscillation is a broadband spectrum rather than discrete. When $L^* \geq 2 - 2.5$, two parallel synchronized vortex streets are formed, which can be either symmetric about the centreline between the cylinders, the "anti-phase case", or anti-symmetric, the "in-phase case". For both of these two cases, the flow is periodic and the flow oscillation is dominated by a single frequency, whose value is close to that for an isolated cylinder.

For two staggered ($0° < \alpha < 90°$) cylinders, studies have been undertaken by Kiya et al. (1980), Zdravkovich (1987), Sumner et al. (2000), Jester and Kallinderis (2003), Akbari and Price (2005), Hu and Zhou (2008a, b) and Tong et al. (2015). Sumner (2010) provided a comprehensive review. The interactions involve four shear layers from the upper and lower sides of two cylinders, Karman vortex formation process as well as two Karman vortex streets. The complex nature of the interactions depends on both the spacing ratio L^* and the alignment angle α. It is suggested that the behaviour of the St data can be classified into three groups by spacing ratio L^*. At all α and small spacing with $1 \leq L^* \leq 1.25$ (Sumner et al., 2000), the behaviour of the flow is similar to that of a single-bluff body. At $\alpha \leq 30°$ and $1.125 \leq L^* \leq 3-4$ (Sumner et al., 2000) the vortex shed by the lower cylinder is mostly suppressed, while at large spacing ratio ($L^* > 3 - 4$) (Sumner et al., 2000), in its