Computers and Fluids 124 (2016) 117–135

Contents lists available at ScienceDirect

Computers and Fluids

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

Dynamics of tandem cylinders in the vicinity of a plane moving wall

James Evon D'Souza, Rajeev Kumar Jaiman*, Chan Keet Mak

Department of Mechanical Engineering, National University of Singapore, Singapore 119077

ARTICLE INFO

Article history:
Received 1 December 2014
Revised 4 October 2015
Accepted 8 October 2015
Available online 28 October 2015

Keywords:
Tandem cylinders
Combined wake-wall interference
Stability analysis
Vortex suppression
Parallel double-vortex configuration
Force dynamics

ABSTRACT

We present dynamics of the flow around two cylinders in a tandem configuration along a moving plane wall. A spectral element method is employed to perform the simulations with high accuracy at Reynolds number $Re = 200$. A moving wall with no-slip boundary is considered rather than a stationary wall to avoid the confusing interaction of the wall boundary layer and thus focus completely on the influence of wall proximity effects on the force and wake dynamics. The influence of the moving wall with gap ratio $e/D = 0.2$–5.0 and longitudinal center-to-center separation $L/D = 1.5-8.0$ on the unsteady force dynamics is examined for the two cylinder configuration. Through detailed analysis of the flow field dynamics, we observe early transition from reattachment to co-shedding behavior. At co-shedding separation distances, the combined wake interference and wall proximity effects lead to a parallel double-row of vortices for the tandem cylinders at $Re = 200$ for $e/D = 0.5$. For a longitudinal separation of $4D$, the ratio of the street width h to distance between two adjacent vortices in the same row l is in good agreement with that obtained from inviscid theory. Finally, we provide detailed flow visualizations, Strouhal number and force coefficient trends and investigate recovery of freestream behavior as the tandem cylinder configuration of varying L/D is gradually distanced further from the moving plane wall.

1. Introduction

Flow past an isolated cylinder in a free-stream beyond a critical Reynolds number manifests itself as alternate vortex shedding in the cylinder's wake. This leads to the cylinder being subject to fluctuating lift and drag components. When such a cylinder is placed in proximity to a plane wall, the symmetry of the flow domain is broken as the wall interferes with the symmetric vortex shedding. Such a scenario is encountered in multiple engineering applications. An isolated pipeline in the free oceanic stream, for example, will experience vortex-induced vibrations if such alternate vortex shedding exists. However, if the pipeline is installed on the seabed itself, the interaction with the oceanic currents will be very much different. On occasion, the erosion of the seabed underneath the pipe structure, the installation method or the general unevenness of the terrain may lead to a gap between the sea bed and the pipeline. The above scenario can be modeled as the flow past a cylindrical structure in proximity to a plane wall. It is common practice to use isolated cylinder hydrodynamic coefficients (drag, lift, and inertia) to calculate the pipeline stability even if the pipeline is trenched or lying on the seabed. However, such an approach may lead to severe inconsistencies between predicted and actual flow induced structural loading. Hence, the need to characterize the nature of the flow and induced forces when the cylinder is in proximity to a plane wall. In particular, the wall-induced lift force is due to two competing mechanisms. First, the presence of a nearby wall breaks the symmetry of the wake vorticity distribution which results in an effective lift force that tends to move the cylinder away from the wall. Second, from inviscid theory one can argue that the flow relative to the cylinder will accelerate faster in the gap between the cylinder and the wall. The resulting low pressure in the gap will induce a lift force directed toward the wall.

The proximity effects of a cylinder to a plane wall at a given Reynolds number are characterized first by defining the gap ratio e/D as the ratio of the spacing between the cylinder and the moving plane wall and the diameter of the cylinder. Taneda's [1] experiments in a water tunnel by towing a circular cylinder parallel to a wall at low Reynolds numbers ($Re = 170$) showed a single vortex street in the cylinder's wake at a gap ratio $e/D = 0.1$. These vortices became unstable and broke down after a few wavelengths of propagation. It was reported that a regular double row of vortices was re-established as the gap ratio was increased to 0.6. Thereafter, several experiments for the flow around a cylinder in the presence of a single plane boundary have been reported at moderately high but sub-critical Reynolds number, $Re = 2 \times 10^4$ to 10^5 [2–5]. The approaching boundary layer implemented in most of the aforementioned studies was turbulent. The similarity among the results reported was that the hydrodynamic forces on the cylinder were modified with a slight variation of the shedding frequency.

* Corresponding author. Tel.: +6566012547.
E-mail address: mperkj@nus.edu.sg (R.K. Jaiman).

http://dx.doi.org/10.1016/j.compfluid.2015.10.010
0045-7930/

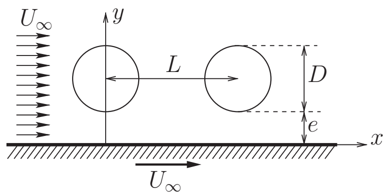

Fig. 1. Schematic of the computational domain and co-ordinate system for tandem cylinders.

Further, the suppression of vortex shedding was observed when the body was closer than a critical distance from the wall. In most studies, this critical spacing was found to be approximately at $e/D = 0.3$ to 0.4 [2–4,6] and decreases with increasing Reynolds number. For smaller gaps, the wake was almost steady and the periodic shedding was strongly inhibited with separation bubbles on the wall. Huang et al. [7] detailed a precise method in order to evaluate the critical gap ratio using 2D stability analysis of the mean streamwise gap velocity. Using Rayleigh's inflection point theorem they identified the critical gap ratio for $Re = 300$, 400, 500 and 600 observing an inverse relation between critical e/D and Reynolds number. They further concluded that the critical gap ratio corresponds to a local minimum of the streamwise maximum mean velocity in the gap. Price et al. [8] have shown experimentally at $Re = 1200$ that for small gap ratios ($e/D \leq 0.125$), the flow through the gap is suppressed or is extremely weak. The separation of the plane wall boundary layer is observed to occur both upstream and downstream of the cylinder. Although there is no regular vortex shedding, there is a periodicity associated with the outer shear layer. They reported that for intermediate gap ratios ($0.125 \leq e/D \leq 0.5$), the flow is very similar to that of very small gaps, except that there is now a pronounced pairing between the inner shear-layer shed from the cylinder and the wall boundary layer. Gap ratios higher than this are characterized by the onset of regular vortex shedding from the cylinder. Rao et al. [9] performed two-dimensional spectral-element simulations for flow past a circular cylinder translating parallel to a wall and linear stability analysis to determine onset of 3D effects in the wake at different gap heights. They observed that a steady two- to three- dimensional transition takes place at $e/D \leq 0.25$. For larger gap ratios the three-dimensional instability manifested itself post initial unsteady transition of the wake. The validity of the stability analysis results were confirmed through three-dimensional direct numerical simulations at $Re = 200$. They observed that the wake transits into a highly non-linear state after a non-dimensional time of 160. A comprehensive study of the more complex problem introduced by a rolling cylinder in close proximity to a plane wall has been detailed by Stewart et al. [10]. A wide range of Reynolds number from 20 to 500 were studied. The linear stability analysis revealed that the critical Reynolds number for three dimensional effects and the dominant mode were highly dependant on the cylinder rotation rate. Similarities were observed to flow past a backward facing step but no clear connection was established between the respective transition mechanisms.

When an additional cylinder is placed downstream of the first, the flow phenomena become further intricate and are now governed by the relative positioning of the two bluff bodies. Thus, in such a tandem configuration of two cylinders in proximity to a plane wall, an additional parameter in the form of the non-dimensional longitudinal spacing between the two cylinders L/D governs the flow dynamics. In the present study, this parameter has been defined in terms of the distance separating the centers of the two cylinders L as shown in Fig. 1. Three flow interference regimes [11,12]: proximity interference, an intermediate wake interference (reattachment) and co-shedding, can be identified for the tandem cylinder configuration. The range of spacing to diameter (L/D) ratio for each of these categories is problem dependent. In the proximity interference regime for $1 \leq L/D \leq 1.2$–1.8, negative drag is produced on the downstream cylinder and vortex shedding from the upstream cylinder is suppressed. The tandem bodies behave like a single bluff body and vortex shedding occurs behind the rear cylinder. In the wake interference or reattachment regime for 1.2–1.8 $\leq L/D \leq$ 3.4–3.8, a number of different phenomena such as shear layer reattachment, intermittent vortex shedding, etc. can be observed as the separation distance is gradually increased. In the regime of large spacing $L/D \geq 3.8$, so-called co-shedding regime, vortex shedding occurs from both the cylinders and there is no interference effect.

The critical separation distance for the onset of the co-shedding regime has been indicated by several researchers [13–15] both numerically and experimentally, for a wide range of Reynolds numbers to be between 3.5 and 5D in terms of L/D. The two-dimensional numerical simulations conducted for isolated tandem cylinders by Mittal et al. [16] and Meneghini et al. [17] showed a sharp increase of the drag coefficient and Strouhal number when this critical spacing was exceeded. This spacing is termed the drag inversion separation, where the drag coefficient of the downstream cylinder changes from negative to positive as the separation distance is increased. The parameter range of $Re = 200$ with $1.5 \leq L/D \leq 4$ chosen by Meneghini et al. enables comparison between an isolated tandem cylinder configuration in a free stream and the near-wall tandem cylinder configuration investigated in the present study.

Recently, Harichandan et al. [18] investigated the flow past square and circular cylinders in single and tandem configuration at $Re = 100$ and 200 in proximity to a plane wall. In their study, no-slip condition was employed at the stationary plane wall and hence the shear layer associated with the wall boundary layer interferes with the proximity effects. Harichandan observed that the wall shear layer leads to early dissipation of vortices shed from the single circular cylinder at lower Reynolds number $Re = 100$. The wall shear in addition effects the upward movement of the vortex pair in the near wake. However, even at this low Reynolds number, a stable separation bubble was observed to form in the cylinders wake and anchors itself to the plane wall. At $Re = 200$ the positive vortices shed from the lower surface of the cylinder de-stabilize the wall boundary layer leading to transient separation from the wall itself in the vicinity of the vortex shedding region of the cylinder wake. Furthermore, these positive vortices were reported to form a chain next to the wall via an anchoring mechanism. Rao et al. [19] performed comprehensive spectral element simulations in order to shed light on vortex dynamics and 3D stability of immersed tandem cylinders sliding close to a plane wall at a very small gap ratio $e/D = 0.005$. 2D simulations were performed in order to study onset of periodic unsteady flow for longitudinal spacings between $2.1 \leq L/D \leq 12$ for $Re \leq 200$. They observed that for higher longitudinal spacings of the order of $L/D \approx 12$, the transition to an unsteady flow occurs with synchronous shedding from both cylinders at a lower Reynolds number than that corresponding to a single cylinder near a wall. At intermediate separations $8 \leq L/D \leq 11$, two dominant frequencies have been reported in the FFT spectra, which can be attributed to the alternate shedding of strong and weak vortex pairs from the upstream cylinder and their interactions with the downstream cylinder. More complex phenomena introduced by rotation of the cylinders in single and tandem configurations have been documented by Rao et al. [20] where a reverse rotation was even shown to suppress three-dimensionality in the wake of a single cylinder.

In the present study, spectral-element based direct numerical simulations are performed for flow past two cylinders in a tandem configuration in proximity to a moving plane wall at $Re = 200$. Though cylinder vortex shedding is very much a 3D phenomena at such high Reynolds numbers, the 2D approximation is still useful in providing valuable insight into fundamental vortex dynamics and force trends. For completeness, initial simulations of a single cylinder near a plane moving wall at $Re = 200$ are performed to characterize