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Pressure field and wake modes analysis of an oscillating cylinder

Simone Mandelli [a,*], Sara Muggiasca [b], Stefano Malavasi [a]

[a] Department of Civil and Environmental Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, Milan, 20133 Italy
[b] Department of Mechanical Engineering, Politecnico di Milano, Via La Masa 34, Milan, Italy

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ABSTRACT

This work proposes a numerical investigation of the main flow field characteristics and pressure field analysis around a freely oscillating rigid circular cylinder immersed in a high Reynolds number flow in the subcritical range. The cylinder is characterized by high value of mass ratio and mass damping, while the damping itself is quite low. Here the numerical results are compared with experimental data obtained in the Politecnico di Milano wind tunnel under the same fluid dynamic and mechanical conditions. The preliminary check of this numerical setup was provided by considering the case of a fixed cylinder in the subcritical region. Based on this benchmark, the full setup was checked by considering fluid dynamic conditions outside the lock-in region.

Finally, a number of points were investigated on the cylinder's steady state response curve in the lock-in region. The numerical model yielded good results in terms of cylinder amplitude response, aerodynamic forces and pressure field analysis, in agreement with the results of the experiment. Analysis of the numerical reconstruction of the flow field evolution is therefore considered to yield further information on the vortex shedding mode, especially in the transition region between 2S and 2P mode.

1. Introduction

The flow around an oscillating cylinder has been widely investigated, primarily from the experimental point of view; Sarpkaya (2004), Williamson and Govardhan (2004) and Bearman (2011) offer an exhaustive overview of the whole field of vortex induced vibration of a circular cylinder. In order to investigate the fundamental mechanisms of VIV, numerous studies have focused on an elastically mounted rigid circular cylinder, with one or two degrees of freedom (Jauvtis and Williamson, 2003), on a flexible cylinder (Brika and Laneville, 1993), on suspended cables (Larsen and Larose, 2015), on a cylinder subject to forced motion (Williamson and Roshko, 1988), and on a cylinder under a uniform or oscillatory flow (Zhao et al., 2012). Regarding an elastically mounted cylinder in a uniform flow, the main dimensionless variables that influence the phenomena are: the mass ratio m^* ($m^*=4m/\rho\pi D^2$), the structural damping ratio ξ, the mass damping parameter $m^*\xi$, the reduced velocity $V/f_N D$, where V is the flow velocity and f_N the natural frequency of a cylinder with a diameter D, and the Reynolds number, Re. These variables depend on the fluid dynamic condition and on the set-up.

In the 60s, Feng performed experimental tests in air with a high mass ratio (Feng, 1968), while Khalak and Williamson (1999) recently performed tests in water at low mass ratios. On comparing their results with Feng's, the latter identified three types of cylinder amplitude response, which they called initial, upper and lower branches, depending on the velocity ratio for the low-mass damping system. Later, they showed that in the case of a high mass ratio, as in Feng's experiment (Feng, 1968), there are only two branches: initial and lower. In addition to the mass ratio and structural damping, the response amplitude is also influenced by the Reynolds number, as underlined by recent studies at high Reynolds number (Raghavan and Bernitsas, 2011; Zasso et al., 2008). On this subject, Govardhan and Williamson (2006) discovered that the Reynolds number plays a decisive role in the "Griffin Plot": peak-amplitude oscillations depend not only on mass damping but also on Reynolds number, and the response amplitude shows higher vibration than expected.

Another important aspect is wake topology, which is related to amplitude response and velocity ratio. On the "vortex map", Williamson and Roshko (1988) reported different vortex shedding modes of a circular cylinder subjected to forced oscillations. Furthermore, as reported by Govardhan and Williamson (2000), in the case of an elastically mounted cylinder in a uniform flow, two main kinds of vortex topology may be observed. In particular, through DPIV measurement, they reported on two main vortex shedding modes, depending on the type of branch, characterized respectively by the shedding of two vortices at every cycle (2S) and every half-cycle (2P) of cylinder oscillation.

* Corresponding author.
E-mail addresses: simone.mandelli@polimi.it (S. Mandelli), sara.muggiasca@polimi.it (S. Muggiasca), stefano.malavasi@polimi.it (S. Malavasi).

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Nomenclature

D	Cylinder diameter [m]
L	Cylinder length [m]
f_N	Natural frequency [Hz]
Re	Reynolds number [–]
S_t	Strouhal number [–]
f_{St}	Strouhal frequency (f_{St}=f_N V/D)
f^*	Frequency ratio (f^*=f/f_{St})
V_s	Strouhal velocity (V_s=f_N D/S_t) [–]
V	Free stream velocity [m/s]
z	Cross-flow cylinder oscillations amplitude [m]
z/D	Non-dimensional displacement [–]
V/V_s	Velocity ratio [–]
m^*	Mass ratio (m^*=$4m/\rho\pi D^2$) [–]
ξ	Structural non-dimensional damping [–]
$m^*\xi$	Mass damping [–]
k	Spring stiffness [N/m]
μ, ρ	Air viscosity, air density [Pa•s, kg/m^3]
C_d	Mean Drag coefficient [–]
C_L	Amplitude of first harmonic Lift coefficient [–]
$C_L(t)$	Lift coefficient [–]
C'_L	Standard deviation of Lift Coefficient [–]
C_p	Pressure coefficient (C_p=$2(p-p_0)/\rho V$) [–]
p	Pressure [Pa]
p_0	Reference pressure [Pa]
h	Characteristic cell size (N_{cell}/Volume) [–]
h_{ref}	Reference cell size
T	Cylinder oscillations' mean period [s]
τ	Non-dimensional time-step $\tau = \Delta tV/D$ [–]
Θ	Angle between wind velocity and a position along the cylinder section

It is important to note that most of these investigations were conducted on cylinders with small diameters ($0.02\ \text{m} < D < 0.09\ \text{m}$), low mass ratio range and low mass damping range (Blackburn and Henderson, 1999; Feng, 1968; Govardhan and Williamson, 2000; Khalak and Williamson, 1999; Klamo et al., 2005), but were also often performed at a low Reynolds number. On the other hand, these studies generally share a key interest in terms of amplitude response, force and wake topology.

In recent years, several tests have been conducted in the Politecnico di Milano Wind Tunnel in order to study the vortex induced vibration of a circular cylinder characterized by a high Reynolds number, low damping but high mass damping (Belloli et al., 2015, 2012; Malavasi et al., 2011; Zasso et al., 2008). In these previous works, a lot of experimental tests were conducted, performing pressure and flow field measurement with the PSV (Particle Streak Velocimetry) technique (Malavasi et al., 2011; Zappa et al., 2013). Frequency analysis, time histories analysis, phase averaged flow field and pressure field visualization were performed. The main interest lies in the in-depth study of forces, power input and system response in the lock-in region in terms of frequency and steady state analysis, and finally, in the identification of the vortex shedding mode through wake visualization and wake frequency analysis. As already observed (Malavasi et al., 2011; Zappa et al., 2013), it was difficult to clearly identify vortex shedding modes in the experimental test. Zasso et al. (2008) measured instantaneous pressure distribution on a cylinder section with the purpose of correlating these measures with the behavior and topology of vortex structures.

As regarding numerical studies, several studies have been conducted at a low Reynolds number with Direct Simulation (DNS)or Large Eddy Simulation (LES) (Blackburn and Henderson, 1999; Blackburn, 2001; Catalano et al., 2003; Dong and Karniadakis, 2005). Instead, less work has been carried out with 3D unsteady RANS simulation at a high Reynolds number (Unal et al., 2010; Wu et al., 2014). Blackburn (2001) showed that 2D DNS of controlled oscillating cylinder is not suitable for the reproduction of the proper cylinder response and they did not found the wake mode as illustrated by Williamson and Roshko (1988). While with a 3D DNS, 2P wake mode was firstly captured with phase averaged contour vorticity plot in a numerical simulation. He suggested the importance of three dimensionality in the wake and consequently, even at low Reynolds number, 3D simulations are required for those analyses. Recently, Dong and Karniadakis (2005) performed a 3D DNS of an oscillating circular cylinder at a high Reynolds number of 10,000. They predict very well displacement and forces coefficients but they did not present the wake structure. Wang and Catalano (2001) found that the computational approach using LES or hybrid scheme, such as DES (Detached Eddy Simulations), showed better prediction than RANS at less computational expense than DNS. Despite the limits of 2D simulation, they were widely applied to an oscillating cylinder problem for the less computational cost. Recently (Wu et al., 2014) performed a 2D RANS simulation at high Reynolds number (up to $Re = 130000$) and they found good agreement in terms of amplitude, frequency response and they identified correctly the vortex shedding in the wake region.

Even with the improvement of computational resources and the case of an oscillating cylinder flow has been widely investigated, the number of 3D URANS simulations at high Reynolds number is quite limited in literature. Moreover, as far as the authors know, there are no numerical works showing pressure distributions compared with experimental results.

In the present work the CFD commercial code StarCCM+ is used to reproduce a number of experimental test conditions with the aim of better understanding the fluid dynamic behavior of the cylinders in different lock-in conditions through an in-depth comparison between experimental and numerical data, particularly on cylinder pressure distribution.

2. Model set-up

Before introducing the numerical study, and discussing the results, we will briefly summarize the experimental set-up of previous investigations considered.

2.1. Experimental set-up

The experimental model involved a smooth acrylic cylinder with an aspect ratio of $L/D = 10$ ($D = 0.2$ m), elastically mounted in the large test section of the Politecnico di Milano wind tunnel ($14\ \text{m} \times 14\ \text{m}$). A constraint system was created using two tensioned wires passing through the cylinder and acting as vertical springs. Possible coupling of horizontal and torsional motions was avoided by separating horizontal-vertical and torsional-vertical frequencies. Moreover, the cylinder was equipped with two large end-plates at the two sides to create two dimensional flow conditions. The main mechanical characteristics of the oscillating system are summarized in Table 1. Due to the dimensions of the test section, blockage effects can be assumed to be negligible. The Strouhal number was estimated to be equal to S_t=0. 18 during a

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