Ocean Engineering 117 (2016) 130–142

Contents lists available at ScienceDirect

Ocean Engineering

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

Effect of tip-flow on vortex induced vibration of circular cylinders for $Re < 1.2 * 10^5$

Omer Kemal Kinaci[a,b,*,1], Sami Lakka[a,1], Hai Sun[a,c,1], Michael M. Bernitsas[a,d,2,3]

[a] Marine Renewable Energy Laboratory, Department of Naval Architecture & Marine Engineering, University of Michigan, 2600 Draper Road, Ann Arbor, MI 48109-2145, USA
[b] Yildiz Technical University, Istanbul, Turkey
[c] Harbin Engineering University, Harbin, China
[d] Department of Mechanical Engineering, University of Michigan, USA

ARTICLE INFO

Article history:
Received 10 July 2015
Received in revised form
19 January 2016
Accepted 20 March 2016
Available online 31 March 2016

Keywords:
Tip-flow correction
Vortex induced vibrations
Computational fluid dynamics
Two-dimensional approximation
Experimental validation

ABSTRACT

In two-dimensional experimental setups, tip-flow cannot be eliminated completely. In one degree-of-freedom Flow Induced Motions (FIM) of circular cylinders placed perpendicular to a uniform flow, three-dimensional effects may become significant. An ideal setup extends the cylinder to the limits of the flow-channel to minimize tip vortices, which reduce the effective length of the cylinder. Depending on how close to two-dimensional the experimental setup is, obtained results may differ. It is difficult to avoid the tip-flow in nature as well. Applications involving Vortex-Induced Vibrations (VIV) have more or less three-dimensional flow characteristics and one of the manifestations of three-dimensionality is the tip-flow. In this paper, the effects of tip-flow on VIV are investigated both experimentally and computationally. It is found that the tip-flow reduces the lift force exerted on the cylinder and narrows down the range of synchronization. Two-dimensional computational simulations become insufficient to grasp the effects of the tip-flow for a cylinder in VIV as the Reynolds number increases. Computational results for vortex-induced vibrations at these relatively high Reynolds numbers (up to $1.2_* 10^5$) in the TrSL3 flow regime are not satisfactory when compared with experimental results. To improve the CFD predictions by introducing three-dimensional (3D) flow characteristics in a two-dimensional (2D) computational environment, a parameter called *tip-flow correction factor* is defined and analyzed. This parameter is introduced to compensate for any deviations from 2D flow approximation that might arise due to the 3D nature of the flow. The tip-flow correction factor is implemented as a multiplier of the force term in the vibration equation to represent the lift-force losses caused by the tip vortex. When compared to the results obtained with straightforward use of the vibration equation, it is found that the tip-flow correction factor improves the agreement between 2D computational results and experimental measurements. This method extends the validity of 2D-URANS simulations at least up to $Re = 1.2_* 10^5$for which experimental results are available in this study.

1. Introduction

A two-dimensional flow is less complex compared to the corresponding three-dimensional flow. The former lacks cross-flow, cellular shedding and tip-vortices, which complicate the flow and becloud our understanding of what is the physically underlying phenomenon. For those reasons, experimental setups are usually designed so that they minimize the three-dimensional effects of the flow, thus allowing isolation of the fundamental aspects of the phenomenon or flow under consideration. Two-dimensional flows are preferred not only in experimental measurements but in computational simulations as well, as the computational cost decreases substantially and the stability of the computational solution increases in 2D analysis.

Although a two-dimensional approach has many advantages, both in terms of understanding the underlying flow and simplifying the computational approach, some aspects of the flow are lost due to this assumption. It is impossible to completely eliminate three-dimensionality in laboratory setups because a moving

---

[*] Corresponding author at: Marine Renewable Energy Laboratory, Department of Naval Architecture & Marine Engineering, University of Michigan, 2600 Draper Road, Ann Arbor, MI 48109-2145, USA.
E-mail address: kinaci@yildiz.edu.tr (O.K. Kinaci).
[1] Post-Doctoral Fellow.
[2] CTO of Vortex Hydro Energy.
[3] Director MRELab, Mortimer E. Cooley Collegiate Professor of Engineering.

http://dx.doi.org/10.1016/j.oceaneng.2016.03.055
0029-8018/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

c	mechanical damping
C_a	added mass coefficient
C_y	lift coefficient
D	cylinder diameter
$f_{n,w}$	natural frequency in still water
$f_{n,v}$	natural frequency in vacuum
f_{osc}	oscillation frequency
F_y	fluid force exerted on the cylinder
k	spring stiffness
L	cylinder length
L_e	effective length of the cylinder
m^*	mass ratio
m_{osc}	oscillating mass
U^*	reduced velocity
U	flow velocity
w_c	width of the test section
α	tip-flow correction factor
ρ	fluid density
ϕ	phase difference
ζ	damping coefficient

cylinder cannot be extended to the boundaries of the flow domain, which are the walls of the recirculating channel. There is no established standard on eliminating three-dimensionality of flows in experiments. The traditional approach is to try to extend the cylinder to the limits of the flow regime or attach large endplates. Some researchers improve two-dimensionality of flows by the addition of endplates (Govardhan and Williamson, 2000; Hover et al., 2004) while the others minimize the gap between the boundary of the flow regime and the cylinder (Feng, 1968; Park et al., 2013). This uncertainty in experiments leads to modeling discrepancies making it harder to evaluate and compare results from different tests. For example, two dimensional flow assumption does not allow investigation of the forces (Hover et al., 1998) and the vortex pattern (Techet et al., 1998) of tapered cylinders. Another example would be the tip effect, which is usually neglected by many researchers but has a strong impact both on the maximum amplitude and the range of synchronization for a circular cylinder in VIV. The fundamental challenge addressed in this study is to provide an explanation of the difference between experimental results due to three dimensional flow effects for cylinders in vortex-induced vibrations. Hover et al. (2004) reported that low-aspect ratio cylinder VIV is dominated by the end-effects and aspect ratios of over 70 are required to observe a clear two dimensional vortex shedding at the mid-span of the cylinder. Norberg (1994) covered a wide range of Reynolds numbers for the flow around circular cylinders and concluded that cylinders that have aspect ratios less than 7 have “bi-stable flow switching between regular vortex shedding and irregular flow” in the subcritical regime.

The scope of this study is to understand the effects of tip-flow in vortex-induced vibrations. Experimental demonstration of tip-flow is discussed in Section 2 and field-test verification is provided in Section 3. Mathematical formulation and CFD simulations for VIV are discussed in Sections 4 and 5, respectively. Results are presented in Section 6 and insight into the use of the tip-flow correction factor in Section 7. Conclusions are presented at the end of the paper.

2. Experimental demonstration of tip-flow and its effects

The free end of a cylinder can cause the flow perpendicular to the cylinder axis to be strongly 3D rendering basic 2D-flow assumptions invalid (Sumner et al., 2004). They reported in their study that the tip flow from the free ends can affect the whole flow around cylinders that have smaller aspect ratios. Their study covers the flow around stationary cylinders showing the different wake modes of cylinders with different aspect ratios. Schematic of the flow around the tip of a cylinder is given in Fig. 1 (Sumner, 2013).

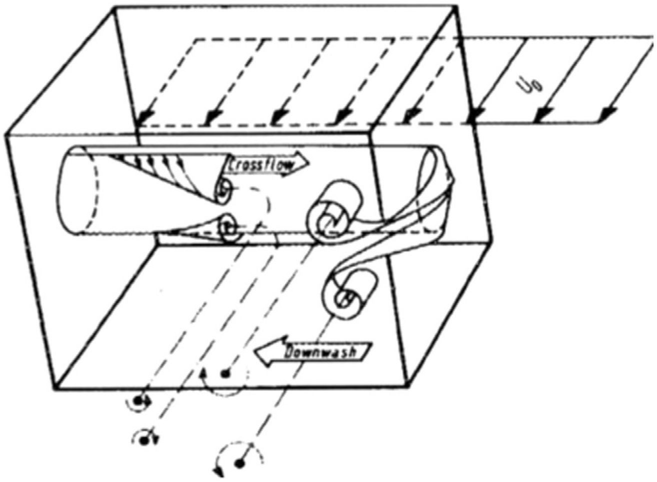

Fig. 1. Illustration of tip-flow for a stationary cylinder in steady, uniform flow (Sumner, 2013).

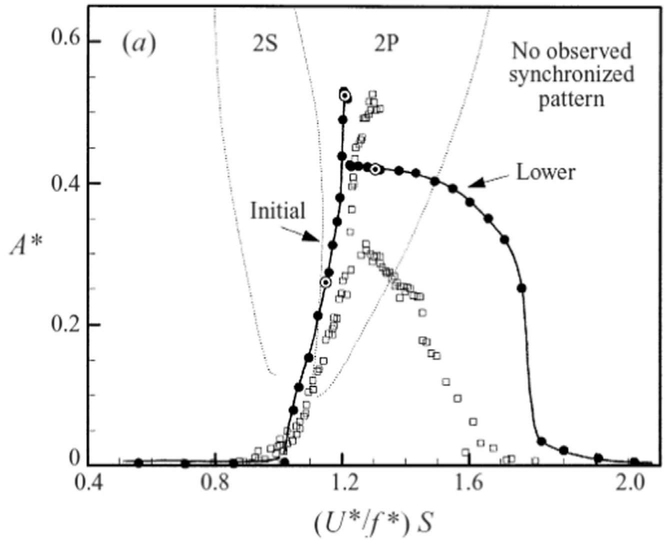

Fig. 2. Smooth cylinder in VIV in steady uniform flow. Comparison of amplitude response with respect to non-dimensional flow velocity. Govardhan and Williamson (2000) in circles and Feng (1968) in squares. The former attributed the difference to their use of end-plates to encourage two-dimensionality. $(m^* + C_A)\cdot\zeta = 0.251$.

Different experimental setups may generate different forms of amplitude graphs even for the same parameters used. Fig. 2 reveals the amplitude curves generated by Feng (1968) and Govardhan and Williamson (2000) for the mass-damping parameter $(m^* + C_A)\cdot\zeta = 0.251$ taken from Govardhan and Williamson (2000). Their results varied from Feng's (1968) results even at the same mass damping parameter. The difference between the two