Experimental Study on Wake Dynamics of D-shaped Bluff Bodies and Ground Effect

Guangyuan Huang [1], Zhigang Yang [2], Chao Xia [2], Richard Jefferson-Loveday [1], Ka Him Seid [3], Randolph Chi Kin Leung [3]

[1]*Faculty of Engineering, University of Nottingham, Nottingham, United Kingdom*
[2]*Automotive Wind Tunnel Center, Tongji University, Shanghai, PR China*
[3]*Department of Mechanical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, PR China*

SUMMARY: (10 pt)
For bluff-body flow, wake dynamics is important and associated with the flow-induced drag, lift, vibration and sound. The wake of bluff bodies placed in ground proximity is more complicated. Because the evolved wake is bounded by or interacted with the ground plane. It is important to understand the wake dynamics of bluff bodies with ground effect, as it is related to numerous engineering applications, such as road vehicles, bridges, and wind farms. In this paper, the wake dynamics of a D-shaped body in ground proximity is investigated experimentally, emphasizing the shear-layer interactions and the ground effect. The experiments are performed in a model wind tunnel at a subcritical Reynolds number of 2.3×10^4 and different gap-to-height ratios. Particle image velocimetry, hotwire velocimetry, and surface oil flow visualization are employed for the measurements. Wavelet analysis is used to examine the wake unsteadiness and Proper Orthogonal Decomposition is conducted to extract the coherent structures of the wake.

Keywords: Wake dynamics, Ground effect, D-shaped body

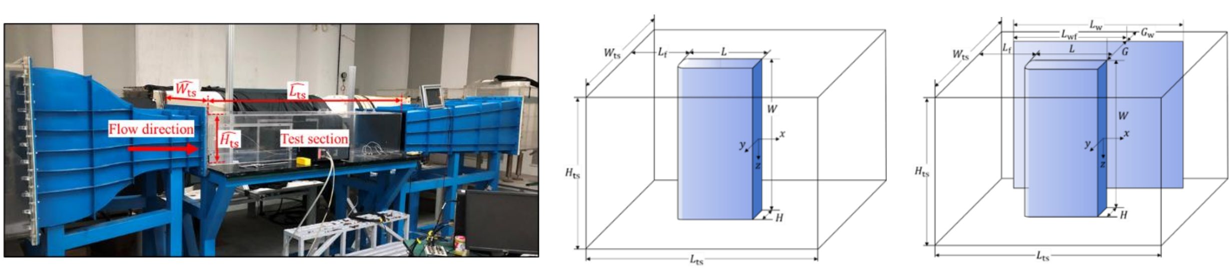
1. INTRODUCTION

For bluff bodies in fluid flows, a massive wake may form at the body's back after flow separation. The wake dynamics plays a significant role in bluff-body flows as it is tightly associated with the flow-induced drag, lift, vibration and sound. Compared with bluff bodies placed in open space, the wake of bluff bodies placed in ground proximity is more complicated. Because the evolved wake is bounded by or even interacted with the ground plane. The wake dynamics can vary dramatically to give the most important feature of such flow (Zhang et al., 2006). A thorough understanding of the wake dynamics of bluff bodies with ground effect is important, as it is related to numerous engineering applications, such as road vehicles, bridges, and wind farms.

The present paper focuses on the wake dynamics of a D-shaped bluff body. This body has become a popular model in automotive aerodynamics and has been widely used in studying wake dynamics, numerical models, and flow control. The previous studies found that the flow around the D-shaped body in open space is dominated by Karman-like vortex streets at the subcritical range (Pastoor et al., 2008; Krajnović et al., 2011; Parkin et al., 2014). A method of phase control was developed to reduce the mean drag of the D-shaped body by 15% via synchronizing the separated shear layers. In a later numerical study on the flow around the D-shaped body in ground proximity, however, few coherent structures were captured in the wake and the same control strategy failed to perform any efficiency (Parkin et al., 2015). The ground effect was considered to be essential and to cause the control failure. Based on these previous results, the present paper aims to investigate the wake dynamics of a D-shaped body in ground proximity from the experimental view, emphasizing the shear-layer interactions and the ground effect.

2. EXPERIMENTAL TESTBED

The experiments were conducted at the model wind tunnel of Shanghai Automotive Wind Tunnel Center. The wind tunnel consists of a circuit loop and a closed test section (as shown in Figure 1a). The closed test section of the wind tunnel and the corresponding experimental layouts. The test section has dimensions of $333 \times 556\,\mathrm{mm}^2$ in cross-section and $2000\,\mathrm{mm}$ in length. The maximum flow speed of the wind tunnel is $44\ \mathrm{m/s}$ and the turbulent intensity at the functional speed is lower than 0.2%. Two flow configurations are considered which present the D-shaped body in free space (FS) and ground proximity (GS). The D-shaped body shares the same geometrical features adopted in the works by Parkin et al. (2014, 2015) and has dimensions of $L = 109.2\ \mathrm{mm}$ in the chord length, $H = 30\ \mathrm{mm}$ in the body height, and $R = 10.5\ \mathrm{mm}$ in the radius of the rounded head. The spanwise width of the model is prescribed as $W = 333\ \mathrm{mm}$, leading to an aspect ratio at $W/H = 11.1$, to ensure a predominant two-dimensional configuration. In FS, the body is mounted vertically at the middle width of the test section, spanning the entire height of the test section (as shown in Figure 1b). The distance between the leading edges of the body and the test section is set as $L_\mathrm{f} = 700\ \mathrm{mm}$. In GP, an additional plate of $L_\mathrm{w} = 700\ \mathrm{mm}$ in length is placed next to the body to approximate the stationary ground (as shown in Figure 1c). The distance from the streamlined head of the ground plate to the rear surface of the D-shaped body is $L_\mathrm{wf} = 120.8\ \mathrm{mm}$, ensuring a thin boundary layer on the ground in the gap. The ground clearance is $G_\mathrm{w} = 6\ \mathrm{mm}$, corresponding a gap-to-height ratio of $G/H = 0.2$.



(a) (b) (c)

Figure 1. (a) an illusion of the wind tunnel; Schematics of the arrangements of the D-shaped body in the test section in (b) FS and (c) GP (dimensions not to scale).

A DANTEC one-dimensional hotwire velocimetry system is utilized to record the time history of instantaneous velocity amplitude in the boundary layer and the wake. A two-dimensional Particle Image Velocimeter (PIV) system is employed to capture snapshots of the instantaneous velocity field. The laser generator and the camera are synchronized by a TSI laser-pulse synchronizer to enable so-called "double-frame/single-exposure" recording. The interrogation window size is set as 32×32 pixels, corresponding to a physical size at $1.85 \times 1.85\ \mathrm{mm}^2$. In addition, surface oil flow visualization is conducted to capture time-averaged surface flow features. Please refer to the previous works (Xia et al., 2018; Huang et al., 2021) for details of the measuring devices and setups. All the measurements were performed at $Re = 2.3 \times 10^4$ to allow comparison against the previous studies. The Reynolds number of the flows is defined based on the corrected freestream velocity and the body height as $Re = U_{\infty,c}H/\nu$, where ν denotes the kinematic viscosity.

3. RESULTS AND DISCUSSIONS

First, the three-dimensionalities of the flow are investigated. The surface oil flow patterns present the features of separations over the D-shaped body. As purposed by Pastoor et al. (2008), the three-dimensionalities of flow steadiness are examined by the variation of fluctuating velocity U' along the spanwise direction. Results show that the wake in FS is weakly disturbed by 3-D fluctuations. This leads to the approximately 2-D flow in FS. While strong three-dimensionalities are observed in GP, suggesting the absolute instability is attenuated by the proximity to a stationary ground.

Second, the time-averaged wake features are investigated. The time-averaged results are calculated based on PIV measurements by the trapezoidal averaging method. Figure 2 shows the time-averaged flow fields in plane $z = 0$ in FS and GP. The gray blocks in the figure discarded the data that are disturbed by strong reflection and the poor illusion of light. The separated shear layers in GP are relatively flatter and longer than those in FS. Therefore, these two shear layers have weaker interactions in the near wake, implying the vortex shedding is attenuated by ground proximity. On the other hand, the boundary layer properties are measured at the trailing edges. The 99%-velocity-based thickness, momentum thickness, and shape factor are obtained and compared between the two cases.

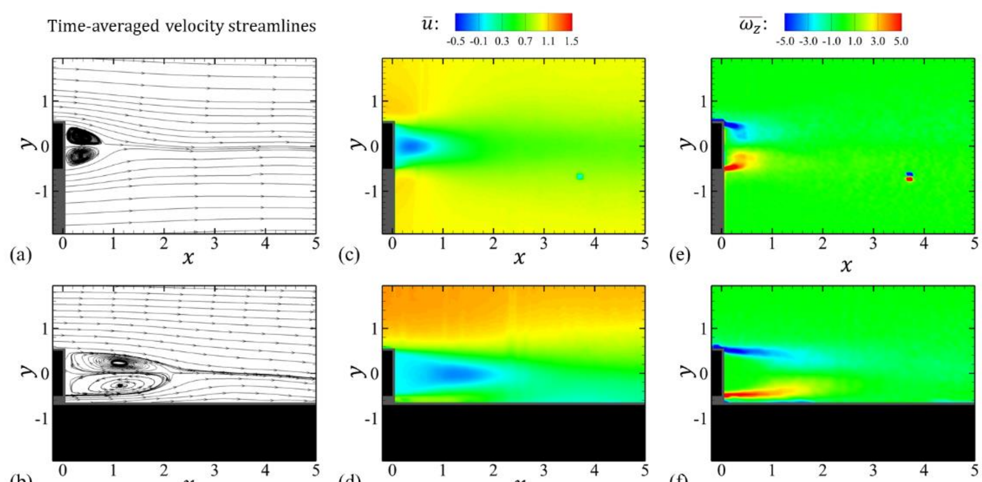
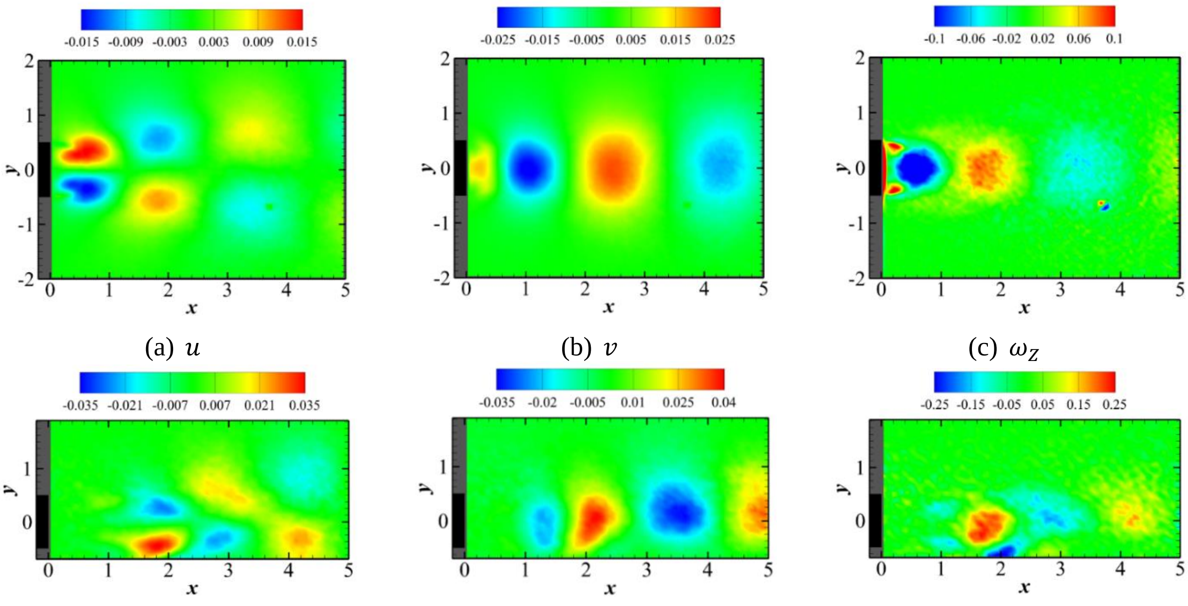


Figure 2. Distributions of time-averaged flow fields in the plane $z = 0$ of (a, c, e) FS and (b, d, f) GS: (a, b) velocity streamlines, (c, d) streamwise velocity $\bar{u}$, and (e, f) spanwise vorticity $\overline{\omega_z}$.

Third, wake unsteadiness is investigated. Reynolds stress components in the plane $z = 0$ are presented. The magnitudes of all the Reynolds stress components in the wake of GP are lower than those in FS. This indicates the vortex shedding is attenuated by ground proximity. Frequency analysis is then performed to examine the flow oscillations using the FFT and wavelet transform.

Finally, the proper orthogonal decomposition (POD) is performed to extract the coherent structures in the wake based on the PIV snapshots (). Figure 3 presents the 1st POD modes of both cases, showing vortex shedding is the leading mode of the GP wake. However, its strength is halved as compared to FS.



(a) u (b) v (c) ω_Z

(d) u (e) v (f) ω_Z

Figure 3. The 1st POD modes of wake in (a-c) FS and (d-f) GP, in terms of various flow variables.

7. CONCLUSIONS

The wake of a D-shaped body in the free space is dominated by the approximately 2-D vortex shedding the most of time. Intermittently, the upper and lower shear layers appear not to interact with each other and detach small-scale vortices. The switch between these two states leads to low-frequency oscillations in the wake. On the other hand, the ground proximity can lead to asymmetric shear layers from the D-shaped body with significantly different flow rates. The vortex shedding can be attenuated and intermittently disappear. When vortex shedding disappears, the lower shear layer is stabilized and the upper shear layer detaches a single row of vortices.

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