European Journal of Mechanics / B Fluids 69 (2018) 46–61

Contents lists available at ScienceDirect

European Journal of Mechanics / B Fluids

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

Turbulence features in a wall-wake flow downstream of a wall-mounted vertical cylinder

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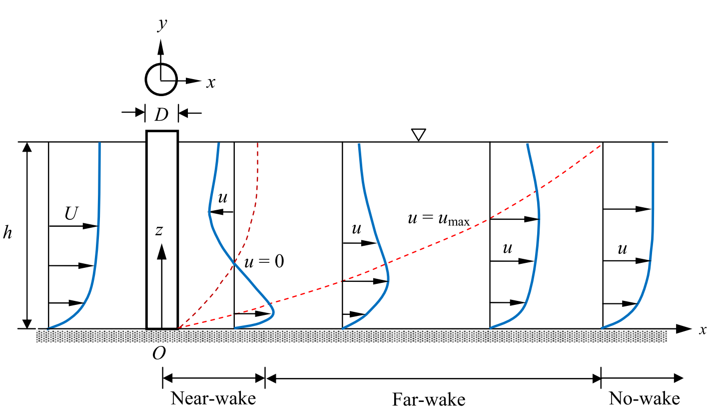
HIGHLIGHTS

- Turbulent wall-wake flow downstream of a wall-mounted vertical circular cylinder was measured and analyzed using the time-averaged methodology.
- The profiles of the turbulent kinetic energy fluxes and budget are illustrated.
- The conditional Reynolds shear stresses are analyzed from the viewpoint of bursting by using the quadrant analysis.
- The Reynolds stress anisotropy is furnished in the form of the anisotropic invariant map and the anisotropy invariant function.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 14 November 2017
Received in revised form 7 January 2018
Accepted 16 January 2018

Keywords:
Flow characteristics
Shear flow
Turbulent flow
Wakes
Hydraulics
Open-channel flow

ABSTRACT

Characteristics of turbulent kinetic energy (TKE) fluxes and budget, conditional Reynolds shear stress (RSS) and Reynolds stress anisotropy in the near- and far-wake flows downstream of a wall-mounted vertical circular cylinder are studied. The TKE fluxes exhibit that the near-wake flow is characterized by an accelerating effect and the far-wake flow by a retarding effect. The TKE budget is explained by using the principle of the TKE conservation. The profiles of TKE budget show that the wall-shear layer of the wall-wake flow is governed by a high negative pressure energy diffusion rate in addition to a high TKE dissipation rate. The conditional statistics of velocity fluctuations were studied to examine the turbulent bursting events by using the quadrant analysis. The conditional RSS profiles illustrate that the near-wake flow is characterized by inward interactions, while the far-wake flow is characterized by sweeps. In the wall-wake flow, the mean duration of bursting events is shorter than their mean interval of occurrence. The Reynolds stress anisotropy reveals that the anisotropic invariant maps appear to be a closed looping trend in the near-wake flow and an open looping trend in the far-wake flow. However, all the profiles, for example, TKE fluxes and budget, conditional RSS and turbulence anisotropy, regain their uninterrupted upstream profiles with an increase in downstream distance.

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https://doi.org/10.1016/j.euromechflu.2018.01.003
0997-7546/

Nomenclature

b_{ik}	Reynolds stress anisotropy tensor [−]
D	Cylinder diameter [L]
d	Median size of sand [L]
E_D	Dimensionless TKE dissipation rate [−]
F	Flow Froude number, $\overline{U}/(gh)^{0.5}$ [−]
F	Anisotropy invariant function [−]
F_{uu}	Spectral density function for u' as a function of frequency f [L^2T^{-1}]
f	Frequency [T^{-1}]
f_{ku}	Streamwise flux of TKE, $\overline{ku'}$ [L^3T^{-3}]
f_{kw}	Vertical flux of TKE, $\overline{kw'}$ [L^3T^{-3}]
g	Gravitational acceleration [LT^{-2}]
H	Hole-size parameter [−]
h	Flow depth [L]
i_E	Mean time-interval between ejections [T]
i_S	Mean time-interval between sweeps [T]
k	TKE, $0.5(\overline{u'^2}+\overline{v'^2}+\overline{w'^2})$ [L^2T^{-2}]
k_w	Wave number [L^{-1}]
P_D	Dimensionless pressure energy diffusion rate [−]
p_D	Pressure energy diffusion rate [L^2T^{-3}]
p'	Fluctuations of hydrostatic pressure relative to mass density of fluid [L^2T^{-2}]
R	Reynolds number characterized by cylinder diameter, $\overline{U}D/\upsilon$ [−]
R_*	Shear-particle Reynolds number, u_*d/υ [−]
$S_{i,H}$	Fractional contribution toward RSS production from Q_i events [−]
S_{uu}	Spectral density function for u' as a function of wave number k_w [L^3T^{-2}]
T	Sampling time [T]
T_D	Dimensionless TKE diffusion rate [−]
T_{dE}	Dimensionless mean time-duration of ejections [−]
T_{dS}	Dimensionless mean time-duration of sweeps [−]
T_{iE}	Dimensionless mean time-interval of ejections [−]
T_{iS}	Dimensionless mean time-interval of sweeps [−]
T_P	Dimensionless TKE production rate [−]
t	Instantaneous time [T]
t_D	TKE diffusion rate [L^2T^{-3}]
t_E	Mean time-duration of ejections [T]
t_P	TKE production rate [L^2T^{-3}]
t_S	Mean time-duration of sweeps [T]
U	Time-averaged upstream flow velocity at an elevation z [LT^{-1}]
$\overline{U}$	Cross-sectional averaged upstream velocity [LT^{-1}]
u	Time-averaged streamwise velocity component at an elevation z [LT^{-1}]
u'	Fluctuations of streamwise velocity component [LT^{-1}]
u_*	Upstream shear velocity [LT^{-1}]
v	Time-averaged spanwise velocity component at an elevation z [LT^{-1}]
v'	Fluctuations of spanwise velocity component [LT^{-1}]
v_D	Viscous diffusion rate [L^2T^{-3}]
w	Time-averaged vertical velocity component at an elevation z [LT^{-1}]
w'	Fluctuations of vertical velocity component [LT^{-1}]
x	Streamwise coordinate or distance [L]
y	Spanwise coordinate or distance [L]
z	Vertical coordinate or distance [L]
δ_{ik}	Kronecker delta function [−]
ε	TKE dissipation rate [L^2T^{-3}]
$\vartheta_{i,H}$	Detection function [−]
ρ	Mass density of fluid [ML^{-3}]
υ	Kinematic viscosity of fluid [L^2T^{-1}]

1. Introduction

Flow past a wall-mounted obstacle is one of the conventional problems in hydrodynamics because of its theoretical importance in particular and practical applications in general. The extended disturbed flow zone downstream of a wall-mounted obstacle is known as the *wall-wake flow*, which plays an important role in riverbed erosion induced by a hydraulic structure, for instance bridge piers, submerged or free surface piercing piles, etc. Besides, the situations of an infinite wall-mounted obstacle can be encountered in our practical life, such as plume motion downstream of stacks, aerodynamics of cooling towers, atmospheric flows and so on. In classical hydrodynamics, an obstacle liable for the wake is commonly termed a *bluff body*. The near- and far-wake flow zones are the two most significant flow zones in bluff body hydrodynamics. They continue up to a certain distance downstream of a wall-mounted bluff body based on the flow condition as well as the size and shape of the body [1]. Beyond the far-wake flow zone, the effects of the wake die down and the flow recovers the uninterrupted upstream profiles. However, this study focuses on the wall-wake flow downstream of a wall-mounted vertical circular cylinder, as shown in Fig. 1. At this end, the previous studies on this problem were aimed at knowing the characteristics of vortex shedding [2–4] and the similarities in turbulent flow [5–9]. Importantly, as the wall-wake flow downstream of a wall-mounted cylinder, considered in this study, is turbulent, a clear understanding of the turbulence characteristics of this kind of flow is highly essential. Despite Dey et al. [5] recently made a considerable progress, in this regard, clarifying the self-similarities in individual profiles of the time-averaged streamwise velocity, Reynolds stresses and third-order moments, the characteristics of turbulent kinetic energy (TKE) flux and budget, turbulent bursting and Reynolds stress anisotropy in the wall-wake flow remain unexplored. The TKE flux and budget describe the contributions from different turbulent mechanisms such as advection, diffusion, dissipation and production [1]. Beside this, turbulent bursting is another important phenomenon, which comprises of four events, such as outward interactions, ejections, inward interactions and sweeps that are distinguished by the quadrant analysis [10]. The bursting phenomenon has significance in describing the coherent structures in a turbulent fluid flow. Further, the Reynolds stress anisotropy is another important aspect that identifies the directional preference of turbulence or velocity fluctuations [11]. To the best of authors' knowledge, no experimental study has so far been carried out to explore these turbulence parameters in the flow past a wall-mounted vertical circular cylinder. Therefore, it motivates to carry out the present study, as an extension of the study by Dey et al. [5].

Thus, the aim of this study is to characterize the TKE fluxes and budget, turbulent bursting and anisotropy in the flow downstream of a cylinder placed vertically on a rough wall.

2. Experimental setup and methodology

The experimental data of Dey et al. [5], where the details of the experiments were available, are used in this paper. However, a brief outline of the experimental setup and methodology is furnished here. The experiments were conducted in a 21 m long, 0.91