August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering
ICWE 16

Characteristics of separated shear layer and its relationship with the underlying surface pressure – A CFD approach

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SUMMARY:
Understanding separated flow past bluff bodies, such as buildings, is crucial to improve the numerical modelling of components and cladding loads. This study aims to validate and utilize CFD to understand better the characteristics of separated flows and associated surface pressure. A suspended square cylinder in a uniform smooth inlet is modelled in LES and validated against PIV experimental data from published literature. The detailed structures of the separated shear layer and related flow features are validated. The mesh refinements in the separation bubble are essential to capture the Kelvin-Helmholtz (K-H) instabilities. Course mesh lowers the K-H frequency and broadens the shear layer thickness. This frequency shift weakens the separation bubble's vorticity strength and reduces the surface pressure fluctuations. Strong cross-correlation and high coherency at the K-H frequency were observed between the surface pressure and the flow field. In future studies, the impact of the free-stream turbulence will be investigated if the K-H frequency remains relevant.

Keywords: Components and Cladding load; separated shear layer; LES; bluff-body aerodynamics

1. INTRODUCTION

The "proper" simulation of components and cladding loads on low-rise buildings and other small structures is one of the outstanding problems of wind engineering (Tieleman et al. 2003). The challenges for wind tunnel testing emanate from the difficulty in modelling the building at the same scale as the atmospheric boundary layer with its details, Reynolds number sensitivity, and the trade-off between the two. Although Large-Eddy Simulation (LES) faces similar trade-off challenges (Geleta and Bitsuamlak 2022), it still offers additional insight for resolving the scaling and Reynolds number discrepancy issues. One of the most critical flow mechanisms that result in some of the highest loads on low-rise buildings is separated flow from the edges. The current study focuses on modelling a separation bubble, its related shear layer, and its interaction with the surface pressure underneath. The study has two objectives: *(i)* to validate the detailed flow characteristics of the frontal boundary layer (FBL) and separated shear layer (SSL), and *(ii)* to investigate the relationship between the separation bubble and the surface pressure beneath it. A suspended square cylinder in a uniform smooth inlet is modelled in LES to attain the objective.

2. LES MODEL FOR SUSPENDED SQUARE CYLINDER

The LES model setup is designed based on the experiments of Lander et al. 2018. Fig.1 shows the computational domain setup, inflow parameters, coordinate system definition, views of data

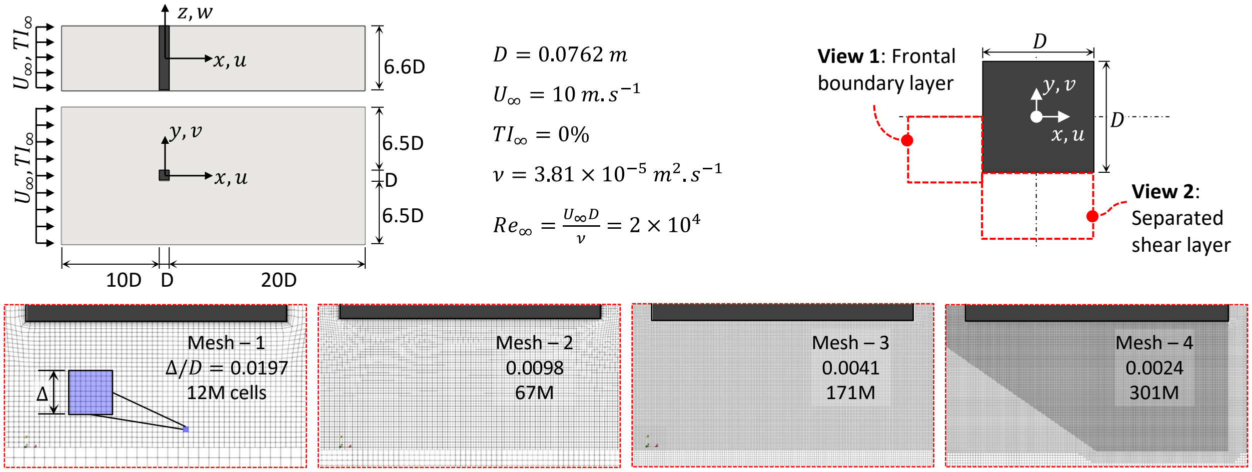

Figure 1. Model setup, basic parameters, coordinate system definition, views of focus, and mesh refinements.

collection for the frontal boundary layer (FBL) and separated shear layer (SSL), and mesh refinements. The free-stream wind speed and viscosity are set up to get the Reynolds number, $Re = 20\,000$, among the cases reported by Lander et al. 2018. The inflow is a uniform smooth inlet of $U_\infty = 10\ m/s$. The domain is meshed in successively refined zones depending on the distance from the cylinder. The primary focus is given to frontal prism layers and SSL regions. Keeping other regions constant, the mesh in View 2 region (i.e., SSL region) is refined in four levels of mesh resolution as shown in Fig. 1. Prism layers are provided so that the mean y^+ stays below 1 for most regions. The WALE sub-grid scale model is used for turbulence modelling.

3. RESULTS AND DISCUSSION

The results from all four cases are presented here. Note that Mesh – 4 is a simulation in progress.

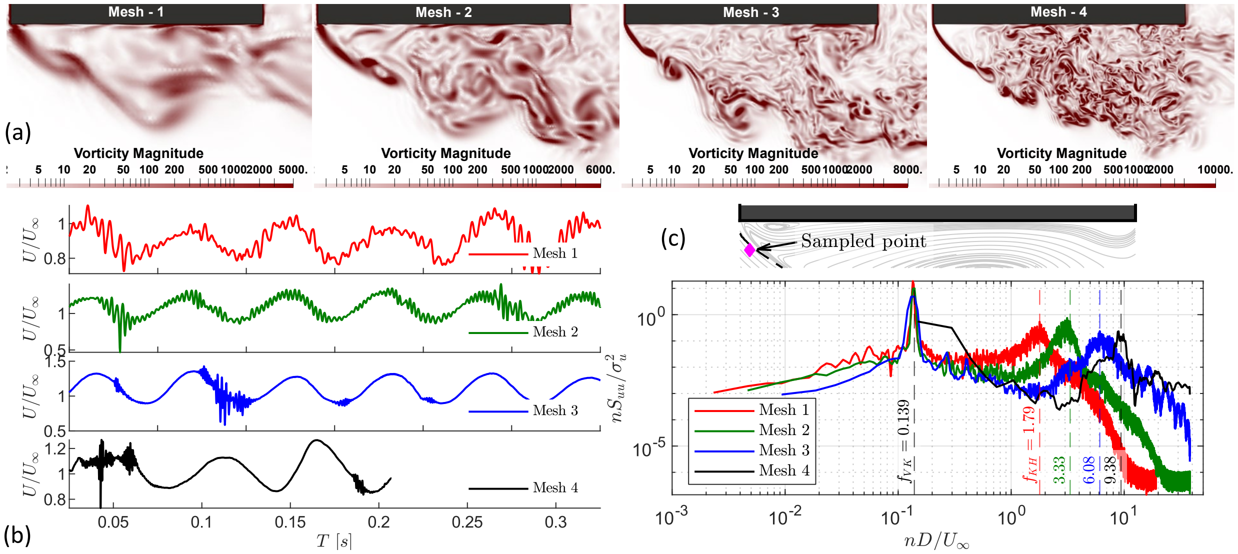

Figure 2. (a) Instantaneous vorticity in View 2, (b) time history, and (c) spectra of $\boldsymbol{u(t)}$ at a point just outside the shear layer near the separation corner.

3.1. Validation

Fig. 2a shows the instantaneous vorticity magnitude plots in the SSL region from the four cases. In all cases, features of SSL, such as laminar shear layer at separation, Kelvin-Helmholtz instability, vortex pairing, and shear layer flapping, are observed to different degrees. The most notable difference is that the scales of these flow structures get smaller as the mesh gets refined, as seen in the time and frequency signatures in Figs. 2b and c. With the observed fixed vortex shedding frequency, $f_{VK} = 0.139$ and Kelvin-Helmholtz frequency $f_{KH} = 9.38$, for Mesh – 4, the ratio $f_{KH}/f_{VK} = 67.5$, is close to 68.5 from Lander et al. 2018 for the same Re. The momentum thickness, θ, (see Lander et al. 2018) along its streamwise centreline axis, ζ, of the SSL as shown in Fig.3a. Fig.3b shows the comparison of θ/D along ζ between the current four cases and two cases from Lander et al. 2018. With the mesh refinements, the results get closer and closer to the experimental reference values. The frontal boundary layer (FBL) is compared with its displacement thickness, δ^*, and momentum thickness, θ_{BL}. Fig.4 shows the comparison with three reference cases named Alv.2017 with $Re = 3900$ (Alves Portela et al. 2017), Tri.2015 with $Re = 22\,000$ (Trias et al. 2015), and Sig.1986 with $Re = 500\,000$ (Sigurdson 1986) as reported by Lander et al. 2018. In all four cases, the current result falls between the references as expected based on Re and Mesh – 4 is expected to improve.

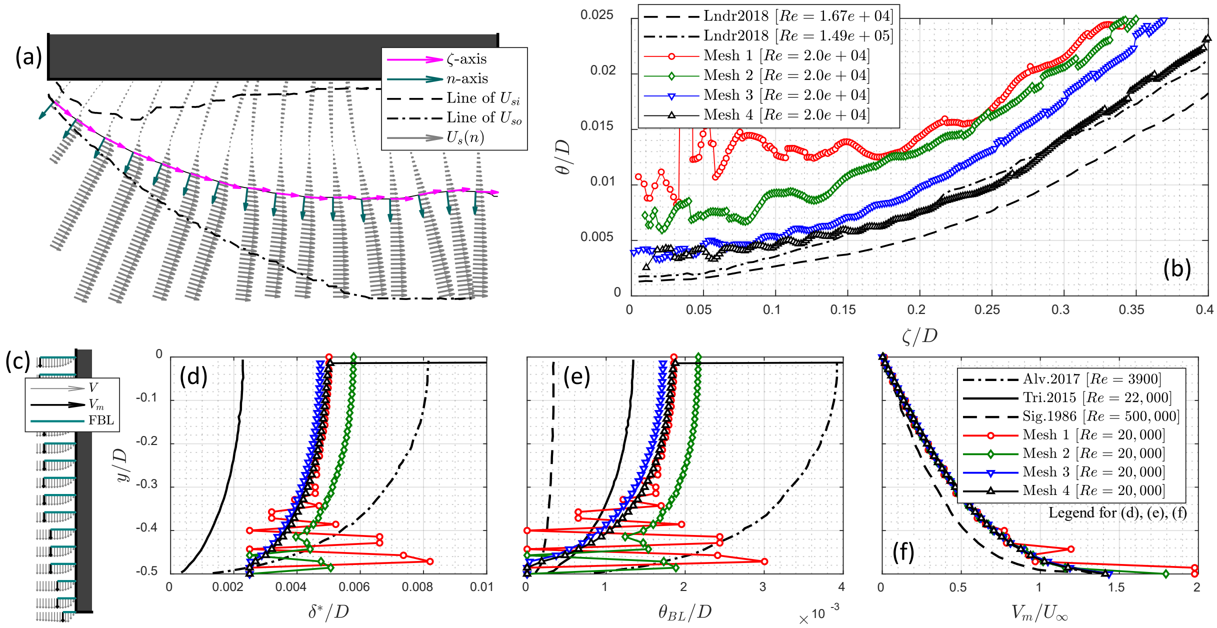

Figure 3. (a) Separated shear-layer parameter definition, (b) momentum thickness, θ/D, comparison, (c) frontal boundary layer, (d) displacement thickness, δ^*/D, (e) momentum thickness θ_{BL}/D, and (f) maximum velocity V_m.

3.2. Relationship between C_p and the velocity field

Fig.5 shows the mean and standard deviation of the pressure coefficient for the current four cases. The standard deviation of C_p shows strong mesh dependence. Fig.6 shows the time-domain and frequency-domain relationship between C_p and velocity. In addition to the importance of low-frequency global instabilities like vortex shedding, the results suggest the importance of resolving high-frequency scales for surface pressure.

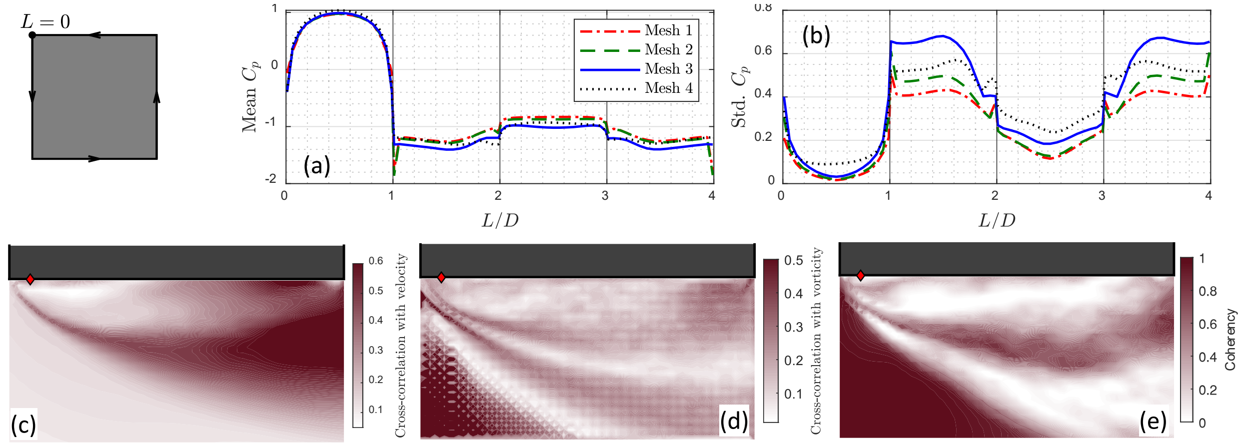

Figure 4. (a) Mean C_p, (b) standard deviation of C_p, maximum cross-correlation of C_p at a surface point near the separation with (c) velocity field, u, (d) vorticity ω_z, and (e) coherency between C_p and the velocity field at f_{KH} in Mesh – 3.

4. CONCLUSIONS

An experimental setup of a suspended square cylinder in a uniform smooth inlet was reproduced in LES with four levels of mesh refinement in the separated flow region. The mesh refinement significantly impacted the flow structure of the flow field and surface pressure statistics. The surface pressure has a strong correlation and coherency with the separated shear layer over a broad range of frequencies. In future of this study, further investigation of the relationship between the pressure and velocity field, consideration of inflow turbulence, and the case of a plate-mounted prism will be investigated.

ACKNOWLEDGEMENTS

We want to thank Dr Daniel Lander for his discussions and for providing us with the experimental data. We acknowledge SHARCNET and the Digital Research Alliance of Canada for providing us with the HPC platforms.

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