RECENT PROGRESSES IN FLUID DYNAMICS RESEARCH
Proceedings of the Sixth International Conference on Fluid Mechanics
AIP Conf. Proc. Vol 1376, 154-156 (2011)

Confinement Effects on Flows Past an In-Duct Rectangular Bluff Body with Semi-Circular Leading Edge

K. F. Yu, R. C. K. Leung*, Z. B. Lu, L. Cheng, H. Y. H. Chan

Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

Email: mmrleung@polyu.edu.hk

Abstract This paper reports a numerical study of a two-dimensional time-dependent viscous flow past a rectangular bluff body with a Reynolds number $Re = 6\,073$ based on bluff body height installed in a flow duct. The leading edge of the bluff body takes a semi-circular profile. The governing equations of the flow are solved with large-eddy simulation (LES) using a commercial computational fluid dynamics software FLUENT. The focus of the present study is to explore the effects of the ratio of the height of the bluff body H and the separation D between the bluff body and the duct wall surface. The numerical simulations are validated with the results obtained from a separate wind-tunnel experiment. Numerical simulations with various D/H are carried out. The numerical results show that the mean and instantaneous flow quantities are strongly dependent on the ratio D/H. The suppression effects of vortex shedding by the neighboring duct wall are highlighted by comparing the unsteady flow structure topology, dominant Strouhal number, lift and drag forces, etc. The mechanism for the suppression of vortex shedding suppression and its variation with D/H are analyzed, and its relevance to generation of flow inducing noise by a bluff body in a flow duct is discussed.

Key words: bluff body, CFD, duct flow

INTRODUCTION

Flow over a bluff body has been studied extensively by many researchers due to many practical applications, such as flow over a high-rise buildings, bridges and ships etc. A bluff body with semi-circular leading edge has engineering interest in the industry of aeronautics and turbo machinery. the flow include complexity of flow phenomena, such as flow separation, free shear layer, vortex interactions, shear layer instabilities and the interaction between a boundary layer, a separation free shear layer and a wake. The flow causes fluctuating drag and lift to the body and the fluctuating cause structural vibration, acoustic noise and resonance. So the flow over a bluff body is very important. Those flow phenomena can be modified by a solid wall which placed near the bluff body. The interaction between a wall and a bluff body leads to significant variations of the Strouhal number, unsteady forces and pressure field etc. [1–5], depending on the confinement (i.e. gap size) of the bluff body. In the present study, two-dimensional numerical simulations were carried out to investigate the effect of different gap ratio on the flow.

FORMULATION OF NUMERICAL PROBLEM

The two-dimensional time-dependent viscous incompressible Navier-Stokes equations are numerically solved with FLUENT computational fluid dynamics software. Large eddy simulation with dynamics sub-grid scale stress model [6] is used in the present study. No slip wall boundary condition is applied at the solid walls. The schematic diagram of the simulation is shown in Figure 1. A rectangular bluff body with a semi-circle leading edge is placed in the center of the channel. The length and the height of the bluff body are $4.23H$ and H respectively. The Channel height and length is $9.09H$ and $168H$ respectively. A Cartesian coordinate system (x, y) is used which the x-direction aligned with the inlet flow direction. The origin of the coordinate system is located at the center of the rear side of the bluff body as shown in Figure 1. The Reynolds number is 6 073 based on the bluff body height H and the maximum inlet velocity U_0. All solution variables are in non-dimensional form. The geometrical length is normalized by the bluff body height H and velocity is normalized by the maximum inlet velocity U_0. Time is normalized by $t_0 = H/U_0$. An experiment of the problem with D/H = 4 has been carried out and the numerical setups are validated through obtaining favorable agreement between numerical results and experimental measurements.

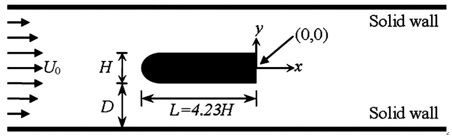

Figure 1: Schematic sketch of the problem

RESULTS AND DISCUSSTIONS

For a flow past a bluff body, vortex shedding is a very important physical phenomenon. The vortex shedding causes the fluctuation of flow properties in the disturbed region. The flow properties can be modified by placed a solid wall in the vicinity of a cylinder. In the present study, the following results are compared for different D/H ratios.

The time evolution of the lift coefficient fluctuation $C'_{\mathrm{L}} = C_{\mathrm{L}} - (C_{\mathrm{L}})_{\mathrm{mean}}$ for different gap ratios is shown in Figure 2. The figure shows clearly that the C'_{L} amplitude of the flow with D/H = 2 is larger than that of D/H = 4. The increass in the amplitude of the fluctuating lift reveals that the strength of vortex shedding is increased. Table 1 shows the mean, RMS and peak to peak value of C'_{L} for different gap ratios. $(C'_{\mathrm{L}})_{\mathrm{rms}}$reveals the magnitude of the fluctuating lift coefficient. The value of $(C'_{\mathrm{L}})_{\mathrm{rms}}$ at gap ratio D/H = 2 is 44% larger than the value at D/H = 4. The larger value of $(C'_{\mathrm{L}})_{\mathrm{rms}}$ indicates that the strength of vortex shedding are enhanced with the small gap ratio.

Figure 3 shows the time evolution of the drag coefficient fluctuation $C'_D = C_{\mathrm{D}} - (C_{\mathrm{D}})_{\mathrm{mean}}$ for different gap ratios. shows the mean, rms and peak-to-peak value of $C'_{\mathrm{D}}$for different gap ratios. Evidently, the values of $(C'_{\mathrm{D}})_{\mathrm{mean}}$ and $(C'_{\mathrm{D}})_{\mathrm{rms}}$ at gap ratio D/H= 2 are larger 40% and 55% respectively than the value at D/H= 4. The small gap ratio increases the blockage of the fluid flow. The flow have to be squeezed through the smaller area available so the velocity within the small gap will be greater than the larger gap. The greater velocity results in the greater shear stress distribution on the top and bottom surface of the bluff body. The greater shear stress results in the greater drag coefficient.

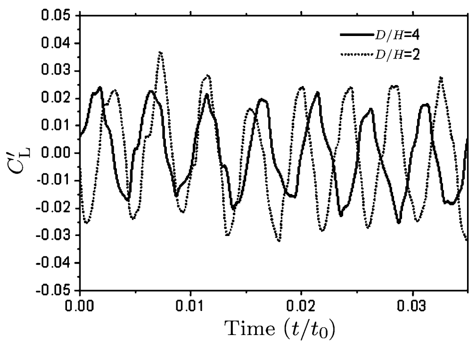

Figure 2: Time evolution of C'_{L} for different gap ratios

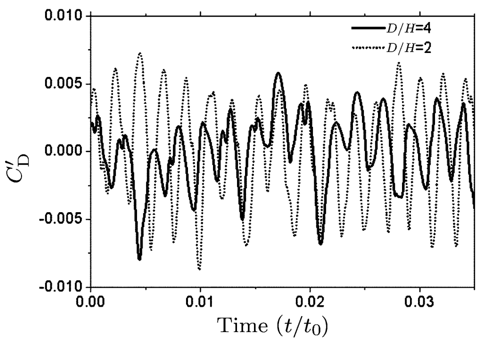

Figure 3: Time evolution of C'_{D} for different gap ratios

Table 1. Statistical average comparison of C'_L for different gap ratios

D/H	$(C_{\mathrm{D}})_{\mathrm{mean}}$	$(C'_{\mathrm{D}})_{\mathrm{rms}}$	$(C'_{\mathrm{D}})_{\text{peak-to-peak}}$
4	–0.000 986	0.012 9	0.053 4
2	0.002 31	0.018 6	0.070 9

Table 2. Statistical average comparison of C'_D for different gap ratios

D/H	$(C_{\mathrm{D}})_{\mathrm{mean}}$	$(C'_{\mathrm{D}})_{\mathrm{rms}}$	$(C'_{\mathrm{D}})_{\text{peak-to-peak}}$
4	0.017 6	0.002 49	0.013 79
2	0.024 7	0.003 86	0.017 5

The Strouhal number *St* is given by fU_0/H where f is the dominated frequency of the lift fluctuation. The *St* indicates the frequency of the shedding vortex behind the bluff body. As shown in Figure 4 and Table 3, the *St* are 0.27 and 0.31 for gap ratio of 4 and 2, respectively. The small gas ratio results in higher *St*. A reduction of duct width by half results in an increase in *St* by 15%. The higher *St* may be due to the induced vortices on the top and bottom solid wall of the channel in the small gap ratio case as shown in Figure 6.

Instantaneous vorticity pattern provides useful information of the vortex formation to compare the vortex shedding phenomena for different gap ratios. The staggered vortices with positive and negative vorticity behind the bluff body are transferred by the main flow to the downstream. Figure 5 shows the instantaneous vorticity contours within a half cycle of C'_{L}variation D/H= 4. Two boundary layers are developed along the top and bottom solid walls of the channel and another two boundary layers are developed along the top and bottom surface of the bluff body. These four boundary layers may be interacted each other resulting in the formation or suppression of the vortex shedding behind the bluff body. Figure 6 shows instantaneous vorticity contours and a half cycle of C'_{L} variation for D/H= 2. The vorticity patterns are generally similar as case of D/H= 4 except vortex formation at the top and bottom of the channel walls.

Clearly the vortex formation and shedding from the bluff body are enhanced by the interaction with the top and bottom boundary layers on the duct walls.

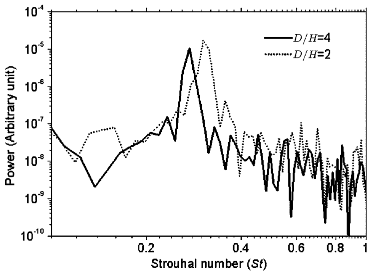

Figure 4: Variation of Strouhal number with gap ratios

Table 3. Statistical average comparison of C_D' for different gap ratios

D/H	4	2
St	0.27	0.31

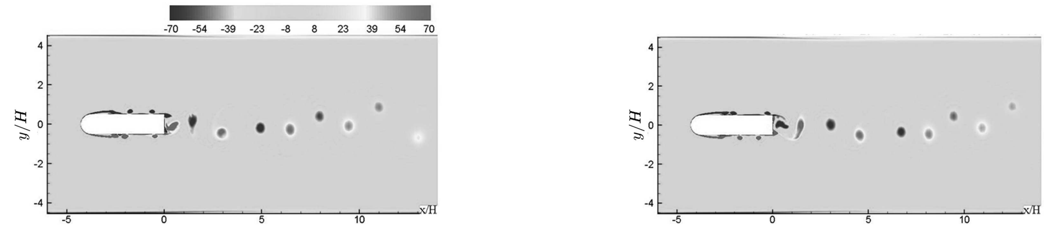

Figure 5: Vorticity distributions within a half cycle of lift variation for $D/H = 4$

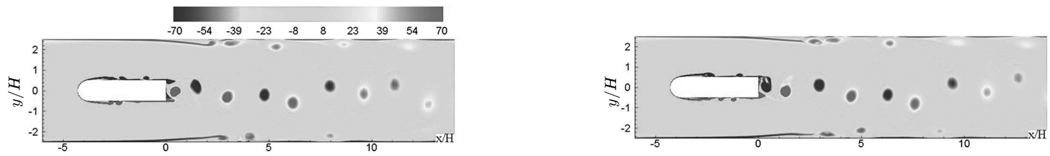

Figure 6: Vorticity distributions within a half cycle of lift variation for $D/H = 2$

CONCLUSIONS

In the present paper, a two-dimensional time-dependent viscous flow past a rectangular bluff body with semi-circular leading edge has been investigated numerically for Reynolds number of 6 073. The simulation results give reasonable agreement with experimental results. The effect of the two walls of the channel on the bluff boy has been compared. The amplitude, rms and the peak to peak values of the fluctuating lift coefficient and drag coefficient are increased with decreasing gap ratio. Smaller gap ratio also increases the Strouhal number. It may be due to the vortices formation at the top and bottom walls of the channel. The induced vortices increase the interaction between the wall layer and the wake.

Acknowledgements

The support received from the Hong Kong Polytechnic University (J-BB2C) and from the University Industry Collaboration Programme, Innovation and Technology Fund of the Hong Kong SAR Government (UIT/194) is gratefully acknowledged.

REFERENCES

1. Martinuzzi RJ, Bailey SCC, Kopp GA. Influence of wall proximity on vortex shedding from a square cylinder. *Expt. Fluids*, 2003; **34**: 585-596
2. Lei C, Cheng L, Armfield SW, et al. Vortex shedding suppression for flow over a circular cylinder near a plane boundary. *Ocean Engg.*, 2000; **27**: 1109-1127
3. Bhattacharyya S, Maiti DK. Vortex shedding suppression for laminar flow past a square cylinder near a plane wall: a two-dimensional analysis. *Acta Mechanica*, 2006; **184**: 15-31
4. Cheng M, Luo LS. Characteristics of two-dimensional flow around a rotating circular cylinder near a plane wall. *Phys. Fluids*, 2007; **19**: 063601
5. Dipankar A, Sengupta TK. Flow past a circular cylinder in the vicinity of a plane wall. *J. Fluids Struct.*, 2005; **20**: 403-423
6. Germano M, Piomelli U, Moin P, et al. A dynamic subgrid-scale eddy viscosity model. *Phys. Fluids A – Fluid Dyn.*, 1991; **3**: 1760-1765