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ScienceDirect
Procedia Engineering 126 (2015) 388 – 392
Procedia Engineering
www.elsevier.com/locate/procedia

7th International Conference on Fluid Mechanics, ICFM7

Comparison of steady blowing and synthetic jets for aerodynamic drag reduction of a simplified vehicle

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Abstract

The objective of this study is to compare steady blowing and synthetic jets for drag reduction of Ahmed body. The results based on LES were validated by force measurement, static pressure coefficient and vortex shedding frequency data from experiment. Based on LES, several forcing parameters, such as jet location, jet direction, excitation velocity and driving frequency are considered. Drag reductions of 3% (using steady blowing) and 9% (using synthetic jets) are reached, respectively. Compared with steady blowing, the results of optimal parameters for synthetic jets, which were installed between the roof and rea r slant, show higher drag reduction efficiency. The difference in the mechanism of flow control on Ahmed body between steady blowing and synthetic jets is studied. The excitation with a certain frequency from synthetic jets can dominate the vortex shedding process. The instability of the shear layers is suppressed to make the flow remain attached on the rear slant, so as to produce a pressure rise and drag reduction.

Keywords: Active flow control; Ahmed body; drag reduction ; steady blowing; synthetic jets;

1. Introduction

In order to reduce fuel consumption, many researchers have attempted many ways to control the flow over the simplified vehicle to lower aerodynamic drag, for example, plasma technique [1] and pulsed jets with valves or MEMS jets [2] have been utilized. Among all the methods, steady blowing [3, 4] and synthetic jets [5, 6, 7] are the most widely used on the simplified vehicle (Ahmed body). However, comparison of the drag reduction capability

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doi:10.1016/j.proeng.2015.11.224

between the flow controlled by using steady blowing and synthetic jets has not been widely argued. Based on numerical studies, this work shows the difference between steady blowing and synthetic jets to reduce the drag for the Ahmed body, and the reason is also presented in the paper.

2. Experimental and Numerical Study

2.1. Experiment

The experiments were conducted in a scaled wind tunnel with open jet. The analysis was performed on Ahmed body with a rear slant angle of 25° scaled as 0.333 of the original model (Fig.1a). The geometric blockage of the model in the wind tunnel is approximately 10%. The Reynolds number based on the length of the body is 4.7×10^5. The body has four supports to simplify tires, which are mounted to a U-steel connected to a 6-axis balance for aerodynamic test. 34 pressure points (Fig.1c) are distributed on half of the whole body to obtain the surface pressure. 1-D hot wire anemometer was used to acquire the vortex shedding frequency. The design of the piezoelectric actuator was referered to the study of [8]. The breadth of the synthetic jet array, which consists of 17 jets, matches the spanwise width of Ahmed body. The test results of synthetic jets show that the mean velocity at the exit could reach 6m/s at 2000 Hz, and 3 m/s at 1000-2700 Hz.

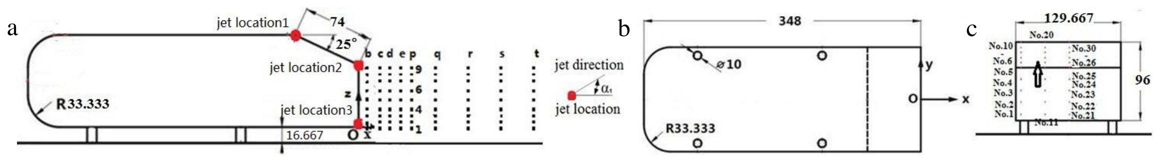

Fig. 1. Experiment Ahmed body dimensions, jet location and test points (a) lateral view (b) vertical view (c) back view.

2.2. Numerical setup

The volume mesh is refined in zones around Ahmed body to solve the boundary layer (Fig.1, zone1), shear layer near the slots (Fig.1, zone2) and the near wake (Fig.1, zone3) to capture more flow structures. With dimensionless wall value $y+<1$, the refined hexahedral mesh (21 million and 18 million) was discussed. The mesh for the natural flow and controlled flow are the same. Based on LES, two subgrid stress models, Smagorinsky-Lilly and Wale, and two time steps, 0.0001s and 0.0005s were discussed.

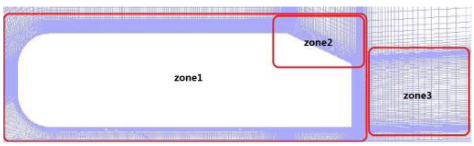

Fig. 2. Refined volume mesh.

2.3. Validation

The difference of numerical methods was summarized. And one case using volume mesh of 21 million, selecting sub-grid stress model WALE and time step 0.0001 s, was better validated than the others with data derived from the wind tunnel experiment, so this case was chosen to do all the following simulations in this paper. The mean drag coefficient (C_D) from LES is higher than the mean C_D from experiment, while the difference is only 1.8%. In addition, the pressure coefficient (Cp) based on LES has good approximation with experiment (Fig.1, Fig.3). The vortex shedding frequency based on LES is larger than experiment by 4.6% (Table 1).

Table1. C_D and frequency for different sub-grid stress models and time steps.

	time step(s)	number of mesh, C_D 17000000	21000000	vortex shedding frequency (H_Z) c6	d6	e6	p6	q6	r6	s6	t6
Wale	0.0001	0.382	0.372	87	87	87	87	87	87	83	87
	0.0005	0.425	0.401	78	78	78	78	83	83	87	78
Smagorinsky-Lilly	0.0001	0.475	0.453	78	78	78	78	91	91	81	78
	0.0005	0.502	0.521	73	83	83	78	78	83	92	68
Experiment	-	0.365		83	83	83	83	83	83	83	83

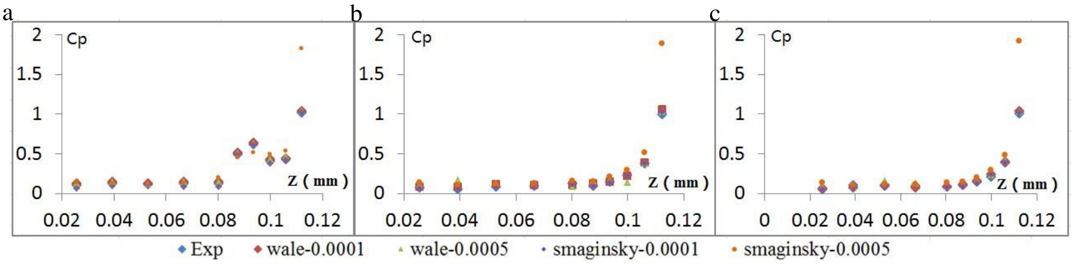

Fig. 3. Surface pressure coefficient, on the plane (a) Y=0; (b)Y=27.913 mm; (c)Y=55.833 mm.

3. Parametric study

Different locations and jet directions were investigated. Results of two excitation velocity exhibit the same trend of drag variation. The main difference of parametric study (Table 2, Fig.1 and Fig.4) between steady blowing (considered to be 0) and synthetic jets (1000-2000 Hz) is excitation frequency.

Table 2. Dimension of different parameters.

Parametric	Range
jet locations(No.)	1、2、3
jet driving frequency(Hz)	0、1000、1500、2000
jet excitation velocity(m/s)	3、6
jet direction(°)	45、65、90

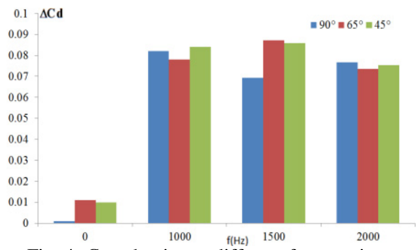

Fig. 4. C_D reduction at different frequencies, at jet location1, mean jet veloctiy 3 m/s, in horizontal direction.

4. Discussion

The following discussion illustrates the difference in mechanism between flow control on Ahmed body by steady blowing and synthetic jets. At location 1, where jets were installed between roof and rear slant, mean velocity at the exit is 3 m/s in horizontal direction with driving frequency 2000 Hz. Drag reduction for synthetic jets is 9%, higher than for steady blowing 3%. In many cases, synthetic jets show greater drag reduction efficiency. The flow from the roof begins to separate and reattach on the rear slant, then the torus structure A (Fig.6) is formed.In natural flow, the second separation zone would form because the reattached flow continue to move along the reverse direction of flow, which is larger than by steady blowing (Fig.7a, b, yellow box), and the position of reattached point is x=0.83 m, while for steady blowing the position of reattached point is around x=0.822 m (Fig.6, arrow-position and Fig.7, golden box). By steady blowing, the angle between the reattached line and the central symmetry line is smaller than natural flow (Fig.7). The velocity is higher near the separation line on the roof because of steady blowing. The momentum added to the boundary layer is higher, which allows the boundary layer to bear larger adverse pressure gradient. Therefore, the pressure increases on the slant for steady blowing and results in drag reduction (Fig.5). It can also be noticed that C-pillor vortex has not been affected by steady blowing (Fig.7, red circle), and the torus structure B and C have no obvious change for steady blowing and the natural flow (Fig.6).

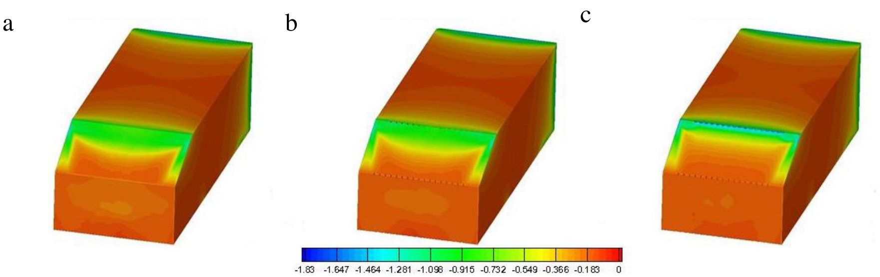

Fig. 5. Pressure coefficient distributions. (a) Natural flow. (b) Steady blowing. (c) Synthetic jets.

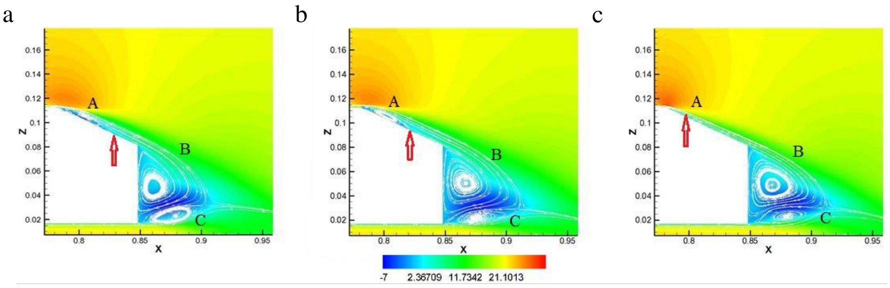

Fig. 6. Mean velocity distribution and streamlines on the plane Y=0. (a) Natural flow. (b) Steady blowing. (c) Synthetic jets.

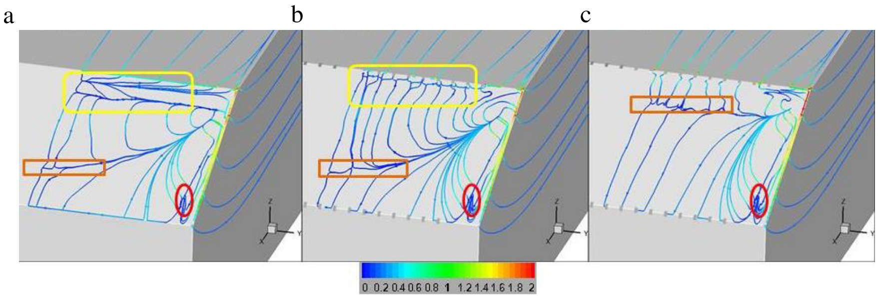

Fig. 7. Time-averaged oil-flow visualization on the rear slant surface. (a) Natural flow. (b) Steady blowing. (c) Synthetic jets.

The velocity is higher around the separation line on the roof because of synthetic jets. The second separation zone disappears (Fig.7c, yellow box). The position of reattached point is around x=0.792 m for synthetic jets and the reattached zone is smaller than for steady blowing. The angle between the reattached line and the central symmetry line is around 45° for steady blowing. However, reattached line is parallel to the separation line on the rear slant (Fig.7c), because the flow in stream direction is controlled by synthetic jets, which means the flow separation from the roof is suppressed and the pressure rise on the rear slant for synthetic jets is more remarkable than steady blowing (Fig.5), which enables more drag reduction. Furthermore, compared with steady blowing, the torus structure B has no obvious change for synthetic jets, while the torus structure C moves along horizontal direction and the near-wake region is elongated [5, 6, 7]. The pressure rises on the vertical surface at rear end of the body (Fig.5).

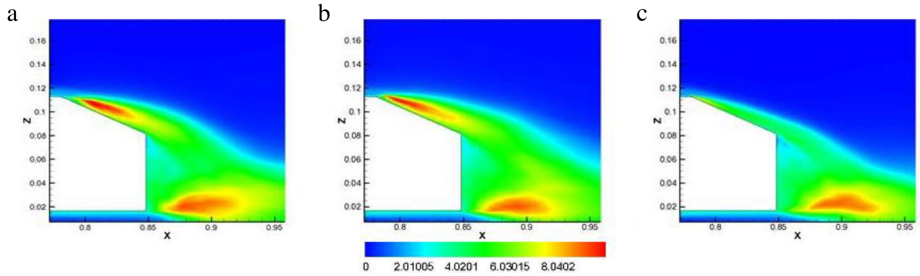

Fig. 8. RMS-velocity distribution on the plane Y=0 (a) natural flow (b) steady blowing (c) synthetic jets.

When steady blowing is on, the region of the high RMS-velocity is relatively smaller than for the natural flow (Fig.8a, b), so the instability of the shear layer is slightly delayed. When synthetic jets are on, the region of the high RMS-velocity is the minimum (Fig.8c), and the instability of the shear layer is suppressed [5]. The reason is that, a vortex shedding process is dominated by excitation frequency from synthetic jets, which means the shear layer instability is suppressed or delayed and then the wake instability could be improved [5, 6, 7]. Therefore, the flow separation can be improved and the pressure be raised.

5. Conclusion

This study shows the difference between steady blowing and synthetic jets to reduce the drag for Ahmed body, and drag reduction of 3% (using steady blowing) and 9% (using synthetic jets) are reached. With jets installed between roof and rear slant, it is limited to control the unsteady wake using steady blowing without driving frequency, while the excitation with a certain frequency from synthetic jets can dominate the vortex shedding process and give rise to suppression of the instability of the shear layer and the wake. Therefore, the flow separation can be controlled resulting in a pressure rise, and accordingly drag reduction can be achieved. Future studies would include synthetic jets with low driving frequency to compare with high driving frequency jets.

Acknowledgements

This work was supported by Major State Basic Research Development Program (Grant No. 2011CB711203). Experimental installation and computing facility of Shanghai Automotive Wind Tunnel Center is gratefully acknowledged.

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