

Effect of Vortex Generator on Flow Field Quality in 3/4 Open Jet Automotive Wind Tunnel

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ABSTRACT

Based on a 1:15 scaled 3/4 open jet automotive wind tunnel, this paper studies the effect of vortex generator on the buffeting phenomenon. The mean velocity, static pressure gradient, turbulent intensity as well as frequencies of fluctuant velocities have been explored experimentally with and without vortex generator. It shows that the less protruding vortex generator could control the buffeting phenomenon and improve the flow quality. Furthermore, the unsteady coherent structures in the jet shear layer have been visualized and analyzed by Detached-eddy simulation (DES). The vortex-ring pairing process is identified in the shear layer along with obvious frequency characteristics and velocity fluctuations. The vortex generator can postpone and restrain this vortex-ring pairing process, then reducing the velocity fluctuations.

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INTRODUCTION

To meet the demand of the auto market growth in China, a full-scale automotive wind tunnel center with capability aero-acoustic climatic condition considerations is built in Shanghai as "Shanghai Automotive Wind Tunnel Center" [1]. At distinct wind tunnel velocities, the flow field undergo severe low frequency pressure and velocity fluctuations like other 3/4 open jet wind tunnels [3,4]. This phenomenon is known as low frequency buffeting phenomenon.

The physical mechanisms of this buffeting phenomenon are not fully understood. It is widely acknowledged that at typical wind velocities of the wind tunnel, whenever the cavity resonant mode in the plenum chamber met with the preferred frequency of vortex shedding in the shear layer, the buffeting phenomenon occurred and create pressure and velocity fluctuations at specific frequency.

Reducing the fluctuations inside the test section is important both for test reliability and structure safety. Therefore, many researches have been carried out to control the buffeting phenomenon [2, 3, 4, 5, 6]. Vortex generator is one of the most widely used method. It can control the buffeting phenomenon by destroying the large-scale flow structure in the shear layer. However, these vortex generators create high frequency noise and can seriously interfere the aeroacoustic test in the wind tunnel [2,4,5]. Nevertheless, a less protruding vortex generator with active flapping is feasible to aeroacoustic research since it doesn't increase the background noise distinctly [6]. Meanwhile, the effect of the vortex generator on velocity profiles and flow structures is not clear.

So in present study, three less protruding vortex generators with four different plunging angles were applied on the nozzle upper plane to study the effect on the buffeting phenomenon. The nozzle without generators was also studied as a reference. The aim of this paper is to fully examine the effect of different plunging angles on velocity profiles and flow structures in 3/4 open jet wind tunnel.

EXPERIMENTAL DETAILS

Experimental Facility

Figure 1 displays the 1:15 scaled wind tunnel, which is chosen to study the effect of the nozzle vortex generator on the buffeting phenomenon. The maximum wind velocity in the scaled wind tunnel is 45m/s. The Dimensions of the wind tunnel is shown in Figure 2(c). The unit in the figure is millimeter. The angle of collectors is set to zero degree.

The arrangement of the vortex generators is shown in Figure 2(a). Three vortex generators were installed on the nozzle upper plate evenly. Which was designed according to previous research [6]. During the test, the vortex generators were fixed on the nozzle upper plate tightly without any vibration. The dimensions of the vortex generators are shown in Figure 2(b). Four different angles were set for the vortex generator. The step of the vortex generator has the same thickness of 5 mm as that of the nozzle.

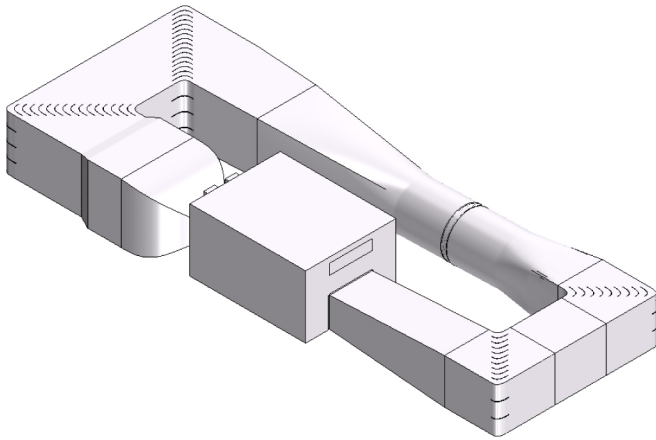


Figure 1. 1:15 Scaled wind tunnel

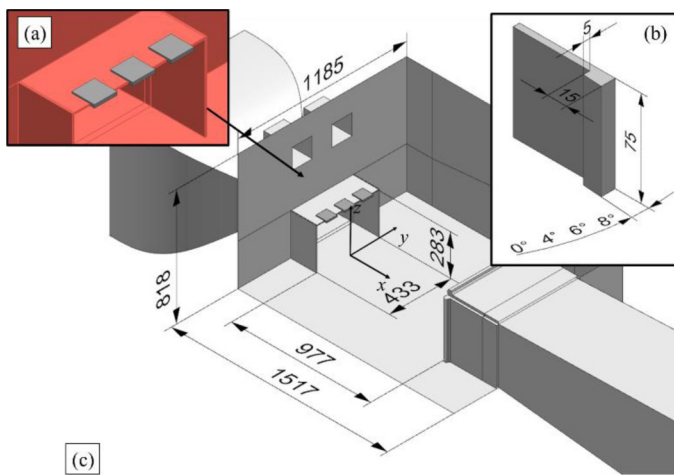


Figure 2. Dimensions of the vortex generator and the wind tunnel

As depicted in Figure 2, the origin of the coordinate system is defined at the floor of the wind tunnel. $z=0$, $x=0$ and $y=0$ define the floor, the nozzle exit plane and the symmetry plane, respectively. x is the streamwise direction, y is the spanwise direction and z is the vertical direction.

Instrumentation and Measurement

The reference velocity U_e of the wind tunnel test section was measured using a pitot static tube connected to an electronic micro-manometer at the center of the nozzle exit. The reference velocity U_e and the nozzle height h are used to normalize the velocities and the dimensions. Mean and fluctuant velocity profiles were obtained using a 2D hotwire probe (DANTEC 55R51) fixed on a traverse system controlled by a computer. The wire was operated at an overheat ratio of 1.4 on a constant-temperature circuit. The signal from the wire was digitalized at a sampling frequency f_s of 5.0 kHz by a 16-bit A-D converter. The sampling time of each measurement location was 6 s, producing 3×10^4 data for each point. The hotwire measurement was performed only on the symmetry plane of the wind tunnel. Seven measurement locations were considered along the flow direction, which were 20mm, 70mm, 150mm, 250mm, 500mm, 750mm and 820mm, each has measurement points in the vertical direction from 40mm to 430mm with increments Δx of 10mm. There were more than 270 measurement points totally. The fast Fourier

transform (FFT) was utilized to get the power spectrum density (PSD). PSDs are obtained using a Hanning window function $h(t)$, which writes, in the discretized form:

$$h_j = 0.5 - 0.5 \cos\left(\frac{2\pi j}{n-1}\right) \quad (1)$$

PSD is defined as:

$$PSD = \sum_{j=(\xi-1)n}^{\xi n-1} u_j^2 h_j e^{-\frac{2i\pi}{n} jk} \quad (2)$$

The window size N_w of FFT was 4096. The resolution of the frequency $\Delta f = f_s / N_w = 1.22 \text{ Hz}$. According to previous studies carried out by Jia et al. [7,8], Zheng et al. [9,10], the pressure and velocity fluctuations in this scaled wind tunnel have higher amplitude at 25m/s and 45m/s. So the measurements were conducted at these two velocities. After the installation of the different vortex generators, the wind tunnel velocity was calibrated using the pitot static tube mentioned above.

NUMERICAL SET-UP

Numerical Methods

The flow field in the wind tunnel was simulated using Improved Delayed Detached Eddy Simulation (IDDES). The time-dependent IDDES (based on SST model) is a hybrid RANS-LES model, which combines the advantages of the delayed detached-eddy simulation (DDES) and the wall-modelled large eddy simulation (WMLES) [19].

Numerical Schemes

A segregated incompressible unstructured finite-volume solver was employed in the simulation. To discretize the convective terms of the momentum equations, a hybrid numerical scheme was used to switch between a Bounded Central Differencing Scheme (BCDS) and a second order upwind scheme, while a second order upwind scheme was used for the turbulent quantities. The temporal discretization was second order. The IDDES simulation was initialized by the steady RANS results.

Computations were performed in the domain shown in Figure 3. The domain consists of contraction section, nozzle, test section, collector and diffuser. The air was injected into the computational domain from the velocity inlet at bottom left and discharged from the flow-split outlet at top right. The flow field was divided into cells using trimmer as depicted in Figure 4. The grid of jet shear layer and the domain with large pressure gradient were densified under the condition that Y^+ in the first layer of boundary layer is less than 5. The velocity magnitude at the nozzle center is 25m/s. The total computational time was 1s. Several monitor points as depicted in Figure 5 have been set on the symmetry plane to calculate the power spectral density of fluctuant velocity through spectral analysis. The data used for the

spectral analysis was sampled from 0.3-1s, and the sampling frequency was 5000Hz. The processing method of the spectral analysis was same as the test.

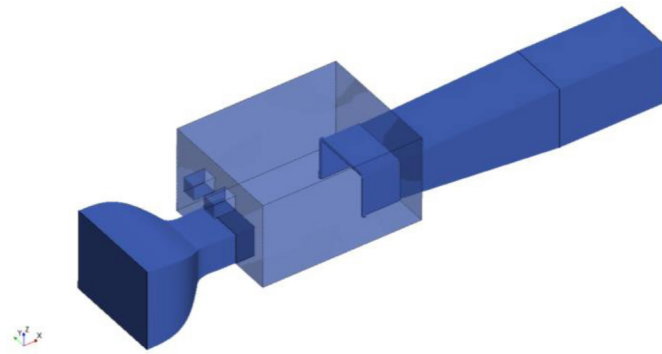


Figure 3. Domain for CFD simulation

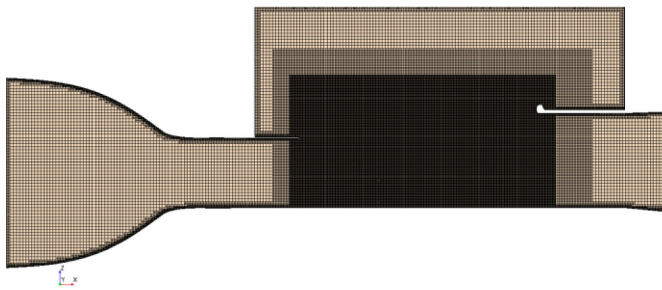


Figure 4. Mesh scheme for CFD simulation

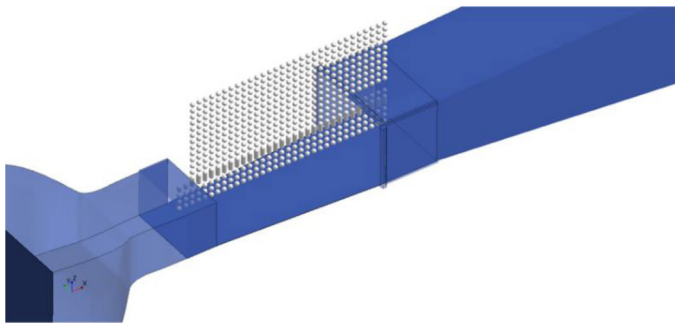


Figure 5. Monitor points on the symmetry plane

Numerical Validation

Take the points near the nozzle and in the test section as sampling to calculate the power spectral density of the fluctuant velocity. Their locations are near the upper plate of the nozzle ($x/h=0.07$, $y/h=0$, $z/h=1.00$), on the jet axis near the balance ($x/h=0.90$, $y/h=0$, $z/h=0.50$). Figure 6 demonstrates that the computational fluctuant velocity power spectra profiles of the nozzle without vortex generator are in good agreement with the experimental results. The difference in Figure 6 between the numerical and experimental results may due to different nozzle velocity profiles and sampling frequency.

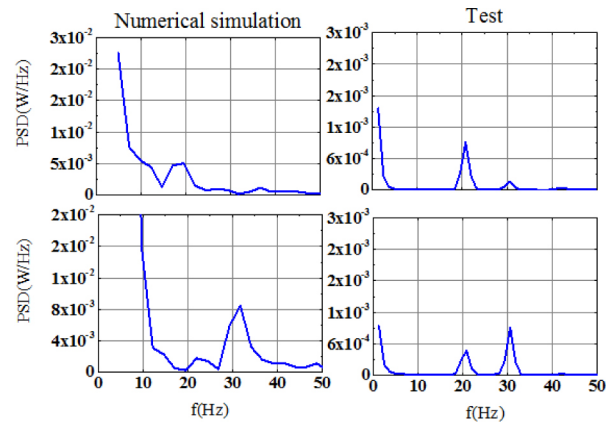


Figure 6. PSD comparison between computational and experimental result. Top: $x/h=0.07$, $y/h=0$ and $z/h=1.00$, Bottom: $x/h=0.90$, $y/h=0$ and $z/h=0.50$

RESULTS AND DISCUSSION

Experimental Results

Mean Velocity

The effect of vortex generators on mean streamwise velocity profiles will be analyzed below. These profiles with different plunging angles are at three stations along the jet, namely $x/h=0.25, 0.90$ and 2.70 , which are located near the nozzle, the balance and the collector, respectively. These three mean streamwise velocity profiles are shown in Figure 7–12.

Figure 7–9 display the results of mean streamwise velocity profiles along the vertical lines on symmetry plane at the three stations mentioned above. The wind tunnel velocity of these three figures is 25m/s. The vertical streamwise velocity profiles U/U_e near the nozzle (Figure 7) perform almost the same for all cases. Note that once move downstream to a position near the balance (Figure 8), the width of the jet would decrease as the plunging angle increases. The position near the collector (Figure 9) also indicates the same result. The 0° case and the uninstalled case have no significant difference. So does the 4° case and the 6° case. Their mean velocity profiles almost coincide in the vertical direction.

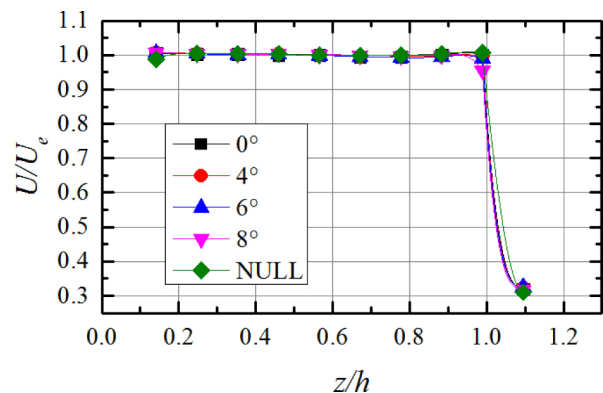


Figure 7. Velocity distribution along $x/h=0.25$, $y/h=0$ at 25m/s

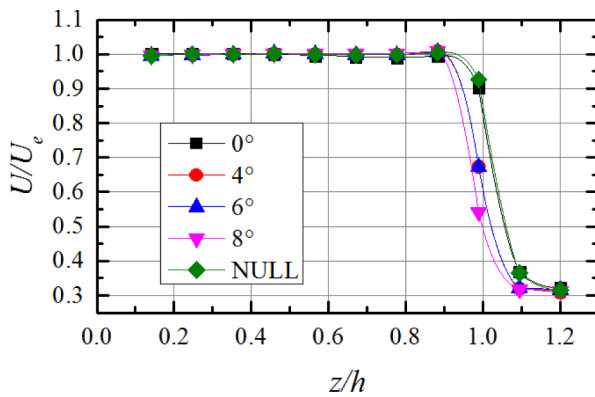


Figure 8. Velocity distribution along $z/h=0.90, y/h=0$ at 25m/s

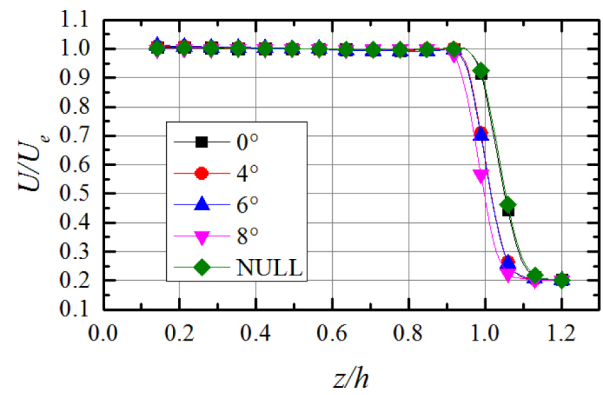


Figure 11. Velocity distribution along $z/h=0.90, y/h=0$ at 45m/s

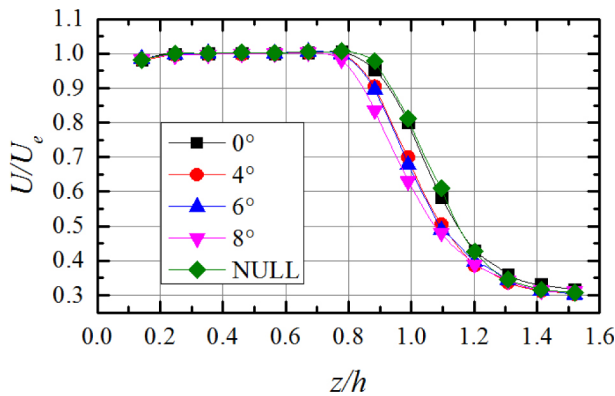


Figure 9. Velocity distribution along $x/h=2.70, y/h=0$ at 25m/s

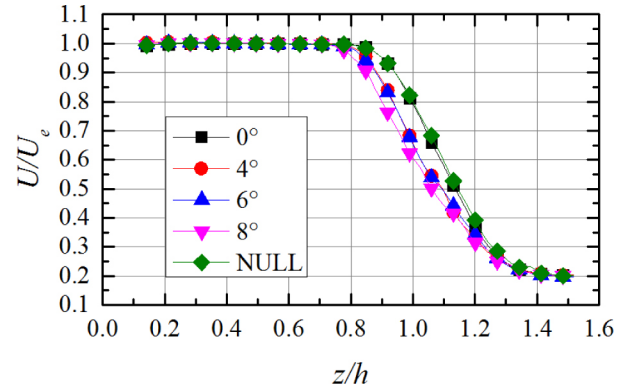


Figure 12. Velocity distribution along $x/h=2.70, y/h=0$ at 45m/s

Figure 10–12 display the mean velocity profiles at the same positions as that in Figure 7–9. The wind tunnel velocity of these three figures is 45m/s. The tendency of mean velocity profiles is basically the same as that in 25m/s.

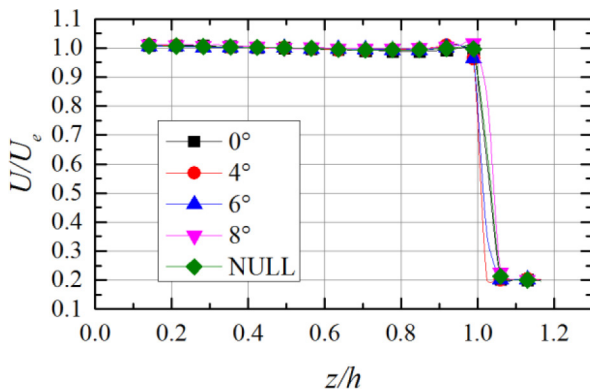


Figure 10. Velocity distribution along $x/h=0.25, y/h=0$ at 45m/s

Static Pressure Gradient

The effect of vortex generators on flow uniformity along the jet axis will be examined using static pressure gradient. The purpose of this examination is to check if there were any large pressure gradients created by different angle of vortex generators. The static pressure gradient profiles are presented in Figure 13 and 14 in the form of pressure coefficient, given by:

$$C_p = \frac{P_s - P_e}{q_e} \quad (3)$$

where P_s is the static pressure at the measurement point, P_e is the freestream static pressure at the nozzle center measured using a pitot static tube, and P_e is the freestream dynamic pressure at the nozzle center, given by:

$$q_e = \frac{1}{2} \rho U_e^2 \quad (4)$$

The flow inside the wind tunnel is considered incompressible because the Mach number is less than 0.3, therefore the density is considered constant, and according to Bernoulli equation, a simplified equation can be obtained as below:

$$C_p = \frac{U_e^2 - U^2}{U_e^2}$$